Measurements of Short-Circuiting within Emergent Marshes

A. F. Lightbody,[1] and H. M. Nepf[2]

[1]Ralph M. Parsons Laboratory, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue 48-216, Cambridge, MA 02139; PH (617) 899-8449; FAX (617) 258-8850; email: lightbod@mit.edu

[2]Ralph M. Parsons Laboratory, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue 48-216, Cambridge, MA 02139; PH (617) 253-8622; FAX (617) 258-8850; email: hmnepf@mit.edu

Velocity heterogeneity is present in nearly all wetland systems and results in some influent water remaining in the wetland for a time much shorter than the mean hydraulic residence time (Wörman and Kronnäs, 2005). This phenomenon, known as short-circuiting, alters the distribution of the chemical and biological transformations that occur within a wetland (Eriksson, 2001; Harvey et al., 2005), so the identification of fast flowpaths is an important step in understanding overall system function. Yet, to date, the contribution of short-circuiting has only been inferred from wetland-scale tracer studies (e.g., Keller and Bays, 2002) and dye studies with sampling stations separated by 100–400 m (e.g., Dierberg et al., 2005), rather than detailed observations of small-scale flow patterns. When short-circuiting is caused by a topographic feature, the fast flowpaths are easily identifiable. For example, in many natural wetlands, macrophytes fringe a central, deeper open channel, which carries a large fraction of water traveling through that wetland (Cooper, 1994; Dal Cin and Persson2000; Stern et al., 2001). Within the Everglades Nutrient Removal Project constructed wetland, abandoned agricultural ditches and borrow canals oriented parallel to flow create dramatic short circuiting (Guardo and Tomasello 1995, Dierberg et al., 2005). It is more difficult, however, to identify fast flowpaths in wetlands that do not contain any obvious channelized features parallel to the flow direction. This paper describes methods for identifying and quantifying the flow within short-circuiting flowpaths in marsh areas of wetlands.

Here, we describe field work within three of the twelve cells that comprise the 360-acre constructed treatment wetlands associated with the J. B. Messerly Wastewater Treatment Plant in Augusta, Georgia (Figure 1). During wetland

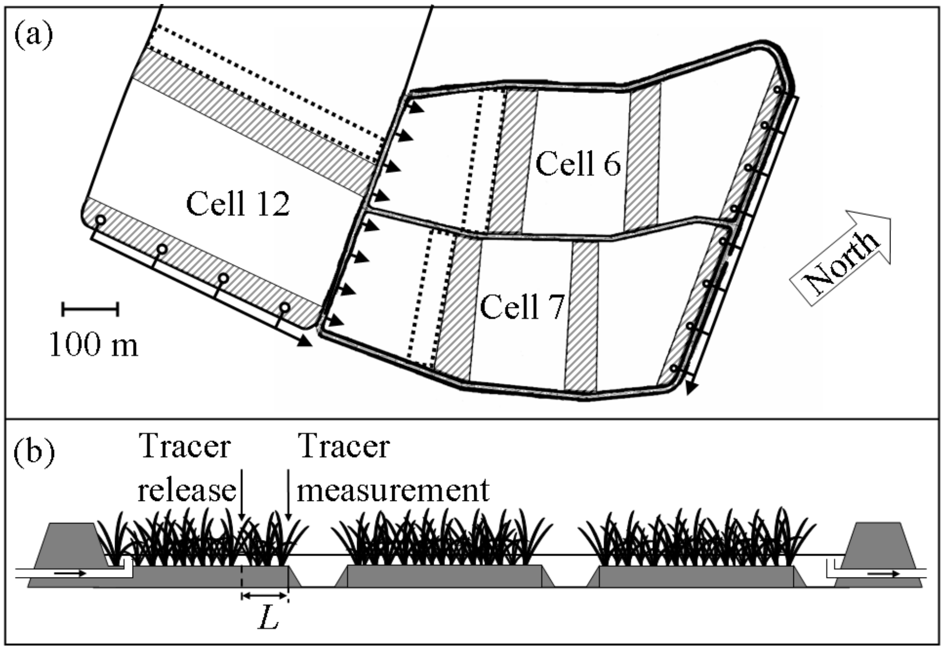

Figure 1. (a) Plan view of the three studied cells within the Messerly wetland. Deep zones are marked by hatching. Thick dotted lines surround the regions where dye studies were performed. (b) Schematic side view of a longitudinal cross-section through one of the cells, highlighting the bathymetry of the deep zones and the location of dye injection and measurement.

construction of Cell 12 in 2000 and Cells 6 and 7 in 2002, extensive grading removed natural microtopography, the remaining bottom topography was configured into an alternating pattern of flat marshes and deeper ditches, and macrophyte seedlings were planted uniformly every 1 m within marsh areas (Eidson and Flite, 2005). By 2006, marsh areas were covered by a dense and apparently uniform canopy of *Zizaniopsis miliacea*. During July 2006, steady flow conditions were present, and precipitation, evaporation, and infiltration were negligible. The plant flow entering each cell created a mean, or plug-flow, velocity of $U_{\mathrm{PF}} = 0.1$ cm s^{-1}.

Detailed tracer studies were used to determine the degree of short-circuiting within one vegetated marsh section of three different cells. Between 100-1000 mL of Intracid Rhodamine WT (Cromption and Knowles 20% liquid solution, density 1.1 g L^{-1}) was released in a line across the cell upstream of a region of dense vegetation of width L = 34–38 m. Over a week or more, Rhodamine WT is not conservative and will sorb to sediments and plant matter, which will result in an underestimation of travel times during a full-scale study in a wetland (Cooper, 1994; Lin et al., 2003; Keefe et al., 2004). However, it has been used successfully in short-term studies of less than 6 days (e.g., Stern et al., 2001; Lin et al., 2003). Our observations of short-circuiting tracer are restricted to less than 6 hr.

The appearance of the dye downstream of the dense vegetation was detected by towing an in-situ fluorometer (Seapoint Sensors, Exeter, New Hampshire) connected to a Conductivity Temperature Depth (CTD) probe (Ocean Sensors, San Diego, California) within an open deep zone along the downstream edge of the vegetation. The expected plug flow time of transit was $t_{\mathrm{PF}} = L/U_{\mathrm{PF}} = 11 \pm 5$ hr, but in each of the three cells examined, we identified between three and six distinct flowpaths contributing to dye transport prior to $t_{\mathrm{PF}}/2 = 6$ hr after release. These flowpaths had the same depth as the rest of the marsh. Detailed observations of flow speed were undertaken in the fast flowpaths using a 2-D sideways-looking acoustic Doppler velocimetry (ADV) probe (Flowtracker, SonTek/YSI, Inc., San Diego, California). The ADV measurements and the dye transport times both indicated that the fast flowpaths had an average velocity of 1.0 ± 0.2 cm s^{-1}. That is, the observed flow velocities within these areas were ten times faster than the expected plug-flow velocity. The flowpaths were narrow with an average width of 2.5 ± 0.5 m and in total occupied only 2–8% of the total cell width, but the fraction of flow traveling within them was 20–70% of the total flow through each wetland cell. These narrow fast flowpaths thus play a large role in transport through marsh regions.

Identifying fast flowpaths within emergent marshes is an ongoing challenge. Airborne laser scanning, vertical aerial photography, and other methods of generating digital elevation models and ground maps suggested by Järvelä et al. (2006) are not able to provide sufficient detail to identify 2-m-wide fast-flow zones through thickly vegetated marsh areas. In this study, we were unable even to use direct visual observation of the marsh edge to identify regions that made a large contribution to short circuiting, so we resorted to detailed and time-consuming dye studies. Airborne photography of a tracer release (Dierberg et al., 2005) has potential but still requires intensive on-the-ground support.

Temperature records taken simultaneously with the dye measurements suggest another possible technique for future identification of short-circuiting flowpaths. We placed temperature loggers (HOBO temperature logger, Onset Computer Co., Bourne, Massachusetts) within three areas within each cell: open water, fast flowpaths, and densely vegetated slow-flow zones. We observed that during the daytime water at the surface of open areas becomes 2°C warmer than water residing in vegetated areas, presumably because dense vegetation shades water passing beneath it. Because water traveled down fast flowpaths as a coherent stream and retained the thermal signature of an open water area upstream, its temperature was 0.9°C greater than water that traveled more slowly through dense vegetation. In fact, on some lateral traverses with the fluorometer and CTD probe, we detected elevated temperatures at the lateral locations where we observed short-circuiting (Figure 2). Therefore, one possible but as yet unexplored technique would be to map the afternoon or evening thermal signature of water exiting marsh regions using an infrared thermal image of the wetland or a high-resolution fiber-optic cable, both of which are now able to detect temperature differences of 0.1°C at 1-m spatial resolution (Loheide and Gorelick, 2006; Selker et al., 2006).

Note, however, that although temperature signatures may help identify the location and width of fast flowpaths, they could not directly quantify the amount of

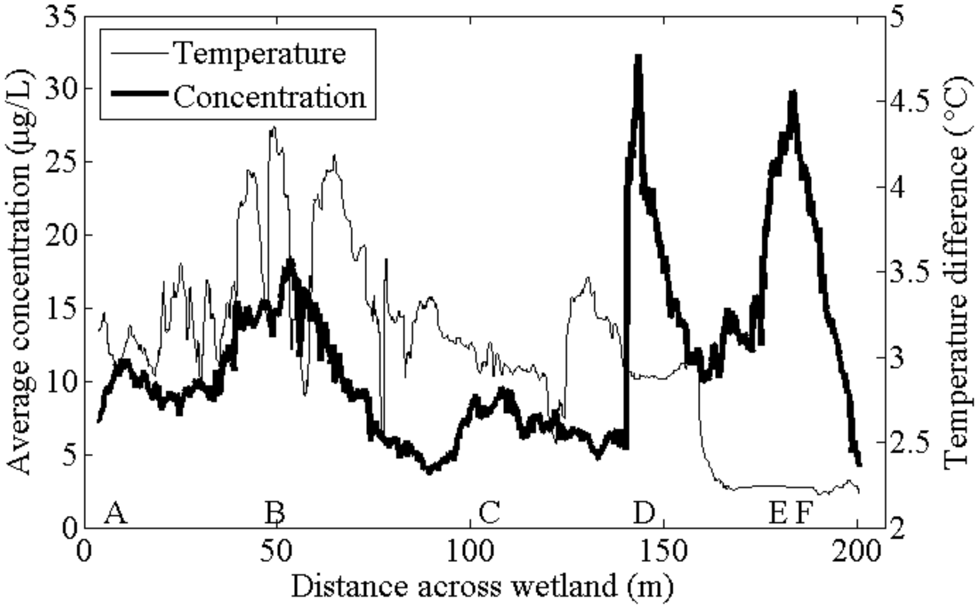

Figure 2. Comparison between lateral locations with short-circuiting flow and water temperature. The thick line shows the average tracer concentration measured exiting a 38-m-long swath of vegetation before $t_{PF}/2$ in Cell 7 on July 19. Letters at the bottom indicate the lateral locations of the six flowpaths subsequently identified in this cell. The thin lines show the difference between 30-cm-deep CTD measurements of temperature taken during boat transects at the downstream edge of the vegetation and a simultaneous stationary logger measurement at the same depth at 3:30 pm on July 24.

short-circuiting flow. One possibility would be to determine the rate at which warm short-circuiting water passing through dense vegetation loses heat, and then use an observed temperature decrease over a known distance to estimate the transit time. Another possibility would be to assume a fixed flow speed for all short-circuiting water. Additional detailed studies that quantify the amount of short-circuiting water in a variety of wetland types and locations are therefore necessary before temperature signatures can be used to identify and quantify the flow within short-circuiting wetland marsh regions.

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