



## Hydroecological factors governing surface water flow on a low-gradient floodplain

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[1] Interrelationships between hydrology and aquatic ecosystems are better understood in streams and rivers compared to their surrounding floodplains. Our goal was to characterize the hydrology of the Everglades ridge and slough floodplain ecosystem, which is valued for the comparatively high biodiversity and connectivity of its parallel-drainage features but which has been degraded over the past century in response to flow reductions associated with flood control. We measured flow velocity, water depth, and wind velocity continuously for 3 years in an area of the Everglades with well-preserved parallel-drainage features (i.e., 200-m wide sloughs interspersed with slightly higher elevation and more densely vegetated ridges). Mean daily flow velocity averaged  $0.32 \text{ cm s}^{-1}$  and ranged between  $0.02$  and  $0.79 \text{ cm s}^{-1}$ . Highest sustained velocities were associated with flow pulses caused by water releases from upstream hydraulic control structures that increased flow velocity by a factor of 2–3 on the floodplain for weeks at a time. The highest instantaneous measurements of flow velocity were associated with the passage of Hurricane Wilma in 2005 when the inverse barometric pressure effect increased flow velocity up to  $5 \text{ cm s}^{-1}$  for several hours. Time-averaged flow velocities were 29% greater in sloughs compared to ridges because of marginally higher vegetative drag in ridges compared to sloughs, which contributed modestly (relative to greater water depth and flow duration in sloughs compared to ridges) to the predominant fraction (86%) of total discharge through the landscape occurring in sloughs. Univariate scaling relationships developed from theory of flow through vegetation, and our field data indicated that flow velocity increases with the square of water surface slope and the fourth power of stem diameter, decreases in direct proportion with increasing frontal area of vegetation, and is unrelated to water depth except for the influence that water depth has in controlling the submergence height of vegetation that varies vertically in its architectural characteristics. In the Everglades the result of interactions among controlling variables was that flow velocity was dominantly controlled by water surface slope variations responding to flow pulses more than spatial variation in vegetation characteristics or fluctuating water depth. Our findings indicate that floodplain managers could, in addition to managing water depth, manipulate the frequency and duration of inflow pulses to manage water surface slope, which would add further control over flow velocities, water residence times, sediment settling, biogeochemical transformations, and other processes that are important to floodplain function.

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### 1. Introduction

[2] Feedbacks between hydrologic and ecologic processes are integral to the function of flowing aquatic ecosystems, and these processes must be understood thoroughly if scientifically based management planning for watersheds is to be fully successful [Allan, 1995; Naiman and Décamps, 1997; Palmer and Poff, 1997; National Research Council, 2003; Palmer and Bernhardt, 2006; Doyle et al.,

2007]. Human alterations of flow regimes have consequences for transport and fate of sediments and energy and nutrient-rich materials, which in turn interact with aquatic, emergent, and riparian vegetation in ways that fundamentally alter biotic productivity, diversity, and overall ecosystems functions of river corridor ecosystems [Poff et al., 1997; Ward et al., 1999; Palmer and Bernhardt, 2006].

[3] Flooding is of considerable importance in structuring aquatic ecosystems because of its enhancement of the transport of sediments and dissolved materials. Redistribution of sediment and dissolved material is a key process that supplements floodplain nutrient budgets and contributes to establishing productive vegetation, which in turn increases

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secondary productivity of the adjacent channels [Junk *et al.*, 1989; Bayley, 1991; Galat *et al.*, 1998; Tockner *et al.*, 2000]. The delivery of large loads of suspended sediment and dissolved materials in flood pulses to riverine floodplains influences fish and bird habitat preferences [e.g., Junk *et al.*, 1989], enhances floodplain ecosystem productivity [Mitsch, 1988; Odum *et al.*, 1995; Day *et al.*, 2003] and biodiversity [Middleton, 2002], and increases the residence time of nutrients and sediment in river corridors [Craft and Casey, 2000; Stromberg, 2001; Nahlik and Mitsch, 2005].

[4] There is less understanding of hydrological processes on floodplains compared with channel flow. For example, the effort to develop and verify a relationship between flow velocity and resistance, which is integral to understanding flow and material transport in shallow aquatic ecosystems, has not progressed nearly as far for floodplains as it has for open channels [Alsdorf *et al.*, 2007]. Most of what is known about floodplain hydraulics comes from the investigations by fluvial geomorphologists who have related floodplain geomorphic features and the grain size of floodplain deposits to general features of flood stage, discharge, flood frequency, and floodwater source [Hupp and Osterkamp, 1985; Pinay *et al.*, 1992; Mertes, 1997; Tooth and Nanson, 2000; Hupp, 2000; Ross *et al.*, 2004].

[5] There are an increasing number of investigations identifying feedbacks between flow and aquatic and riparian vegetation, including interactions that cause adjustments in channel width [Huang and Nanson, 1997; Harvey *et al.*, 2003; Anderson *et al.*, 2004], channel depth [Hey and Thorne, 1986; Huang and Nanson, 1997], and also relationships between changing channel morphology and the frequency of flood or drought occurrences [Bendix and Hupp, 2000; Tabacchi *et al.*, 2000; Harvey *et al.*, 2003; Griffin and Smith, 2004; Smith, 2004]. On longer time scales of decades to centuries, the interactions between hydraulics and vegetation are fundamental contributors to changing geomorphology of riverine and wetland floodplains. In expansive wetlands with organic soils such as the Everglades [Larsen *et al.*, 2007], Okavango Delta [Ellery *et al.*, 2003; Gumbricht *et al.*, 2004], and Brazilian Pantanal [Silva *et al.*, 1999], the topography evolves toward characteristic linear features of channels (i.e., sloughs) interspersed between more densely vegetated ridges.

[6] Underlying long-term geomorphic and ecological evolution of floodplains are fundamental hydrodynamic interactions between flow and the architecture of the submerged, emergent, and riparian vegetation communities that impede flow on floodplains. Hydrodynamic theory and experiments both indicate that drag on vegetation stems is the dominant form of flow resistance in vegetated flow systems [see Nepf, 2004, and references therein]. In all but the most sparsely vegetated wetland environments, flow resistance due to bed roughness and wind shear on the water surface tend to be relatively unimportant. Thus, vegetative flow resistance is important in controlling the rate of down-gradient transport of nutrient and energy-rich compounds on floodplains [Leonard and Reed, 2002; White *et al.*, 2004] with additional processes such as interception of suspended particles on vegetation stems imparting further controls [Saiers *et al.*, 2003; Palmer *et al.*, 2004]. Not nearly enough is known about these processes in field situations, especially over full wet seasons or during flood pulses. Our objective

was to obtain such a record in the Everglades with the goal to determine the relative importance of the hydrological and ecological factors that determine flow conditions.

### 1.1. Everglades Hydroecology

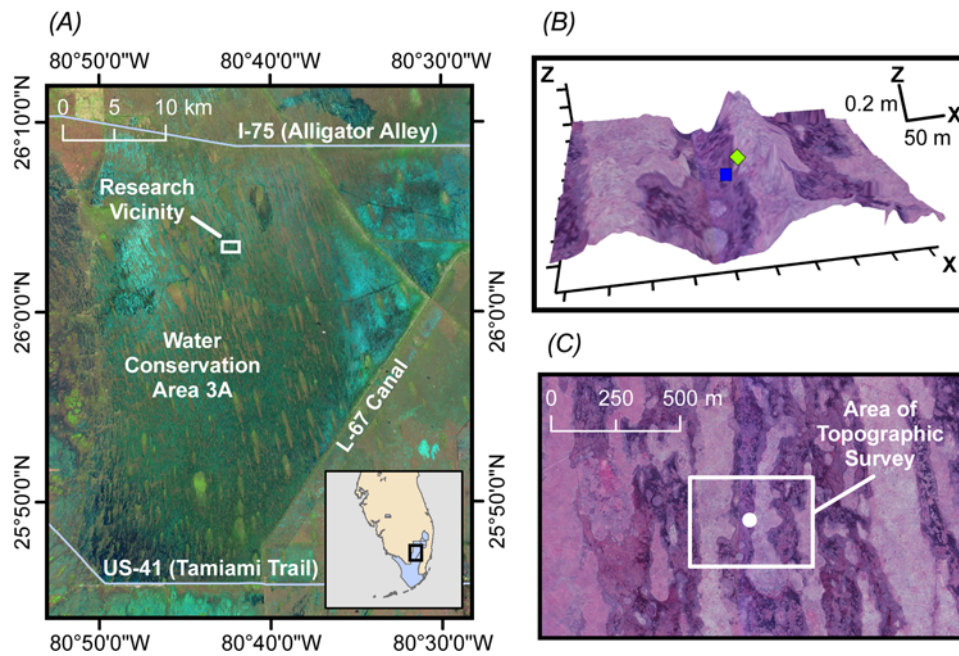
[7] The Everglades is one of the world's very large, subtropical, low-gradient peatlands vegetated with emergent macrophytes tolerant of very low nutrient conditions. A century ago the flowing surface water of the Everglades was controlled only by inputs from rainfall, overflow from Lake Okeechobee (situated at the Everglades northern boundary), and shallow surface and subsurface drainage from surrounding uplands. Over the past century the Everglades' flow system has increasingly been managed for water conservation and flood control. An extensive system of levees now encloses large water storage basins in the central Everglades and a system of canals, spillways, and hydraulic pumps moves water between these basins.

[8] Everglades' wetland flow velocities are generally in the subcentimeter per second range and water depths typically range from 0 to 70 cm deep [Riscassi and Shaffranek, 2004]. These flows are categorized as laminar to transitional [Lee *et al.*, 2004;]. Flow velocities vary vertically [Bazante *et al.*, 2006; Harvey *et al.*, 2005, Leonard *et al.*, 2006] in accordance with drag characteristics of the vegetation [Lee *et al.*, 2004; this study]. The concentration of suspended particles is generally low in the Everglades [Bazante *et al.*, 2006], but the fate of these particles is important because they sequester a significant percentage of available phosphorus, the limiting nutrient in the Everglades [Noe *et al.*, 2007]. In addition to being a dominant factor controlling flow resistance, wetland vegetation also accounts for significant removal of suspended particles by interception on plant stems [Saiers *et al.*, 2003; Huang *et al.*, 2008].

[9] Over the past century, much of the preexisting Everglades' ridge and slough landscape was degraded by anthropogenic causes (Science Coordination Team, South Florida Ecosystems Restoration Working Group, The role of flow in the Everglades ridge and slough landscape, 2003, available at [http://sofia.usgs.gov/publications/papers/set\\_flows](http://sofia.usgs.gov/publications/papers/set_flows)). It has been proposed that topographically degraded areas and their accompanying depletion of biodiversity can be restored through changes in water management practices [National Research Council, 2003]. However, the main factors responsible for this degradation are still in question, in part because of a lack of knowledge of flow and sediment transport and redistribution processes in the ridge and slough environment [National Research Council, 2003]. Previous measurements of flow and vegetation characteristics within different plant communities of the Everglades exist [Lee *et al.*, 2004; Leonard *et al.*, 2006], but the short-term nature of these measurements limits their use for seasonal or multiyear interpretations. Available longer-term flow measurements [Riscassi and Schaffranek, 2004] generally lack the needed ancillary quantitative measurements of vegetation characteristics and local water surface slope that are necessary for a theory-based analysis of interactions between flow inputs and flow resistance over a range of water depths.

### 1.2. Present Research

[10] The present study sought to advance our knowledge of interactions between flow and vegetation on floodplains



**Figure 1.** (a) Satellite image of the parallel-drainage landscape composed of tree islands, ridges, and sloughs in Everglades Water Conservation Area 3A with identification of the research vicinity. (b) Three-dimensional image of the landscape topography for a 500-m  $\times$  300-m area in the immediate vicinity of the velocity measurement site in the slough (blue square) and ridge (green diamond). A single increment on the  $x$  axis represents 50 m, but on the vertically exaggerated  $z$  axis, one increment equals 0.1 m. (c) Section of a digital orthophoto quadrangle (DOQ) image (also used in Figure 1b) showing the research vicinity in the context of surrounding ridges (lighter areas) and sloughs (darker areas).

through instrumentation for continuous flow measurement over 3 years in the Everglades. This long-term data set allowed the relative importance of various factors controlling flow to be assessed, including topographic and vegetative variability, water depth, water surface slope, and vegetative flow resistance. The conclusions derived from the data and modeling interpretations are relevant to all vegetated floodplains and especially to low-gradient floodplains like the Everglades. In addition to providing insights about floodplain hydraulics and their relation to vegetation, the results contribute to increased understanding of related functional attributes, such as advection, dispersion, and reaction of dissolved and sediment-associated nutrients and contaminants, entrainment and redistribution of suspended sediments, as well as other processes that influence health and sustainability of aquatic ecosystems with floodplains.

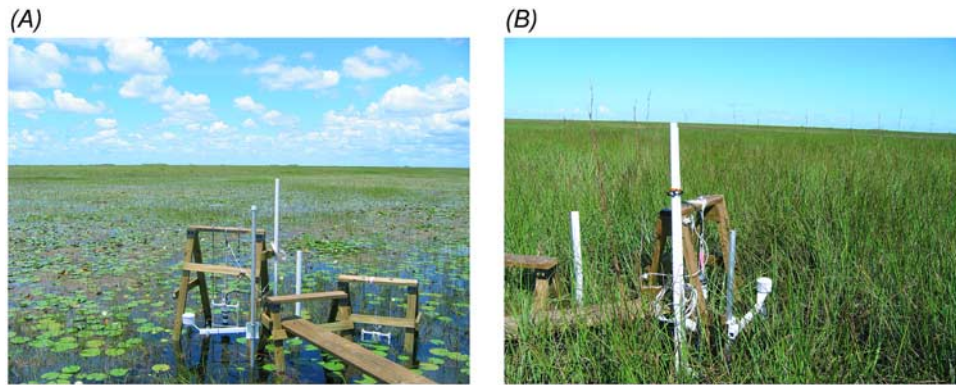
## 2. Research Site Characteristics

[11] The central Everglades comprises several very large basins referred to as water conservation areas that have been constructed between Lake Okeechobee to the north and Everglades National Park to the south. A site in central Water Conservation Area 3A (WCA-3A) which contains the largest remaining area of remnant ridge and slough landscape was selected to monitor flows. The research site ( $26^{\circ}03'23.7''\text{N}$ ,  $80^{\circ}42'19.2''\text{W}$ ), known as site WCA-3A5, is located in an area with characteristic parallel-drainage features consisting of elongated tree islands and sawgrass ridges separated by less densely vegetated sloughs in a NNW-SSE alignment (Figure 1a). Continuous measurements of flow velocity, water level, water temperature, air

temperature, wind speed and direction, and precipitation were made at the site from August 2005 through February 2008.

[12] Interannual variation in flow and water level are referenced by water year (May through April of the following year). The Everglades' wet season typically occurs from May to October and the dry season occurs from November to April, although the beginning and end of the wet season are significantly linked to the onset and length of the tropical storm and hurricane season. Hydraulic structure operations also variously affect the timing and extent of wet seasons within the storage basins that comprise the central Everglades and Everglades National Park located farther to the south. Water levels at the research site typically range from 10–70 cm above the bed surface in the slough during the wet season (May–October) and from 40 cm above to 40 cm below the peat surface in the slough during the dry season (November–April). The bed surface is composed of a relatively loose 3 to 7 cm thick layer of flocculent organic matter (floc) on top of a layer of denser and more refractory peat (approximately 1.2 m thick) that is situated above a sand and limestone aquifer system [Harvey *et al.*, 2004].

[13] Ground surface elevations were measured at a spacing of 2 to 5 m along five east–west transects and at additional points between transects to quantify the local topography. Topographic data were combined and kriged to produce the 3-D plot of ground surface elevations illustrated in Figure 1b. The plot of elevations is overlain on a digital orthophoto quadrangle (DOQ) image of the area that is shown in Figure 1c. Ridges are typically 100 m wide and are separated by sloughs that are 100–250 m wide. The 3-D



**Figure 2.** Photographs of velocity measurement platforms in the (a) slough and (b) ridge located in Water Conservation Area 3A at the site shown in Figure 1.

plot of ground surface elevations in Figure 1b illustrates the ridge and slough topographic patterning with ridges typically being 20–30 cm higher than intervening sloughs. Color variations in the DOQ image of Figure 1c identify different vegetation community types, with the lighter colored ridges being densely colonized by a monospecific stand of sawgrass (*Cladium jamaicense*) compared with the darker colored sloughs, which have a more diverse assemblage of vegetation consisting of water lily (*Nymphaea odorata*), spikerush (*Eleocharis* spp.), floating bladderworts (*Utricularia* spp.), and floating and epiphytic forms of periphyton primarily colonizing the bladderwort and spikerush species (Figure 2). The transition from slough vegetation to predominantly sawgrass on the ridges typically occurs over a 10–20 m horizontal distance.

[14] On 24 October 2005 the eye of Hurricane Wilma, a category 3 storm, passed directly over the research site, eliminating the floating *Utricularia* mats and associated periphyton. Although the floating mat remained mostly absent through the 2006 water year, there was partial compensation through increased growth of epiphyton on stems and leaves of emergent macrophytes. By the third year the floating mat had begun to reestablish itself but was still relatively sparse.

### 3. Theory and Methods

#### 3.1. Mechanics of Flow Across Vegetated Floodplains

[15] In steady uniform flow, the gravitational force driving horizontal flow of surface water is balanced by the sum of vegetative drag and bed shear [Burke and Stolzenbach, 1983]. Written in units of force per unit mass, or acceleration, the appropriate depth-averaged force balance is

$$gS = \frac{1}{2} \bar{C}_D a U^2 + \frac{\tau_0}{\rho H} \quad (1)$$

where gravitational forcing is the product of gravitational acceleration,  $g$ , and energy slope,  $S$ . Vegetative drag (first term on right-hand side of equation (1)) is the product of a bulk vegetative drag coefficient,  $\bar{C}_D$ , mean water column velocity,  $U$ , and the projected frontal area of vegetation per unit volume,  $a$ . The last term is the bed shear term which equals bed shear stress,  $\tau_0$ , divided by water density,  $\rho$ , and water depth,  $H$ . Since bed shear is typically much less

than the vegetative drag in these systems [Kadlec, 1990; Abdelsalam et al., 1992; Leonard and Luther, 1995; Fathi-Maghadam and Kouwen, 1997] bed shear can effectively be ignored for flow through vegetation. Note that water depth has no direct control over flow through vegetation if bed shear is ignored. This is especially likely if the vegetation is emergent, i.e., if it extends entirely through the flow and protrudes above the water surface. However, water depth can still be indirectly important in controlling velocity if the frontal area of vegetation varies substantially with height over the depth range that water level typically varies.

[16] Recent experimental work developed and verified drag formulations that are relevant for emergent vegetation at the typical vegetation densities and flow conditions of the Everglades. Flow in the Everglades is laminar and only occasionally transitional to turbulent [Riscassi and Schaffranek, 2004; Harvey et al., 2005], as characterized by a stem-based Reynolds number  $< \sim 200$  ( $Re_d = Ud/\nu$ , where  $d$  is average stem diameter and  $\nu$  is the kinematic viscosity). A key area of investigation in vegetated flows is improving the functional relationships that affect the vegetative drag term in equation (1). Researchers measuring drag on single cylinders demonstrated a strong negative dependence of the drag coefficient on flow velocity under laminar but not turbulent flow conditions [Dennis and Chang, 1970; Fornberg, 1980; summarized in the textbook by Panton, 2005]. At higher flows, stem wakes become turbulent and  $\bar{C}_D$  begins to lose its dependency on Reynolds number although it retains its dependence on vegetation properties. Raupach [1992] used physical reasoning to extend the theory of drag on single cylinders to multiple cylinders. Studies such as Bokaian and Geoola [1984], Nepf [1999], and Tanino and Nepf [2008] tested theory in laboratory flumes with multiple cylinder arrays representing vegetation. Nepf [1999] demonstrated that  $\bar{C}_D$  is negatively related to the area fraction of vegetation in the bulk volume,  $ad$ , i.e., the product of the frontal area of all cylinders and cylinder diameter. The negative relationship is the result of wake sheltering behind cylinders that causes drag from the whole array to be less than the sum of drag from individual stems. Nepf's [1999] numerical model of the negative relationship between bulk drag and  $ad$  provided a good fit to the central tendency for a variety of published experimental data.  $\bar{C}_D$ 's dependency on vegetation characteristics was also determined in real vegetation by Lee et al. [2004]. Their

expression for drag was in terms of  $a$  and  $1/s$  (i.e., where  $s$  is stem spacing which is equal to  $(d/a)^{0.5}$ ), which when rearranged results in  $\bar{C}_D$  scaling with  $(ad)^{-0.5}$ . Thus, it is very similar to *Nepf's* [1999] model relationship which has a slope of approximately  $-0.5$  on a log-log plot of bulk drag versus  $ad$  for values of  $ad$  above  $10^{-2}$ .

[17] For the laminar flow conditions in the Everglades and many other wetlands and floodplains with surface flow, it is necessary to specify the functional relationship between drag and Reynolds number in addition to specifying the relationship with vegetation characteristics. Because of the difficulty of precisely calculating the effect of Reynolds number on cylinder drag, the functional relationship is typically determined empirically [Panton, 2005]. Some investigators choose to apply empirical relationships developed from experiments using a single cylinder [e.g., *Lightbody and Nepf*, 2006], while others have collected sufficient data to measure the functional relationship in their own experimental system [e.g., *Lee et al.*, 2004].

### 3.2. Analysis of Vegetative Drag

[18] All of the calculations we made with Everglades data assumed locally steady conditions even though the Everglades flow system is characterized by gradually varying flows. This assumption is valid in flow systems when flow changes are slow relative to energy and fluid transport rates through the region represented by the measurements. Ignoring the effects of bed shear on flow resistance, the drag force per unit mass in flow through a vegetation canopy can be expressed as

$$gS = \frac{1}{2} \bar{C}_D \rho a U^2 \quad (2)$$

in flow that is uniform (or nearly so). *Lee et al.* [2004] estimated drag in Everglades vegetation and its dependency on characteristics of the vegetation and on Reynolds number. Measurements were made in the field and in experiments where sawgrass was planted in flumes. *Lee et al.* had a goal to incorporate functional relationships for drag's dependencies explicitly as a part of the drag term in equation (2). They performed a Buckingham Pi dimensional analysis to express drag as a function of dimensionless scaling terms using the following variables: water density, viscosity, velocity, flow depth, stem spacing, and stem diameter. Regression analysis identified one term ( $d/s$ ) that was poorly correlated with dimensionless drag and could be eliminated from the expression. The other two terms were combined and the expression was rewritten in terms of the drag coefficient  $\bar{C}_D$ . *Lee et al.'s* [2004] equation used stem spacing,  $s$ , as a variable where  $s = (a/d)^{0.5}$ . We rewrote the equation by eliminating  $s$  to emphasize agreement with previous work that  $\bar{C}_D \sim (ad)^{-0.5}$  because of increased wake sheltering at higher densities that reduces bulk drag [Nepf, 1999]. The new expression is

$$\bar{C}_D = 2K_0 \text{Re}_{d,h}^{-k} (ad)^{-0.5} \quad (3)$$

where the Reynolds number is either a stem diameter-based Reynolds number ( $\text{Re}_d = \frac{Ud}{\nu}$ ) or a water depth-based Reynolds number ( $\text{Re}_h = \frac{UH}{\nu}$ ) depending on how the dimensionless scaling terms are grouped, and  $K_0$  and  $k$  are

constants related to drag's dependence on Reynolds number that need to be determined empirically from further data analysis. In their analysis *Lee et al.* [2004] ultimately chose to develop the scaling for drag on the basis of a water depth-based Reynolds number. When we repeated the Buckingham Pi dimensional analysis we grouped the terms differently to ensure that scaling was based on a stem diameter-based Reynolds number, to be consistent with physical reasoning that stem diameter and not water depth is the most relevant length to scale flow through emergent vegetation. As in their dimensional analysis, we also identified a dimensionless term (in our case  $H/(d/a)^{-0.5}$ ) that was poorly correlated with drag that could be eliminated from equation (3).

[19] The derived expression for  $\bar{C}_D$  with its empirical coefficients (equation (3)) was substituted into the force balance (equation (2)) to produce

$$gS = K_0 \text{Re}_{d,h}^{-k} (ad)^{-0.5} a U^2 \quad (4)$$

which was rearranged to allow drag's dependency on  $\text{Re}$  to be estimated by isolating  $\text{Re}$  and the empirical coefficients on the right-hand side of the equation and collecting the other more easily measured terms on the left side in a term that we refer to as a dimensionless drag coefficient,  $F^*$ :

$$F^* = \frac{gS}{U^2 a (ad)^{-0.5}} = K_0 \text{Re}_{d,h}^{-k} \quad (5)$$

The empirical coefficients  $K_0$  and  $k$  in equation (5) were estimated by linear regression of daily averaged measurements of  $F^*$  and  $\text{Re}$  plotted on log axes.  $F^*$  was computed using daily average measurements of mean water column velocity,  $U$  and water surface slope,  $S$ , respectively, as described in sections 3.5 and 3.7. Depth-averaged stem diameter and frontal area were computed each day by interpolating the incremental values of  $d$  and  $a$  reported in Table 1 for the average depth of surface water observed on that day.

[20] According to *Lee et al.* [2004] and previous authors cited therein, the fitting coefficient  $k$  expresses the dependence of drag on Reynolds number whereas the fitting coefficient  $K_0$  expresses how the characteristics of the stems themselves (i.e., details of stem shape and the roughness of the stem surface) affect drag. We conducted the regression analysis to determine these empirical coefficients twice using both our and *Lee et al.'s* slightly different approaches (i.e., using the stem diameter-based Reynolds number that we advocate and also using the water depth-based Reynolds number following *Lee et al.*). The purpose of conducting the analysis twice was to see how different the results were and to judge which was more useful to improving understanding of the controls on vegetated flow.

[21] In addition to developing functional relationships for vegetative drag, we also wanted to take the analysis a step further by assuming constant viscosity properties and rewriting (4) as a scaling equation:

$$S \sim U^{2-k} d^{-0.5-k} a^{0.5} \quad (6)$$

The scaling exponents in equation (6) were enumerated after inserting the value for  $k$  that was determined by regression analysis that used equation (5) to determine

**Table 1.** Mean Frontal Area, Stem Diameter, and Vegetation Biovolume in Slough and Ridge Subenvironments at the Water Conservation Area 3A-5 Study Site<sup>a</sup>

	Vegetative Frontal Area, <i>a</i> (cm <sup>-1</sup> )					Count-Weighted Mean Stem and Leaf Diameter, <i>d</i> (cm)					Vegetation Biovolume, <i>V<sub>v</sub>/I<sub>b</sub></i>				
	0–17 cm	17–37 cm	37–57 cm	57–77 cm	Above Water	0–17 cm	17–37 cm	37–57 cm	57–77 cm	Above Water	0–17 cm	17–37 cm	37–57 cm	57–77 cm	Above Water
Slough: <i>Eleocharis</i>															
<i>elongata/Bacopa</i>															
<i>caroliniana</i>															
<i>Eleocharis elongata</i>	2.0E-02	1.5E-02	1.2E-02	4.5E-03	2.5E-03	0.10	0.10	0.10	0.10	0.09	1.5E-03	1.2E-03	8.7E-04	3.4E-04	1.8E-04
<i>Bacopa caroliniana</i>	5.2E-03	3.6E-03	2.0E-03	3.7E-04		0.34	0.36	0.50			1.4E-03	1.0E-03	5.9E-05		
<i>Nymphaea odorata</i> <sup>b</sup>	5.0E-04	5.5E-03	3.6E-04	3.7E-04		0.41	0.42	0.45	0.47		1.6E-04	2.3E-04	1.3E-04	1.4E-04	4.3E-04
<i>Utricularia purpurea</i>		3.8E-03	1.0E-03			0.04	0.04	0.04			3.3E-03	3.3E-03	5.8E-04		
<i>Panicum hemitomon</i>	4.7E-05	1.7E-04		6.5E-04	4.8E-04	0.23	0.21	0.21	0.32	0.15	8.6E-06	2.7E-05		3.2E-05	1.5E-05
All species combined	2.6E-02	2.9E-02	1.5E-02	5.5E-03	3.0E-03	0.12	0.11	0.11	0.11	0.10	3.1E-03	5.8E-03	1.6E-03	5.1E-04	6.3E-04
Ridge: <i>Cladium jamaicense</i>															
	0–13 cm	13–33 cm	33–53 cm	Above Water		0–13 cm	13–33 cm	33–53 cm	Above Water		0–13 cm	13–33 cm	33–53 cm	Above Water	
<i>Cladium jamaicense</i>	2.1E-02	1.6E-02	3.7E-02	4.4E-02		1.04	0.89	0.75	0.60		1.4E-02	7.2E-03	1.4E-02	1.3E-02	
<i>Utricularia foliosa</i>	7.5E-03		9.1E-05			0.04		0.23			3.2E-02		1.6E-05		
<i>Cephalanthus occidentalis</i>	9.7E-05		9.3E-05	6.0E-03		0.24		0.23	1.15		1.8E-05		1.7E-05	2.8E-04	
<i>Panicum hemitomon</i>	7.1E-05	8.6E-04	1.2E-04	2.2E-05		0.35	0.31	0.08	0.21		2.0E-05	2.1E-04	4.6E-07	8.2E-07	
<i>Justicia angusta</i>	1.9E-05	6.3E-05	1.4E-04	1.3E-04		0.30	0.02	0.35	0.32		3.4E-07	1.5E-05	3.9E-05	3.1E-05	
All species combined	2.8E-02	1.7E-02	3.8E-02	5.0E-02		1.00	0.71	0.72	0.63		4.6E-02	7.4E-03	1.4E-02	1.3E-02	

<sup>a</sup>Data include live and dead macrophytes categorized by height increments, with each increment referenced by its height range in height above the floc surface. Vegetation data are also reported for live and dead plant material collected above the water surface at time of sampling. Blank cells indicate that the species was not present in that vertical increment.

<sup>b</sup>Floating *Nymphaea odorata* leaves were not used in frontal area calculations.

drag's dependence on Reynolds number. Equation (6) can then be rearranged to determine scaling for  $U$  in terms of its dependence on water surface slope, vegetation stem diameter, and vegetation frontal area (i.e.,  $S$ ,  $d$ , and  $a$ ).

### 3.3. Continuous Measurements of Flow Velocity in the Slough and Ridge Subenvironments

[22] Flow velocities were measured over three water years at 30-min intervals at two fixed equipment locations at site WCA-3A5, one in the slough and one 14 m east on the ridge at site WCA-3A5. The research site was visited approximately monthly. Equipment locations were accessed via a platform that bridged the ridge to slough vegetation transition, providing access to both a water lily slough (Figure 2a) and a sawgrass ridge (Figure 2b) 20 cm higher than the slough. At each equipment location the flow velocity was measured at a fixed depth in the water column using 10 megahertz (MHz) acoustic Doppler velocimeters (ADV) manufactured by SonTek/YSI. The ADV approach can measure flow velocity to a resolution of  $0.01 \text{ cm s}^{-1}$  with an accuracy of 1% of measured velocity [SonTek, 2001]. Velocities were sampled at a frequency of 10 Hz in one minute bursts collected every 30 min. Velocity samples were filtered and edited according to standard criteria suggested by the instrument manufacturer as well as specific criteria that were developed and refined in a prior Everglades study [Riscassi and Schaffranek, 2002]. A minimum statistical correlation of 70% per sample and a minimum of 200 valid samples per burst were used as quantitative filters. Data with an acoustic signal-to-noise ratio (SNR) of 5 dB or less were subjected to additional quality assurance checks described in the next section. The resulting quality assured data set of 30-min point velocities was averaged to produce daily values which were modeled to produce daily velocity profiles and subsequently daily mean water column (i.e., depth-averaged) velocities that were used in further analyses. Modeling procedures are explained in section 3.5.

[23] The heights of the ADV sensors were determined mainly by the need to keep the sensor transducers submerged until the next site visit. The height of each ADV sensor was adjusted to keep the sampling volume approximately at or slightly below the middle depth of the water column anticipated for the deployment period. Sensor heights were based primarily on estimates of water levels for the next month, which usually proved successful in keeping the ADV transducers submerged between site visits. Over the 3-year time period of observations, the height of the ADV "point" sampling volume in the slough varied between 4 and 58 cm above the floc surface while the ridge ADV sampling volume height varied between 3 and 40 cm. The absolute minimum height of the downward looking ADV sensor head was approximately 7 cm above the top of the floc layer which fixed the sampling volume approximately 1.5 cm above the top of the floc. Since it was impossible to keep the sensor depth at a constant percentage of the total water depth (because of continuously changing water levels), the method of computing mean velocity needed to be account for those changes. Ancillary data collected at the WCA-3A5 platform to improve the interpretation of the ADV data included water level, water temperature measured at increments throughout the water column, air temperature, wind velocity, and rainfall.

### 3.4. Velocity Profile Measurements

[24] During the approximately monthly site visits, velocity profiles were collected at both the ridge and slough equipment locations. Velocity profiles were collected at the identical horizontal locations where the ridge and slough flow velocities were measured using the same ADV sensors deployed for continuous monitoring. This was accomplished by briefly interrupting that continuous monitoring long enough to complete one profile at the ridge and one at the slough for each site visit. Fewer profiles were collected on the ridge over the 3-year period because it was dry on several visits. In total, seventeen vertical velocity profiles were collected in the slough and eleven on the ridge over 3 years in water depths that ranged between 9 and 71 cm. For the profiles, velocities were measured at 10 Hz in 1 or 2 min bursts yielding 600 or 1200 samples, respectively, at each depth increment. Flow velocities were measured at 1.5, 3, or 6 cm depth increments throughout the water column, depending on total water depth, apparent vertical variability in vegetation architecture, and overall favorability of measurement conditions and time constraints.

[25] Criteria for editing the velocity profile data were developed as an extension of those used in the editing of the continuous point velocity data. In addition to using the same minimum 70% correlation filter used previously for point velocity data, a phase space threshold despiking process was also applied to the profile data [Goring and Nikora, 2002; Wahl, 2003]. SNR values were monitored continuously during collection of the vertical velocity profiles to determine if the ADV sample volume was obstructed by vegetation and as an indicator of the vertical location of the top of the floc, which proved useful for determining the minimum sampling height of the vertical velocity profile. The large number of samples averaged for each burst and the filtering and quality assurance procedures used to edit and process the data served to provide confidence that the maximum possible resolution ( $0.01 \text{ cm s}^{-1}$ ) reported for this instrumentation [SonTek, 2001] was achieved in these measurements.

### 3.5. Use of Velocity Profiles to Estimate Mean Water Column Velocity Estimates From Point Data

[26] In order to investigate long-term seasonal factors potentially affecting ridge and slough transport conditions, a robust interpolation method was needed that could use vertical profiles of flow velocities collected approximately monthly to estimate interim mean water column velocities from continuously monitored point velocity data. Mean water column velocities at the time of the site visits were computed directly from the profile data collected on those days. The method for computing mean water column velocities during interim periods had to use a velocity measurement at a single height (i.e., the fixed height of the ADV sensor). We used the modeling approach of Lightbody and Nepf [2006] to predict full velocity profiles in the ridge and slough on the basis of the measured vegetation characteristics and continuous measurements of velocity at a single height in the water column.

[27] Lightbody and Nepf's [2006] approach is based on a solution to the force balance for steady, uniform flow through vegetation (equation (2)) that predicts the vertical profile of vegetated flows as a function of the vegetation's

architecture, as represented by the frontal area parameter. The depth-dependent velocity is

$$u(y) = \bar{u} \sqrt{\frac{\bar{a}}{a(y)}} \quad (7)$$

where  $u(y)$  is flow velocity as a function of height above the bed,  $a(y)$  is vegetation frontal area as a function of height above the bed, and  $\bar{a}$  and  $\bar{u}$  are the reference frontal area and velocity measurements, respectively, i.e., measurements at a height specified by the investigator. According to *Lightbody and Nepf* [2006], equation (7) is only valid for emergent vegetation canopies that protrude entirely through the flow where the drag coefficient can be assumed to be constant with depth, and where the vegetation biovolume, i.e., the volume of plant material per water column bulk volume, can be accurately estimated as the product of frontal area and average stem diameter. The simplifications of equation (7) are typically met for situations where  $ad < 0.10$ , and for hydraulic conditions where  $Re_d$ , the stem diameter-based Reynolds number ( $Re_d = Ud/\nu$ , where  $\nu$  is the kinematic viscosity), ranges between 10 to 10,000.

[28] In our application of the *Lightbody and Nepf* [2006] approach, the point velocities came from the slough and ridge ADV sensors and the vegetation data collected in close proximity to those sensors were used. After the point velocity data were quality assured (see section 3.3) velocity values were averaged for the slough and ridge sites on a daily basis, followed by modeling to produce an average velocity profile in the slough and ridge for each day. The final step was to compute for each day the daily mean water column (i.e., depth-averaged) velocity for the slough and ridge using the equation below which is the integration of equation (7) over the water column depth  $H$ :

$$U = \frac{1}{H} \int_0^H \bar{u} \sqrt{\frac{\bar{a}}{a(y)}} \quad (8)$$

Unit width discharge (i.e., discharge through a cross section of unit width) in the slough and ridge was also averaged daily by multiplying each daily mean water column velocity by its corresponding daily mean water depth. The daily averaged quantities described above comprise the data set used in further analyses and are provided in the auxiliary material.<sup>1</sup> Data were summarized further for the entire study period by averaging mean water column velocities and discharges over the days in the data set with concurrent data in both the slough and ridge (239 days) and also over the total time period where surface water flow occurred (469 days) which included a significant fraction of time when flow only occurred in the slough.

### 3.6. Measurement of Vegetation Characteristics Affecting Drag

[29] During August 2005, detailed measurements were made of vegetation architecture, including sorting by species, counting the number of stems and leaves and measuring their diameters and widths, as well as determining the total biovolume of stems and leaves. All emergent and floating vegetation was collected within floating 0.25 m<sup>2</sup> square quadrats located randomly in undisturbed vegetation

in both the ridge and slough vegetation communities at site WCA-3A5. All data are reported herein on the basis of 1 m<sup>2</sup> of bed area.

[30] The quadrats were randomly tossed in each vegetation community and then adjusted to a position level with the water surface by returning any emergent stems displaced by the quadrat frame to their original orientation. Before beginning sampling, the quadrat location was secured by inserting PVC posts into the peat at the four corners of the quadrat frame. All live and dead macrophyte material located within the vertical planes defined by the quadrat boundaries was harvested by cutting material from above the water surface and then downward in 20 cm vertical increments. Plant material was sorted by species, bagged, and stored on ice until processing. Periphyton that was only loosely attached to the macrophytes was removed and not analyzed (except for periphyton attached to bladderwort *Utricularia* spp.) because of the physical disruption that occurred during harvesting, storage, and analysis.

[31] The diameter of every plant stem longer than 15 cm (or 10 randomly selected stems if the stem count exceeded 10) was measured for each species in every increment of the vegetation sample. Stem diameter was measured using a micrometer in the middle of the stem fragment along the widest dimension (major axis) and perpendicular to that dimension (minor axis). The width of leaves was measured at the widest point. Sawgrass (*Cladium jamaicense*) measurements needed to be handled differently because of the leaf's unique v-shaped cross section. Sawgrass leaf width was measured across the widest part of the v-shaped stem (i.e., across the top of the "v"), with an additional measurement of the minor axis dimension (i.e., from the base of the "v" to one of its tips). The average diameter of *Utricularia* spp. stems is difficult to determine because fronds are actually collections of very fine and dense leaflets, and, for the present study, we used a previous estimate of *Utricularia purpurea* stem diameter [Harvey et al., 2005].

[32] The vegetative biovolume fraction (referred to as "biovolume") is the volume of plant stems and leaves ( $V_V$ ) expressed as a fraction of the bulk volume of the water column ( $V_B$ ) [Nepf, 1999; Lee et al., 2004]. We determined  $V_V$  using two approximations. The first method was a dimensional volume calculation using the geometric measurements of plant architecture. The dimensional volumes of stems and leaves (excluding floating aquatic plants such as *Utricularia* spp.) were calculated as elliptical cylinders, with the exception that *Cladium jamaicense* leaves were calculated as solid triangular prisms. The second method was a displacement volume measurement. Plant material of each species from each depth increment was blotted or drip dried and then submerged in a graduated cylinder partially filled with water and the change in total volume was measured. For most species the dimensional and displacement volumes were similar (Pearson product moment correlation:  $r = 0.978$ ,  $p < 0.001$ ,  $n = 33$ ) and dimensional volume was used as an estimate of  $V_V$  in further calculations. After volume estimates were completed, dry mass was determined by drying all material at 60°C until consecutive measurements agreed.

[33] Flow resistance in vegetated environments is affected by specific characteristics of individual stems and by bulk

<sup>1</sup>Auxiliary material data sets are available at <ftp://ftp.agu.org/apend/wr/2008wr007129>. Other auxiliary material files are in the HTML.



characteristics such as stem density [Nepf, 1999; Lightbody and Nepf, 2006]. Vegetation frontal area of vegetation per unit volume  $a$ , generally referred to as frontal area, incorporates information about average stem diameter and stem density, and is therefore a useful integrator of vegetation's effect on the bulk characteristics of form drag. We computed frontal area as

$$a = \frac{n \cdot d}{A_Q} \quad (9)$$

where  $n$  is total leaf and stem count,  $A_Q$  is the surface area of the quadrat, and  $d$  is average stem diameter computed as the counterweighted average of leaf and stem diameters of the various species. Vegetation data are compiled in Table 1.

### 3.7. Estimation of Water Surface Slope

[34] Prior to 2006, the number of water level stations and precision of the vertical datum surveying were insufficient for our purpose of accurately estimating the extremely small water surface slope in central WCA-3A. Beginning in the 2006 water year (May 2006 to April 2007) a number of new water level stations were established in the vicinity of the research site (comprising a total of 13 water level measurement sites, including one on our research dock). These data were vertically referenced to one another through precision surveying and made accessible through the Everglades Depth Estimation Network (EDEN) database available at <http://sofia.usgs.gov/eden/models/watersurfacemod.php> [see also Pearlstine et al., 2007]. The slope of the water surface in the vicinity of our research site was estimated for each day of the study using the EDEN transect plotter application, available at <http://sofia.usgs.gov/eden/edenapps/transectplotter.php>. The transect plotter imports water surfaces created by radial basis function interpolation of daily median water level data, and calculates slope along a specified transect [Pearlstine et al., 2007]. We used the transect plotter to determine slope in a narrow, rectangular polygon (0.7 km wide by 4.3 km long) centered on the study site and oriented approximately parallel to the ridge and slough topography (which our flow measurements indicate is approximately parallel to the dominant flow direction).

[35] As a check, we independently determined slope using daily water surface elevation data from the 13 water level stations and interpolated water level using a kriging method. We then used ArcGIS to determine the average of all the individually determined water surface slope values for each cell in the polygon. The resulting slopes from the two approaches were very similar and therefore we only used the EDEN transect plotter in further analyses because of its simplicity and wide availability.

[36] To increase reliability of the water slope estimates, slopes were only generated for days when the ground surface of the computational polygon was completely inundated by surface water. Total surface water inundation in the vicinity of WCA-3A5 was verified by comparing water levels with ground surface elevation data obtained from high-resolution topographic surveys by USGS at <http://sofia.usgs.gov/eden/models/groundelevmod.php> [see also Jones and Price, 2007a, 2007b]. Vertical accuracy of the elevation data was  $\pm 15$  cm and horizontal distance between data points was approximately 400 m [Jones and

Price, 2007a]. The time period when water level data available from a sufficient number of EDEN water level stations met the established criteria (i.e., complete submergence within the computational polygon surrounding the WCA-3A5 site and concurrent ADV data) was 1 August 2006 to 1 January 2007 for the 2006 water year and 1 August 2007 to 15 January 2008 for the 2007 water year. To support further analysis we also obtained measurements of surface water inflows to WCA-3A through hydraulic structures at its northern boundary from the South Florida Water Management District database at [http://my.sfwmd.gov/dbhydroplsql/show\\_dbkey\\_info.main\\_menu](http://my.sfwmd.gov/dbhydroplsql/show_dbkey_info.main_menu).

## 4. Results

### 4.1. Patterns in Velocity Profiles and Mean Water Column Velocities

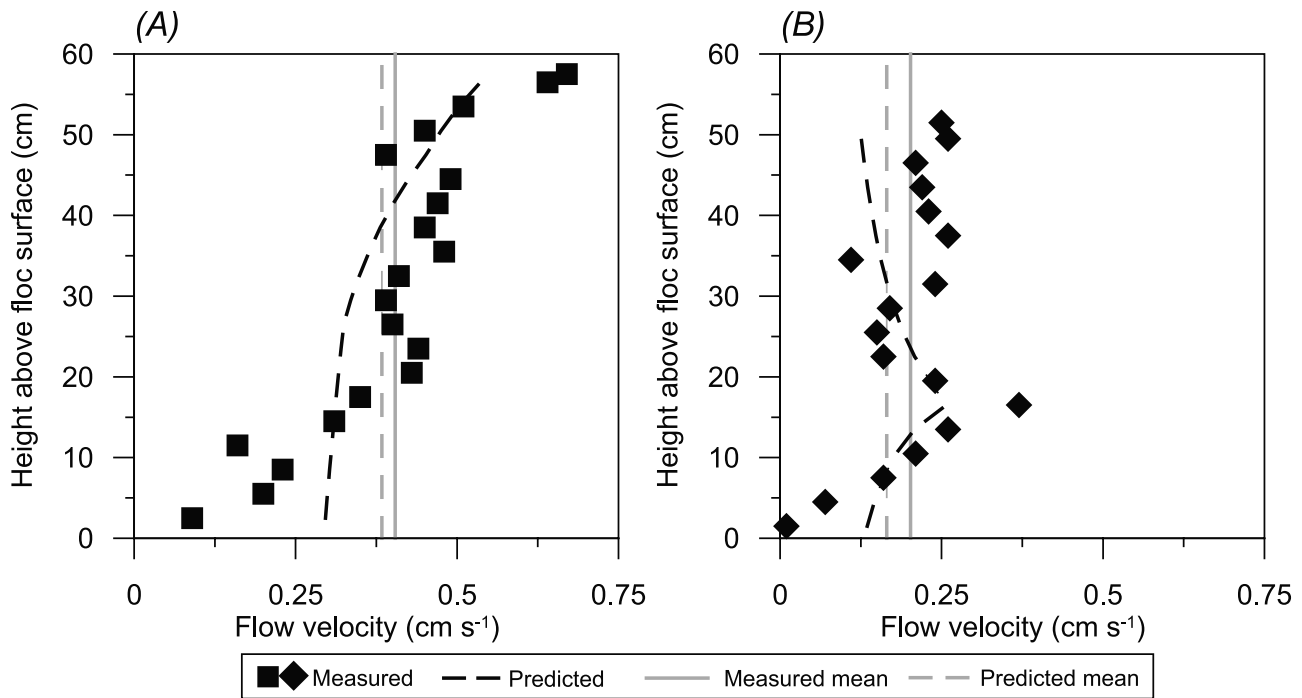
[37] Vertical patterns of velocity differed substantially between the slough and ridge. Slough velocities generally increased monotonically with height above the bed, whereas velocities on the ridge varied nonmonotonically above the bed with the highest velocity on the ridge occurring low in the water column. These depth patterns are illustrated by two representative velocity profiles selected from a total of 28 slough and ridge velocity profiles (Figure 3).

[38] The favorable agreement between measured velocity profiles and velocity profiles estimated by the Lightbody and Nepf [2006] approach is illustrated in Figure 3. In the ridge example (Figure 3b) the predicted profile is similar in shape to the measured profile, capturing the nonmonotonic pattern of variation. In the slough example (Figure 3a) the predicted and measured profiles both increase monotonically with height (Figure 3a) but the measured velocity profile is logarithmic in appearance while the predicted profile is more sigmoidal in shape. In terms of relative error the predicted profiles differ most markedly in the lowest 5 cm of the water column, most likely because the estimation method does not account for the effects of bed drag. The depth interval where velocity is affected by bed drag is usually only a relatively small part of the water column, however, which reduces the significance of the relatively poor fit near the bed to the estimation of mean water column velocities. The root-mean-square error for the two example profiles, calculated by comparing predicted and measured velocities at each 3 cm depth interval, was  $0.08 \text{ cm s}^{-1}$  and  $0.09 \text{ cm s}^{-1}$  for ridge and slough, respectively.

[39] The overall reliability of mean water column velocities estimated from point data using the Lightbody and Nepf [2006] approach was assessed by predicting  $U$  on the basis of vegetative frontal area data and a point velocity measured just prior to collecting a complete velocity profile, and comparing predicted  $U$  with  $U$  calculated directly from the profile. Root-mean-square errors of approximately  $0.08 \text{ cm s}^{-1}$  for the slough and  $0.13 \text{ cm s}^{-1}$  for the ridge were found between predicted and measured  $U$  for 17 slough and 11 ridge profiles. These values approximate the uncertainty in the daily mean water column velocities estimated from our continuous point velocity data.

### 4.2. Summary Statistics Indicating Flow Differences Between Slough and Ridge

[40] Over the 3 years of the study the mean daily water column flow velocities ranged between  $0.02$  and  $0.79 \text{ cm s}^{-1}$ ,



**Figure 3.** Representative measurements of flow velocity for (a) slough and (b) ridge, obtained on 8 November 2005 and 21 September 2005, respectively. Each plot includes the predicted flow velocity profile and a comparison between the measured and predicted mean water column velocities.

with ninety percent of all values falling between 0.10 and 0.59  $\text{cm s}^{-1}$ . The complete data set of daily averaged measurements is included in the auxiliary material, and unit (30-min interval) data are available upon request from the corresponding author. The mean water column flow velocity in the slough was 0.36  $\text{cm s}^{-1}$  in the slough compared with 0.28  $\text{cm s}^{-1}$  in the ridge during the time period of concurrent measurements (Table 2). This difference (29%) between slough and ridge velocities is statistically significant (paired  $t$  test,  $t = 7.132$ ,  $p \leq 0.00001$ ,  $n = 239$  days). Unit width discharge also was greater in the slough compared to the ridge because of both the higher velocity and greater water depth. Slough discharge was 115% greater than the ridge for the time period of concurrent data and 205% greater than the ridge for the total period of flow which includes times when the slough was conveying water but the ridge was dry (Table 2). Greater discharge through the slough is indicated by the proportional contributions of slough flow (86%) and ridge flow (14%) to total discharge through the ridge and slough landscape (Table 2). These proportional contributions were calculated by multiplying the unit width discharges for the total flow period by the appropriate percentage coverage in the landscape (i.e., 66.5% slough and 33.5% ridge from Wu *et al.* [2006]).

### 4.3. Ridge-Slough Difference in Vegetative Drag

[41] According to Lee *et al.* [2004] and previous authors [Wu *et al.*, 1999; Tsihrintzis, 2001], the intercept and slope of regression relationships (i.e.,  $K_o$  and  $k$ , respectively) on log-log plots of dimensionless drag versus Reynolds number quantify the characteristics of drag. The parameter  $K_o$ , i.e., the “intercept,” quantifies the relative effects of vegetation properties such as stem shape and surface rough-

ness on drag for a given flow condition, whereas the parameter  $k$ , i.e., the slope, quantifies drag’s negative dependence on Reynolds number.

[42] We found that dimensionless drag is consistently higher in the ridge compared to the slough across a range of flow conditions (Figure 4a). Greater vegetative drag in the ridge is indicated by the difference in intercepts in Figure 4a. The  $\log(K_o)$  value for the ridge ( $2.37 \pm 0.04$ ) is significantly greater than the slough  $\log(K_o)$  value ( $0.29 \pm 0.05$ ) ( $t$  test of different intercepts,  $t = 33.1$ ,  $p \leq 0.0000001$ ,  $n = 193$ ). In contrast, there is little difference between ridge and slough in terms of drag’s dependence on Reynolds number. The difference between ridge and slough slopes, i.e., the  $k$  values ( $1.54 \pm 0.03$  and  $1.73 \pm 0.08$ , respectively), is barely statistically significant ( $t$  test of different slopes,  $t = 2.21$ ,  $p = 0.028$ ,  $n = 193$ ), but the difference is small enough to be visually indistinguishable in Figure 4a and is probably limited in its practical significance.

### 4.4. Scaling Analysis to Assess the Relative Importance of Factors Controlling Flow Velocity

[43] The next step of the velocity scaling analysis developed in section 3.2 was to incorporate the dependency of vegetative drag on Reynolds number that was quantified in the previous section. Figure 4 compares results using a Reynolds number computed by normalizing flow velocity by stem diameter (Figure 4a) with the approach used by Lee *et al.* [2004], who normalized flow by water depth (Figure 4b). Better results using stem-based normalization of the flow condition are indicated by the greater explanatory power of the models in Figure 4a. The variance explained by linear regressions was greater for stem-based normalization of flow ( $R^2 = 0.97$  and  $0.81$  for ridge and slough, respectively) compared with water depth-based normalization ( $R^2 = 0.46$

**Table 2.** Summary Statistics for Mean Water Column Flow Velocity and Unit Width Discharge at the Slough and Ridge Measurement Locations at the Water Conservation Area 3A-5 Study Site

	Slough	Ridge
<i>Concurrent Flow Data Set<sup>a</sup></i>		
Number of days	239	239
Mean water column velocity (cm s <sup>-1</sup> )	0.36	0.28
90% velocity range (cm s <sup>-1</sup> )	0.16–0.56	0.11–0.50
Percent faster in slough	29	
Mean unit width discharge (m <sup>3</sup> m <sup>-1</sup> d <sup>-1</sup> )	157	73
Percent greater in slough	115	
<i>Total Period of Flow Data Set<sup>b</sup></i>		
Number of days	469	469
90% velocity range (cm s <sup>-1</sup> )	0.10–0.59	0–0.46
Mean unit width discharge (m <sup>3</sup> m <sup>-1</sup> d <sup>-1</sup> )	113	37
Percent greater in slough	205	
Weighted slough and ridge contributions to unit width discharge through landscape <sup>c</sup> (m <sup>3</sup> m <sup>-1</sup> d <sup>-1</sup> )	74.8	12.3
Proportional contribution to discharge from slough and ridge	86	14

<sup>a</sup>Concurrent data include all days with valid flow records on both the ridge and slough and exclude days when a low water level only permitted flow in the slough.

<sup>b</sup>Period of flow data includes all days for which valid flow records are available, including days when a low water level only permitted flow in the slough.

<sup>c</sup>Weighting uses areal percentage of ridges (33.5%) and sloughs (66.5%) in well preserved regions of the Everglades ridge and slough landscape from Wu et al. [2006].

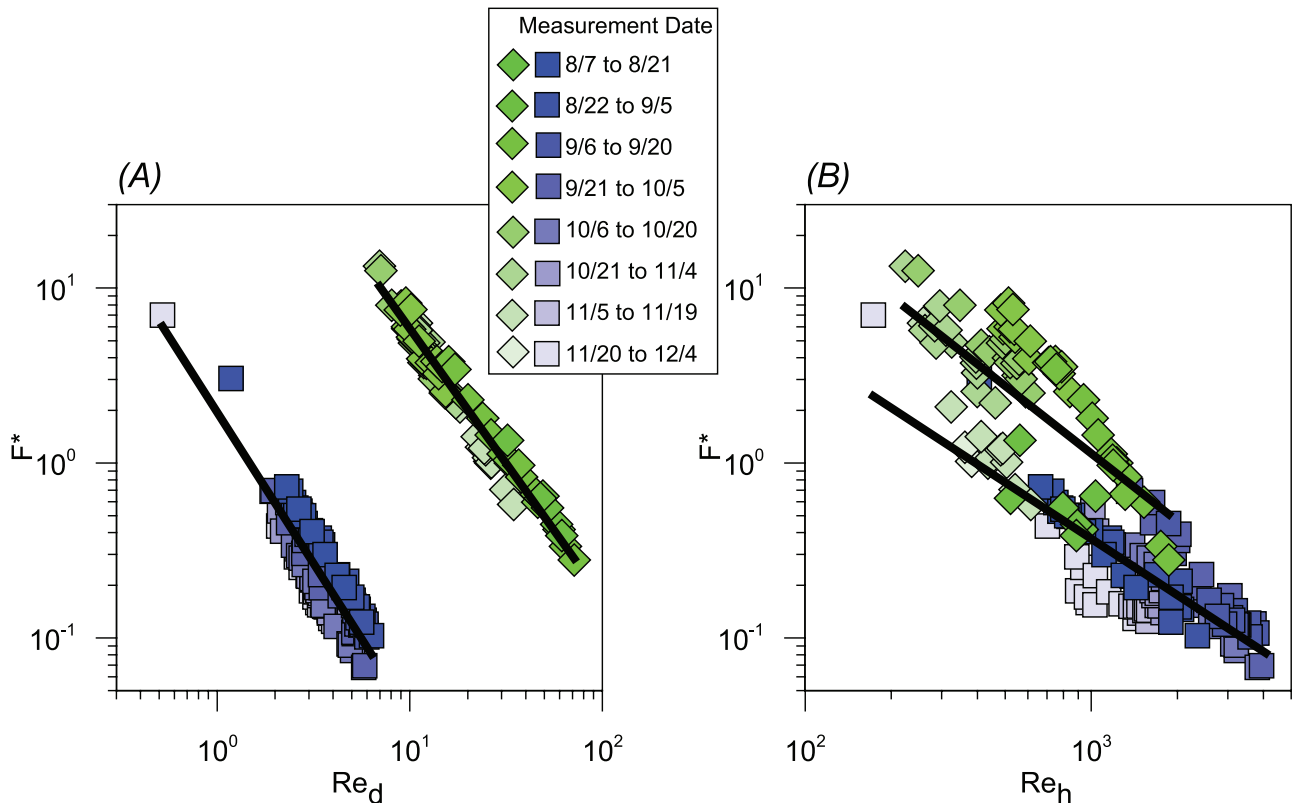
and 0.66 for ridge and slough, respectively). Standard errors of the dimensionless drag relationships were also lower for stem diameter-based normalization of flow, with values of the standard error for ridge and slough equaling 0.07 and 0.13 for stem-based normalization, respectively, and 0.31 and 0.18 for depth-based normalization of flow, respectively. Finding that stem-based normalization of flow performed better than water depth-based normalization is consistent with the expectation that the onset of turbulence and its effects on drag are better characterized by a Reynolds number based on stem diameter rather than water depth. Water depth matters less to drag in situations where plants stems protrude completely through the flow.

[44] The final step to derive the scaling results was completed by substituting the *k* value (i.e., the slope of the relationship between the normalized drag coefficient and Reynolds number) into equation (6). The choice of the *k* value for the ridge or slough produced similar results since the values differed little, and from a practical viewpoint were indistinguishable. We used the *k* value for the ridge which produced the following velocity scaling relationships in the Everglades:

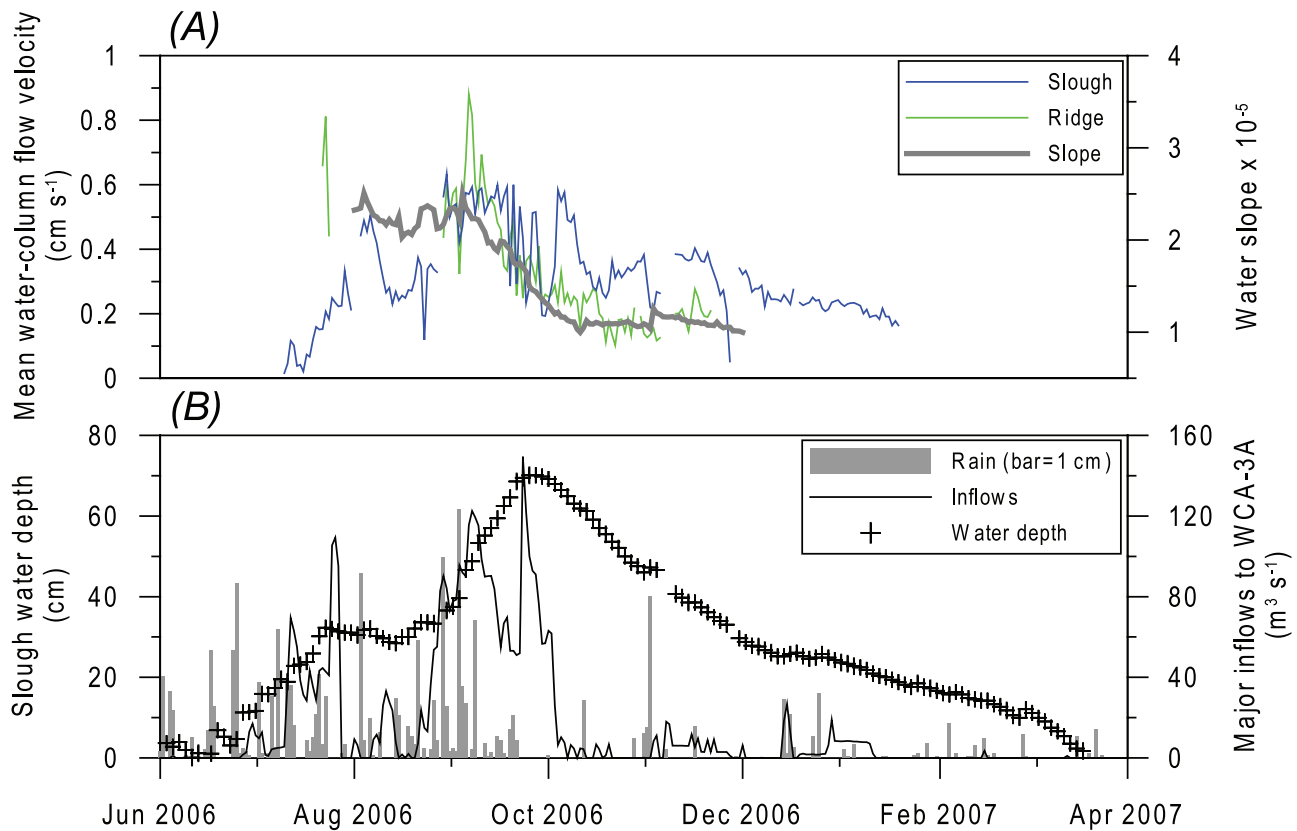
$$U \sim S^2, d^4, a^{-1} \tag{10}$$

**4.5. Role of Pulsed Surface Water Inputs in Controlling Everglades Flow Velocity**

[45] The data set for the 2006 water year was used for evaluating the role of pulsed surface water inflows on flow velocities. Flowing surface water was first observed in the



**Figure 4.** Dimensionless drag ( $F^*$ ) for slough (blue squares) and ridge (green diamonds) plotted versus (a) a Reynolds number based on stem diameter and (b) a Reynolds number based on water depth. Measurements are for the 2006 water year with the shade of symbols lightening later in the year.



**Figure 5.** (a) Mean water column velocities and water surface slopes for the slough and ridge measurement sites for the 2006 water year. (b) Water depth and precipitation at the research site along with data about surface water inflows to Water Conservation Area 3A. Surface water inflows are the sum of major water inflows measured by the South Florida Water Management District at hydraulic control structures located at the northern end of WCA-3A. Although the period when standing surface water was present lasted 9 months, the period for velocity measurements was shorter (lasting from 21 July 2006 to 21 January 2007) because of minimum water depth requirements for valid measurements and for site access. Valid estimates of water surface slope estimation were for a slightly shorter period of time lasting between 8 August 2006 and 6 December 2006.

slough in early June 2006 of that water year, and it became deep enough to measure flow on 10 July. Surface water flow was measured intermittently on the ridge between 21 and 25 July, followed by continuous measurements after 28 July. Wetting up of the peat and the onset of flow occurred because of rain but also because of the arrival of the first major release of surface water from upstream hydraulic structures into WCA-3A (Figure 5). Water depths were still relatively low at that time and continued to fluctuate for most of August as the first flow pulse subsided and an even larger second pulse was released.

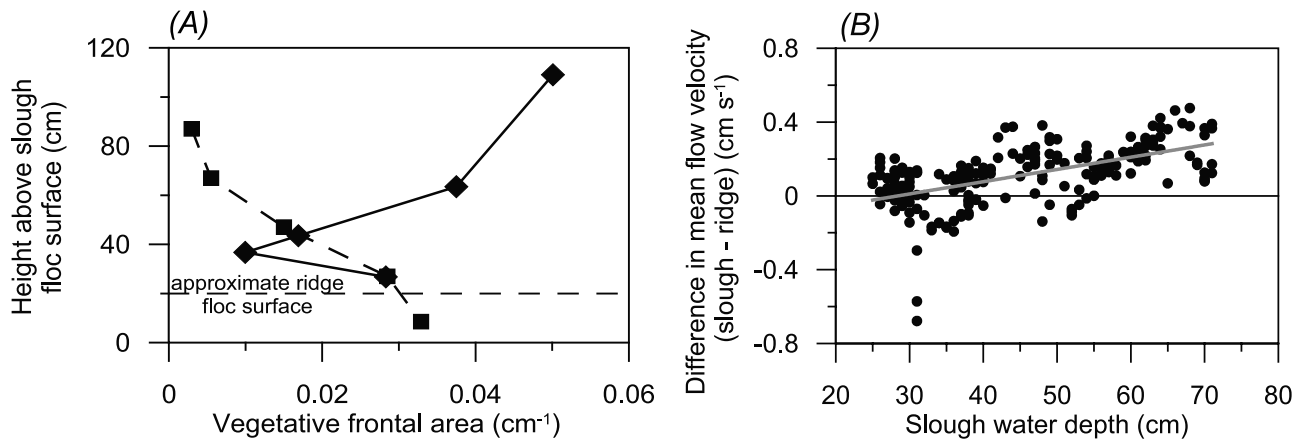
[46] Water surface slopes and velocities quickly achieved their peak following the onset of flow and remained high throughout the end of July and most of August as the first flow pulse moved through, followed by a second larger flow pulse. After the arrival of a second major flow pulse, water depth began to increase rapidly (beginning about 1 September). After the second flow release stopped (approximately 7 September), water surface slope and flow velocity began to decline exponentially even though water depth was still increasing (by approximately 15 cm in 6 days). Water surface slope and flow velocity continued to

decline as water depth peaked approximately 1 October after which the rate of decline slowed for the remainder of the water year (Figure 5).

[47] Overall, water surface slope increased locally by a factor of 2 and flow velocity by a factor of 2–4 on the wave's leading edge relative to later in the water year. Water surface slope and flow velocity were greatest very near the time of first arrival (on the rising limb) of the flow pulse and declined rapidly on the trailing edge of the pulse, suggesting an association with the dynamics of the gravity wave that was generated by the flow release from the upstream hydraulic structures.

#### 4.6. Effect of Vertically Varying Architecture of Slough and Ridge Vegetation

[48] Plant communities in the slough and ridge are both relatively sparse compared with vegetation that has been studied by others to quantify vegetative drag. Live and dead vegetative biomass amounts to 225 g dw m<sup>-2</sup> in the slough and 1,560 g dw m<sup>-2</sup> on the ridge. Vegetation frontal areas in the Everglades range between 0.005 and 0.035 cm<sup>-1</sup> (Table 1). Vegetation in the Everglades differs in its canopy



**Figure 6.** (a) Frontal area of vegetation as a function of height above the floc surface for the slough (squares) and ridge (diamonds) velocity measurement locations. The dashed horizontal line indicates the relative height of the ridge floc surface (20 cm) above the height of the slough floc surface. (b) Difference of slough and ridge flow velocities plotted versus water depth showing the trend of progressively greater difference in flow velocities as water depth increases.

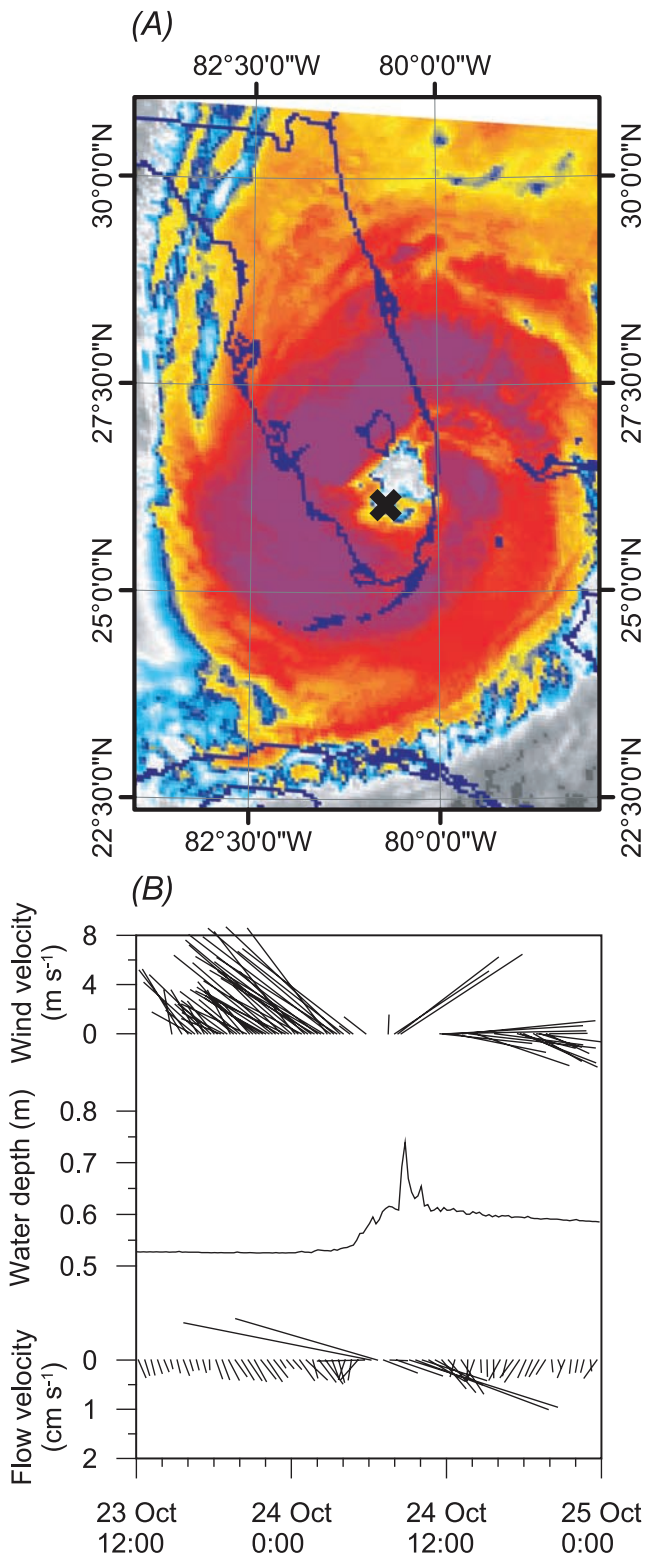
architecture between slough and ridge in several ways, including exhibiting distinctly different vertical patterns in frontal area (Figure 6a). Whereas the frontal area of slough vegetation exhibits a pattern that decreases with height above the bed, the frontal area of ridge vegetation initially decreases and then reverses trend and increases with height. The crossing point where ridge and slough frontal areas are equivalent is at a height of 23 cm above the ridge surface (43 cm above the slough surface) (Figure 6a).

[49] The contrasting vertical patterns in vegetation frontal area in the slough and ridge have implications for vegetative drag, causing it to vary differently in each plant community as the water level changes. For example, flow resistance is likely to be similar in the ridge and slough at water depths that are below the height at which the vegetative frontal areas are equivalent. In contrast, there is likely to be greater flow resistance on the ridge at water depths that are greater than the height where frontal areas are equivalent. A larger difference between flow velocities at greater water depths is supported by a positive linear relationship between the slough-ridge velocity difference versus water level (i.e., slough velocity minus ridge velocity =  $0.007 \times$  water depth - 0.188), which is statistically significant ( $F = 90.912$ ,  $p \leq 0.0001$ ,  $n = 195$  days) despite having only a moderate  $R^2$  of 0.32 (Figure 6b). The implication is that, because of vertical patterns in vegetative drag, the fraction of Everglades flow routed through sloughs increases as water depth increases (up to a point that ridge vegetation is completely inundated, a very rare event).

[50] Flow velocities in the Everglades are typically too low to cause meaningful bending of sawgrass stems and leaves (J. W. Harvey et al., personal observations during flow enhancement experiments in 2002, 2005, and 2007), although the less rigid stems of *Eleocharis elongata* have been observed to bend at velocities exceeding  $3 \text{ cm s}^{-1}$  in field flume experiments conducted in the slough. The situation in the Everglades therefore contrasts with flow in open channels with submerged aquatic vegetation where the vegetation reconfigures its orientation at higher flow velocities to reduce its frontal area [Sand-Jensen, 2003].

#### 4.7. Other Factors Influencing Everglades Flow Regime: Wind and Extreme Meteorological Events

[51] Typically there was no significant relation between flow velocity and wind speed or direction, as indicated by a subset of the data that showed lack of correlation between flow velocity and wind direction ( $r = -0.104$ ,  $p \leq 0.478$ ,  $n = 49$  days) and between flow velocity and wind speed ( $r = -0.146$ ,  $p \leq 0.282$ ,  $n = 56$  days). Flow velocities were elevated during severe storms however. On 24 October 2005 Hurricane Wilma traversed the Everglades from southwest to northeast with the eye centered about 30 km to the north but extending over the WCA-3A5 research site. During the 24 h preceding passage of the eye over the site, wind speed increased from typical daytime wind speeds of  $2\text{--}4 \text{ m s}^{-1}$  to a maximum of  $14 \text{ m s}^{-1}$ . Wind speeds slowed briefly to near zero as the eye passed (Figure 7). The wind direction, which was toward the northwest prior to passage of the eye, shifted to east-southeast after the eye had passed. Over a period of several hours preceding the arrival of the eye, water level rose approximately 10 cm above the prehurricane level. Flow velocity increased rapidly (over a time period of approximately 30 min) to a maximum of  $4.0 \text{ cm s}^{-1}$  toward a direction  $79^\circ$  west of north. The eye passed relatively quickly over the site (in about 30 min), followed immediately by an even greater spike in water level to 22 cm above the prehurricane water level. The increase in water level was accompanied by another period of elevated flow velocities lasting 45 min with a maximum velocity of  $4.9 \text{ cm s}^{-1}$  toward a direction  $112^\circ$  east of north (Figure 7). Within approximately 4 h following the passage of the eye, flow velocity and water level had almost completely recovered to more typical prehurricane conditions. Flow velocities were very similar to velocities prior to the hurricane and water levels stabilized at an elevation approximately 6 cm above prehurricane levels. The changes in direction of flow velocity, and also the rapid decline of flow velocities after the eye passed over the site did not correspond with wind speed, which changed direction at a different time than flow velocity did, and which continued to be strong for 24 h after the hurricane. These observations



**Figure 7.** (a) GOES 12 IR satellite image showing location of Hurricane Wilma at 7:55 A.M. Eastern standard time on 24 October 2005. The cross shows the location of the WCA-3A5 research site. (b) Wind velocity vectors, water depth, and flow velocity vectors measured at the slough location at our research site before, during, and after Hurricane Wilma. Vectors in Figure 7b indicate wind or flow direction, with due north at the top of the plot, directly over the origin of each vector.

suggest that the very high measured flow velocities were not driven directly by shear effects from hurricane winds. Rather, elevated flow velocities were more likely caused by the shorter time scale influence of the inverse barometric pressure effect, which locally raises and then lowers the water level during time periods of substantial shifts in atmospheric pressure. The inverse barometric effect is known to increase ocean currents during passage of a hurricane and likely explains the observed increased in flow velocities associated with Hurricane Wilma in the central Everglades.

## 5. Discussion

### 5.1. Relative Importance of Factors Controlling Velocity

[52] Frictional resistance in vegetated flow environments is dominated by drag distributed through the water column rather than by shear or form drag on the bed [Kadlec, 1990; Abdelsalam et al., 1992; Leonard and Luther, 1995; Fathi-Maghadam and Kouwen, 1997]. The reliability of using Manning's equation to simulate flow in vegetated environments has therefore been questioned [Kadlec and Knight, 1996]. Many recent models of flow through vegetation substitute power law equations for Manning's formulation of the velocity rate law [Hammer and Kadlec, 1986]. The parameters of those models are typically used as fitting coefficients [Bolster and Saiers, 2002], which suggests a need for greater understanding of how vegetation characteristics and gravitational forcing affect velocity in vegetated systems.

[53] Our results highlight the importance of vegetation structural characteristics (i.e., stem biovolume, frontal area, and diameter) that contribute to flow resistance on a low-gradient floodplain with sparse to moderately dense vegetation. Frontal areas in the Everglades range between 0.005 and 0.035 cm<sup>-1</sup>, which is 50 to 100% lower than measurements in a salt marsh vegetated with smooth cordgrass (*Spartina alterniflora*) [Lightbody and Nepf, 2006], an order of magnitude lower than the macrophytes in a constructed Michigan wetland [Kadlec, 1990], and 2 orders of magnitude lower than fertilized and well watered lawn grasses [Chen, 1976]. In general our results are consistent with previous work in suggesting that drag is a strong negative function of vegetation volume fraction and Reynolds number, i.e.,  $C_D \sim (ad)^{-0.5}$  and  $C_D \sim Re_d^{-k}$  [e.g., Nepf, 1999; Lee et al., 2004]. Although drag differs considerably among the different wetland plant communities, the slopes of the relationships between drag and Reynolds number were relatively similar in the Everglades slough and ridge plant communities (Figure 4) and in several other communities in previously cited references [e.g., Lee et al., 2004; Chen, 1976]. These studies suggest a similar dependence of drag on Reynolds numbers for laminar to transitional flow through a variety of vegetation communities. A more comprehensive comparison is beyond the scope of the present investigation but is desirable for future work.

[54] Our findings support the overall need for parameterizations of floodplain flows that go beyond the use of typical roughness coefficients appropriate for streams and rivers (e.g., Manning's  $n$ , Darcy-Weisbach friction factor  $f$ , Chezy resistance coefficient  $C$ ). Ultimately a fluid dynamical approach will serve best for developing efficient but accu-

rate models for floodplain flows that embody the detailed interactions between the complex forces driving and resisting flow on floodplains. We took a first step to identify the relative importance of factors controlling flow velocity by substituting our field estimated relationships for the vegetative drag coefficient (with its dependencies on vegetation characteristics and Reynolds number) back into the force balance equation for vegetated flow. Rearrangement of the resulting equation indicated that  $U$  scales with  $S^2$ ,  $d^4$ , and  $a^{-1}$  and had no direct dependence on  $H$ . These scaling results differ considerably from velocity scaling in open channels where, according to Manning's equation,  $U$  scales with  $H^{2/3}$  and  $S^{1/2}$ . Not only is the Manning equation insufficient for modeling flow resistance around vertical, cylindrical-type features such as plant stems, but it also is not valid for the range of flow conditions typically encountered in many wetlands and vegetated floodplains where flows may transition between laminar and turbulent regimes. The scaling results presented here are a first step toward characterizing complex shallow flows through vegetation on a low-gradient floodplain, and will need to be experimentally and theoretically validated by other investigators.

[55] The scaling relationships predicted a greater dependence on stem diameter ( $U \sim d^4$ ) and water surface slope ( $U \sim S^2$ ) with a lesser dependence on vegetation frontal area ( $U \sim a^{-1}$ ) and no dependence on water depth. We also directly interpreted the apparent controls on velocity by analyzing 3 years of field data, from which we identified water surface slope as a primary control. Temporal variation in the driving force for flow, i.e., the water surface slope, was responsible for two to three times variation in flow velocities, with highest velocities occurring when the water surface slope was greatest, i.e., on the rising limb of flow pulses that lasted several weeks or more. The importance of water surface slope in controlling flow velocity was generally consistent with the results of our dimensional analysis, although field results are more complex than suggested by the scaling analysis because of interactions among multiple factors.

[56] In contrast to water surface slope, spatial differences in vegetation architecture only accounted for a relatively small difference (29%) in average flow velocity. Since frontal area and stem diameter are positively related in this vegetative system (i.e., both are greater in ridges) the effect of variation in these characteristics on flow velocity is diminished because of opposing effects (according to the scaling analysis) that greater frontal area and greater stem diameter have on flow velocity. Furthermore, vegetation frontal area and stem diameter are even more complex because they vary vertically within a single vegetation community more than they do between the distinct ridge and slough communities (see section 5.2).

[57] Water depth had a secondary role in controlling Everglades flow velocities by determining the extent of submergence of vegetation that varies vertically in its drag characteristics, in contrast to the scaling relationship which suggested that water depth should be unimportant in controlling velocity in vegetated flows. Our field investigation also observed the role of severe storms, for which the inverse barometric effect can locally increase flow velocity (by as much as an order of magnitude) for very short periods of time. The result of these interactions between

controlling variables was a relatively small difference between average flow velocities in the two vegetation communities. In general we can expect that interactions between vegetative and hydraulic variables will produce nonlinear relationships controlling velocity that often will not conform to simple univariate scaling relationships.

[58] The role of stem diameter in influencing velocity is the least clear of the new scaling results, in part because of a lack of corroborating theory and laboratory experiments where stem diameter is varied (while maintaining stem shape) in order to examine effects on flow velocity under controlled hydraulic conditions. Such experiments could be relatively easily conducted in the laboratory but to our knowledge have not yet been performed. General theory of flow through cylindrical objects [e.g., Panton, 2005] indicates that stem diameter regulates the onset of turbulence in vegetated flows as well as the pressure distribution around stems and downstream of stems. These effects have a direct influence on the size and characteristics of stem vortices, which directly affect the bulk drag characteristics of the canopy [Nepf, 1999]. Our preliminary scaling results suggest a strong positive relationship between stem diameter and flow velocity, other factors being equal. We caution that these results are preliminary and need to be evaluated experimentally and theoretically.

## 5.2. Flow Velocity Differences Between Distinct Floodplain Vegetation Communities

[59] On average, flow velocity was 29% lower in ridges compared with sloughs because of greater vegetative drag in ridges. Greater vegetative drag in the ridges resulted in part from greater vegetation biovolume and generally greater vegetation frontal area compared to sloughs. Frontal area and vegetative drag were nearly equal at lower water levels but diverged at higher water levels because of increasing frontal area and thus higher vegetative drag in ridge vegetation at greater heights in the canopy. The result was velocity differences in shallow water (~25 cm deep in the slough) that were indistinguishable between ridge and slough but that grew increasingly as water depth increased up to a maximum velocity difference of  $0.4 \text{ cm s}^{-1}$  (i.e., causing a two times higher flow velocity in the slough) in water near the typical maximum annual depth (70 cm). This highlights the secondary role of water depth in controlling flow velocity. An additional aspect of vegetative flow resistance that was not considered in the present study is the role of the floating aquatic *Utricularia purpurea*. *Utricularia* adds significantly to frontal area and decreases flow velocity in sloughs of Everglades National Park [Harvey et al., 2005]. However, *Utricularia* was not a significant contributor to flow resistance in our study because of its removal by Hurricane Wilma in the fall of the first measurement year of our study.

## 5.3. Role of Flow Pulses and Gravity Waves in Controlling Floodplain Flow Velocities

[60] Surface water inflows to large vegetated floodplains such as the Everglades, Okavango Delta, and others are typically in the form of seasonal pulses of surface water overflow from large lakes or rivers [Junk et al., 1989; Bayley, 1991; Light and Dineen, 1994; Dong, 2006]. In the present-day managed Everglades flow pulses still propagate through the wetland in the form of gravity waves that

increase water surface slope and flow velocity. Rather than being caused by overflow of Lake Okeechobee as they were in the past, flow pulses now are associated with managed water releases through hydraulic structures at the upstream boundary of the large basins that comprise the central Everglades [Harvey *et al.*, 2004]. The gravity waves produced by flow pulses in WCA-3A are responsible for increasing water surface slope by a factor of 2 and velocity by a factor of 2–4 for several weeks at a time in the vicinity of our research.

[61] The primary influence of water surface slope on floodplain flows in the Amazon was recognized by Meade *et al.* [1985] and more recently by Alsdorf *et al.* [2007], although floodplain investigations generally do not evaluate the relative importance of water surface slope relative to other variables such as vegetation characteristics or microtopography. Often the mechanics of riverine flood pulses have not been characterized in detail [Hupp, 2000]. Floodplain studies commonly generalize their findings by interpreting geomorphological features. Typical interpretations include riverine floods that are transmitted overbank either by avulsions or backwater flooding at locations of low topographic elevation of the naturally occurring channel levees [Hupp and Osterkamp, 1985]. The studies by Smith [2004] and Griffin and Smith [2004] demonstrated that overbank flows are resisted primarily by vegetative drag for a fairly wide range of plant density and architecture. Few direct observations of the dynamics of riverine floods on floodplains have been made. Investigations on low-gradient floodplains have the advantage of lower overall velocities and longer recessions, making field observations easier.

[62] Flow pulses across the very low gradient Everglades floodplain originate as water releases from hydraulic control structures that connect the large enclosed storage basins. When the control structures are opened, waves of small amplitude but very long wavelength are created that propagate into the wetlands. Given the relative importance of inertial, pressure, gravitational, and frictional forces under laminar to transitional flows through sparse to moderately dense vegetation, flow pulses in the Everglades are likely to be of the diffusive type [Julien, 2002]. Properties of a particular wave initially will be determined by the wave amplitude and frequency at the point of release. After release, the wave speed and attenuation are strongly affected by the average topographic gradient of the Everglades landscape ( $\sim 10^{-5}$ ) and the frictional resistance due to drag on vegetation as the wave propagates down gradient. At a particular location the peak magnitude and duration of elevated flow velocities and their peak magnitude are controlled by all of the above factors.

[63] Thus, while the initial properties of a gravity wave in the Everglades are likely to be largely under the control of Everglades water managers who operate hydraulic structures, the wave's propagation and attenuation characteristics in the wetland are determined more by inherent hydrogeomorphological and ecological characteristics such as topographic slope and vegetation architecture. Water management is currently targeted to achieve water level objectives in the wetlands. There is latitude however to manage both the timing and magnitude of flow pulses to comanage water levels and water velocity.

#### 5.4. Flow Comparison Between the Heavily Managed and Less Constrained Everglades

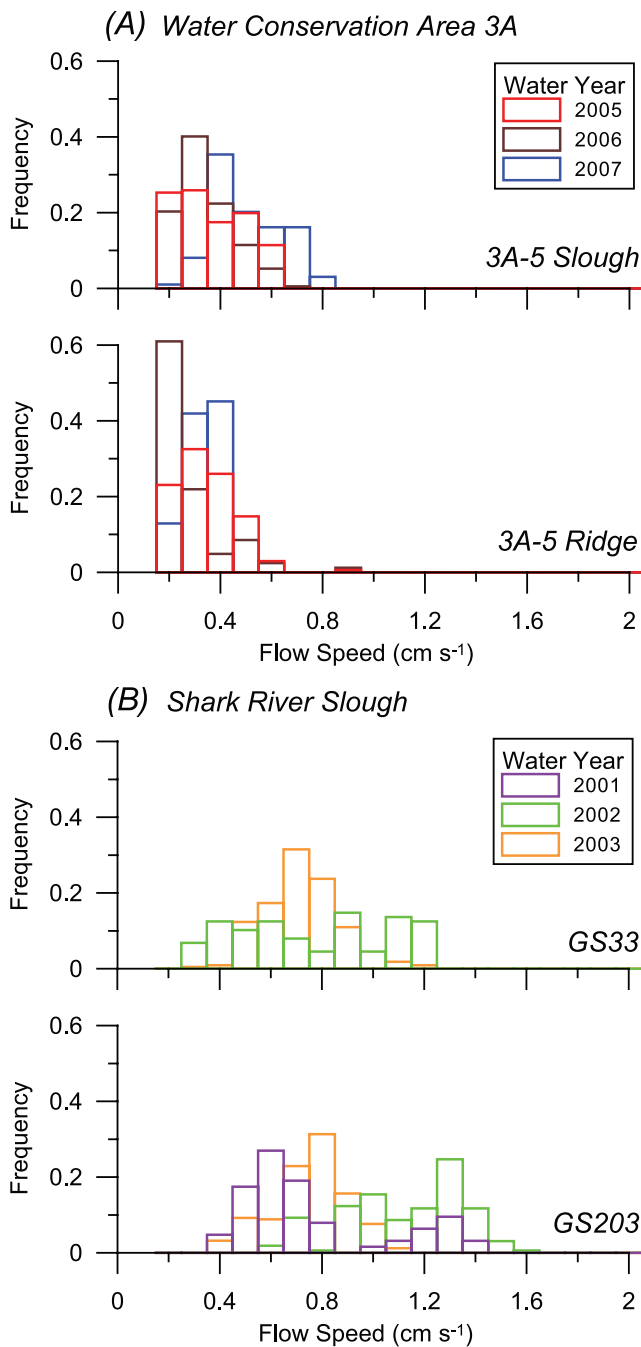
[64] To better understand the implications of changing Everglades hydrology over the past century, it is useful to compare our velocity measurements from the Water Conservation Area 3A basin where water levels are managed by opening and shutting hydraulic structures with the less intensively managed and more free-flowing wetlands of the southern Everglades in Everglades National Park (ENP). Like WCA-3A, surface water inflows to Shark River Slough (the principal 10-km wide flow way through ENP) are controlled by hydraulic structures at its northern end. However, unlike WCA-3A, Shark River Slough does not have artificial levees at its southern end that restrict outflow.

[65] A continuous record of point measurements of flow velocities made in the water column between early 2001 and late 2003 at four wetland sites in Shark River Slough ranged between 0.20 and 2.43  $\text{cm s}^{-1}$  [Riscassi and Schaffranek, 2004]. At the two sites most similar in vegetation to the WCA-3A sites (an *Eleocharis* slough site, GS33, and a sawgrass site, GS203) mean velocities were 0.68 and 0.83  $\text{cm s}^{-1}$  compared to the mean velocities of 0.36 and 0.28  $\text{cm s}^{-1}$  that we measured in the WCA-3A5 slough and ridge sites, respectively. These average flow velocities in ENP are approximately double what was measured in WCA-3A (Figure 8), although consideration must be given to the fact that 2001–2003 was wetter on average (132 cm of precipitation per year) than the measurement 2005–2007 measurement period (91  $\text{cm a}^{-1}$ ). Wetter conditions alone do not appear to account for differences in flow velocities between ENP and WCA-3A, since one of the measurement years in WCA-3A [2005] had precipitation nearly as high as the 3 years in ENP, yet flow velocities were not correspondingly higher in WCA-3A in that year (Figure 8). Larger flow pulses are also unlikely to account for higher velocities in ENP because the southern Everglades receives most of its inflow from hydraulic structures draining WCA-3A, and thus the flow pulses reaching Shark River Slough are likely to be attenuated rather than enhanced relative to flow pulses in WCA-3A. We believe that greater flow velocities in Shark River Slough are more likely due to the greater water surface slope in Shark River Slough (determined using the water surface slope methods outlined in this paper to be approximately  $6 \times 10^{-5}$  in central Shark River Slough) compared with 1 to  $3 \times 10^{-5}$  in the vicinity of our site in WCA-3A. The greater water surface slope in Shark River Slough is in part the result of a greater ground surface slope in Shark River Slough ( $5.6 \times 10^{-5}$ ) compared with the central Everglades in WCA-3A ( $3.3 \times 10^{-5}$ ). Also, backwater effects that lessen water surface slope are less likely to occur in Shark River Slough because of the lack of levees at its downstream end. In contrast, closure of hydraulic structures at the downstream levees in WCA-3A often creates pooled (i.e., non-flowing and relatively deep) conditions in WCA-3A.

#### 5.5. Implications for Water Management and Ecosystem Restoration in the Everglades

[66] It is believed by many that water management practices implemented during the past century in the Everglades for the purpose of flood control caused a reduction in the magnitude of flow pulses, with a corresponding reduction in overall flow velocities in the Everglades [Light and Dineen, 1994; Dong, 2006]. The Comprehensive Everglades





**Figure 8.** (a, b) Frequency histogram comparing multiyear flow velocity measurements that indicate greater flow velocities in the southern part of the Everglades in Everglades National Park [Riscassi and Schaffranek, 2004] compared with our measurements from the similarly vegetated sites in water conservation area 3A. For comparison purposes the data plotted are all daily average velocities computed from point measurements and not the model-processed, depth-averaged velocities.

Restoration Plan ([http://www.evergladesplan.org/about/rest\\_plan\\_pt\\_01.aspx](http://www.evergladesplan.org/about/rest_plan_pt_01.aspx)) addresses the need to reconsider operational practices of managing water depth and controlling floods by diverting large proportions of flow pulses through canals to the Atlantic Ocean and Gulf of Mexico.

Our results suggest that the goal of increasing flows to better match predrainage conditions could best be addressed by producing more energetic seasonal flow pulses through the interior wetlands which will increase flow velocities as well as increase the overall downstream conveyance of water. Using operational practices to manipulate water depth alone has been the typical historic management practice, however our results suggest that adjusting operational practices at hydraulic structures to increase water surface slope and water depth is likely to be a more effective strategy than simply focusing on water depth alone. More needs to be known about the propagation and attenuation properties of diffusive waves in the wetlands of the Everglades, as these offer Everglades water managers increased opportunity to manipulate flow velocity, water residence time, sediment dynamics, and other processes. One particularly important objective may be to achieve threshold velocities that redistribute sediment from slough bottoms onto ridges, which is considered essential for preserving the highly valued ridge and slough topography, biodiversity, and habitat connectivity of the Everglades [Larsen *et al.*, 2007].

[67] Advancements made here and in related publications indicate a growing understanding of the hydroecological relationships that control flow in shallow, vegetated aquatic ecosystems. Characterizing these complex field conditions across the full extent of large floodplains may be one of the most significant barriers to progress in applying the new understanding to conservation and restoration of aquatic ecosystem functions and services. Recent advancements in remotely sensing the water surface on floodplains of moderate gradient [e.g., Alsdorf *et al.*, 2007] and low gradient [e.g., Wdowinski *et al.*, 2004] are showing promise in making it feasible to accurately estimate water level and water surface slope on expansive floodplains wherever they occur. Thus, we believe that uncertainties in floodplain flow prediction in the near future will shift toward the need to more accurately characterize the influence of spatial and seasonal variability in vegetation architecture (and associated microtopography) on flow resistance.

## 6. Summary and Conclusions

[68] Flow measurements over 3 years in this low-gradient floodplain with moderate vegetative drag compared the influence of spatially variable vegetation architecture and topographic elevation, and temporally variable water surface slope and water depth, on flow velocity. The Everglades is an extremely low gradient floodplain with moderate vegetative drag, with flow measurements indicating that velocities were generally below  $1 \text{ cm s}^{-1}$  with ninety percent of daily average mean water column velocities between  $0.10$  and  $0.59 \text{ cm s}^{-1}$ . Except during an extreme meteorological event (a direct hit by a hurricane when the velocity increased to  $5 \text{ cm s}^{-1}$ ), flow velocities were below the threshold for turbulent flow ( $Re_h = 1500$ ) or turbulent stem wakes ( $Re_d \sim 200$ ) [Nepf *et al.*, 1997]. Water surface slope was the most important control on flow velocity in the Everglades because of the effect of seasonal flow pulses in creating gravity waves that increased the driving force for flow. In contrast, differences in canopy architecture accounted for a relatively minor component of variation in flow velocity.

[69] Flow through the Everglades occurs primarily through sloughs (86% of total discharge) because of higher velocities and deeper water compared with intervening ridges. Average velocity in the slough ( $0.36 \text{ cm s}^{-1}$ ) was 29% higher than the ridge because vegetative drag is typically being less in the slough. Because of vertical variation in canopy architecture, frontal areas in sloughs and ridges were approximately equal at low water depths and as a result there was no appreciable difference in velocity at low water depths. In deeper water, the frontal area of sawgrass increased with increasing height which caused vegetative drag to increase and flow velocity to decrease in the ridge. In contrast, frontal area decreased with height in the slough, with opposite effects on vegetative drag and flow velocity. Flow discharge (per unit width) in the slough was 115% greater than the ridge during time periods of concurrent flow, in part because of the topographic difference between the ridge and slough (20 cm) that kept water depths 30 to 200% deeper in the slough. Appreciable flow occurs in the slough at low water levels when the ridge is dry, as indicated by a 205% greater discharge in the slough compared to the ridge for all days with flow.

[70] Spatial differences between slough and ridge velocities were relatively small whereas the much more significant (order of magnitude) increase in velocity that occurred as a result of the inverse barometric pressure effect during hurricane passage was short in duration (hours). More important to Everglades flow patterns was the tendency for velocities to be two to three times greater early in the wet season ( $0.6\text{--}0.8 \text{ cm s}^{-1}$  compared with  $0.2\text{--}0.3 \text{ cm s}^{-1}$  later in the wet season). Greater flow velocities were related to arrival of the leading edge of gravity waves released as flow pulses through water management structures.

[71] Velocity scaling estimates developed from simple theory and from Everglades field measurements indicated a positive dependence of the square of water surface slope and fourth power of stem diameter, and a negative dependence on vegetation frontal area. The importance of water surface slope and vegetation frontal area were clearly evident in the data whereas the importance of stem diameter was less evident. Stem diameter influences velocity in several ways, by regulating the onset of turbulence as well as influencing the pressure distribution around stems and downstream of stems which then influences the characteristics of stem vortices that are known to directly affect the bulk drag characteristics of the canopy [Panton, 2005]. Our scaling results also implied that there should be no direct dependence on water depth, which differs substantially from open channel flow where Manning's equation suggests that velocity depends relatively equally on water depth raised to the two thirds power and the square root of slope. Further analysis of Everglades field data demonstrated that water depth is indirectly important as a control on flow velocity through its influence on the extent of submergence of vegetation communities that vary vertically in their frontal area.

[72] The primary importance of water surface slope in controlling flow velocity has implications for managing low-gradient floodplains including wetlands constructed for water treatment. The typical practice of managing water depth in wetlands to control velocity, residence time,

sediment settling and other processes important in wetland function could potentially be accomplished more effectively by also managing the frequency and magnitude of flow pulses to achieve desired surface water slope and velocity conditions. At their point of origin at the hydraulic structure, the amplitude and frequency of pulses are under the control of water managers. Once released into the wetlands, the wave's speed and attenuation are determined by the topographic slope and characteristics of vegetative flow resistance as the waves propagate through the wetland. The duration and peak magnitude of elevated water velocities are controlled by all of the above factors. Managing flow pulses might be an effective means for Everglades water managers to restore a regime of greater flow velocities more representative of the pre-drainage Everglades. The frequency and magnitude of water releases into the Everglades would need to be manipulated in accordance with the mechanics of wave propagation and attenuation in flow through vegetation, in order to achieve desired goals of sediment and phosphorus redistribution envisioned to be important in maintaining topographical pattern and biodiversity in the Everglades.

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