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ORIGINAL PAPER

Factors Controlling Surface Water Flow in a Low-gradient Subtropical Wetland

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Abstract Surface water flow patterns in wetlands play a role in shaping substrates, biogeochemical cycling, and ecosystem characteristics. This paper focuses on the factors controlling flow across a large, shallow gradient subtropical wetland (Shark River Slough in Everglades National Park, USA), which displays vegetative patterning indicative of overland flow. Between July 2003 and December 2007, flow speeds at five sites were very low (<3 cm s^{-1}), and exhibited seasonal fluctuations that were correlated with seasonal changes in water depth but also showed distinctive deviations. Stepwise linear regression showed that upstream gate discharges, local stage gradients, and stage together explained 50 to 90% of the variance in flow speed at four of the five sites and only 10% at one site located close to a levee-canal combination. Two non-linear, semi-empirical expressions relating flow speeds to the local hydraulic gradient, water depths, and vegetative resistance accounted for 70% of the variance in our measured speed. The data suggest local-scale factors such as channel morphology, vegetation density, and groundwater exchanges must be considered along with landscape position and basin-scale geomorphology when examining the interactions between flow and community characteristics in low-gradient wetlands such as the Everglades.

Keywords Florida Everglades · Flow resistance · Restoration · Water speed · Water velocity

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Introduction

Overland flow is recognized as a formative factor shaping many wetland characteristics, even in low-gradient systems (Foster et al. 1983; Rietkerk et al. 2004; Larsen et al. 2007). For example, variable patterns of sediment and organic matter deposition and erosion in flow systems generate spatial variations in hydroperiods and vegetation. Surface water flow is also a primary transport factor for dissolved and colloidal nutrients (Reddy et al. 1999; Noe et al. 2007), and it influences the rate at which energy and substances are exchanged across the sediment-water interface (White et al. 2004; James et al. 2008). Vegetative productivity in wetlands in some cases is enhanced by flow (Brinson et al. 1981; Cronk and Mitsch 1994), and the vegetative resistance to flow, particularly in low-gradient wetlands, controls turbulence regimes and affects dispersion rates of water column constituents (Nepf et al. 1997; Nepf 1999; Lee et al. 2004; Noe et al. 2007; Ho et al. 2009).

Disruptions to flow patterns are common in large wetlands near population centers that are concerned with flood control and water supply (Templet and Meyer-Arendt 1988). Habitat changes are known to accompany these disruptions. For example, flow patterns in the remnant Florida Everglades are highly regulated using a system of over 1,600 km of canals, levees, and dikes (Light and Dineen 1994). The canal and levee system has substantially altered the quantity, quality, timing, and spatial distribution of surface water flows in the Everglades (Fennema et al. 1994), and significant changes in the landscape have resulted from these hydrologic alterations (Bancroft 1989; Brown et al. 1994; Ogden 1994; Sklar et al. 2001a; Wu et al. 2006).

Despite the low gradients and relatively shallow water in the Everglades freshwater marshes, flow speed and water depth have been generally recognized as important factors shaping the microtopographic variations that characterize the elevated sawgrass ridges and deep water sloughs found throughout the Everglades (Olmsted and Armentano 1997; Leonard et al. 2006; Larsen et al. 2007). Specifically, flow speed has been recognized as an important factor in particulate settling and re-suspension in this system (Bazante et al. 2006; Leonard et al. 2006; Larsen et al. 2007), while water depth has been closely related to vegetation growth (Kolopinski and Higer 1969; Davis and Ogden 1994; Olmsted and Armentano 1997; Childers et al. 2006) and consequently the flow resistance, which affects flow speed and bed shear stress. The direction of overland flow is also considered important in the evolution of the Everglades, and it is thought that prior to human alterations the direction of overland flow matched the orientation of the ridge and slough formations (Sklar et al. 2001a; SCT 2003).

Continuous measurements of flow velocity (speed and direction) in the Everglades have been produced in a few studies (Riscassi and Schaffranek 2002, 2003, 2004). Large-scale flow patterns have also been measured at a few locations (Ho et al. 2009). However, to date there exist no synoptic investigations of the multiple factors that lead to spatial variability in flow patterns across the Everglades. Important issues to be resolved include a better understanding of how water velocity dynamics in wetlands are influenced by water management and other hydrologic variables, and how these relationships change over time with changes in the vegetation community.

This paper focuses on describing hydrologic drivers that influence flow patterns within Shark River Slough (SRS), a shallow gradient, large subtropical wetland which is the primary drainage feature of Everglades National Park (ENP) in Florida, USA. Specifically, we use a combination of linear and nonlinear regression analyses to quantify the relationships between flow patterns, water depths, and other hydrologic parameters such as rainfall, stage gradients, and discharge rates at upstream control structures. We discuss factors that influence the spatial and temporal variability in our measurements and the feedbacks between flow patterns and habitat characteristics which may affect the ongoing restoration planning that aims to restore and preserve the water resources for both the Everglades ecosystem and human needs (U.S. ACE 1999).

Site Description

SRS extends from the northern edge of ENP to the mangrove oligohaline zone near the Gulf of Mexico. The average annual air temperature in this region is 24°C, and the average annual precipitation is 1320 mm (McPherson and Halley 1997). The region is characterized by distinct wet (June–November) and dry seasons.

SRS receives inflow from the Tamiami Canal on the northwestern boundary of ENP through four gated structures (S12A, S12B, S12C, and S12D, see Fig. 1). Inflows on the northeastern boundary of ENP are controlled through discharges from the S333 gate into the L29 canal, from which water enters SRS through culverts beneath Tamiami Trail. The S334 structure routes water from the L29 canal to the L31 canal on the eastern boundary of ENP. Thus, the total amount of water discharged into SRS is approximately equal to the sum of the discharge through S12s and the difference between flows at the S333 and the S334. An extension of the L67 canal and levee (L67-Ext.) extends into ENP and separates the eastern and western portions of SRS. All water control structures are managed by the South Florida Water Management District (SFWMD).

Five sites were chosen for this study. In 2002, three monitoring stations were constructed in the vicinity of three tree islands, known as Black Hammock (BH: lat 25.61108 N, long 80.68950 W), Gumbo Limbo Hammock (GL: lat 25.63052 N, long 80.74298 W), and Satin Leaf Hammock (SL: lat 25.65905 N, long 80.75708 W). SL has been referred to as Indian Camp Hammock and Tiger Hammock in other documents. These three sites were located among patches of sawgrass (*Cladium jamaicense*) on the northwestern edge of each tree island. Floating algal mats (periphyton), emergent species such as spikerush (*Eleocharis cellulosa*), and dense submerged vegetation (*Utricularia* spp.) were abundant at these sites. Black Hammock and SL were decommissioned in 2005, and two new sites were added at Chekika (CH: lat 25.74627 N, long 80.65365 W) and Frog City (FC: lat

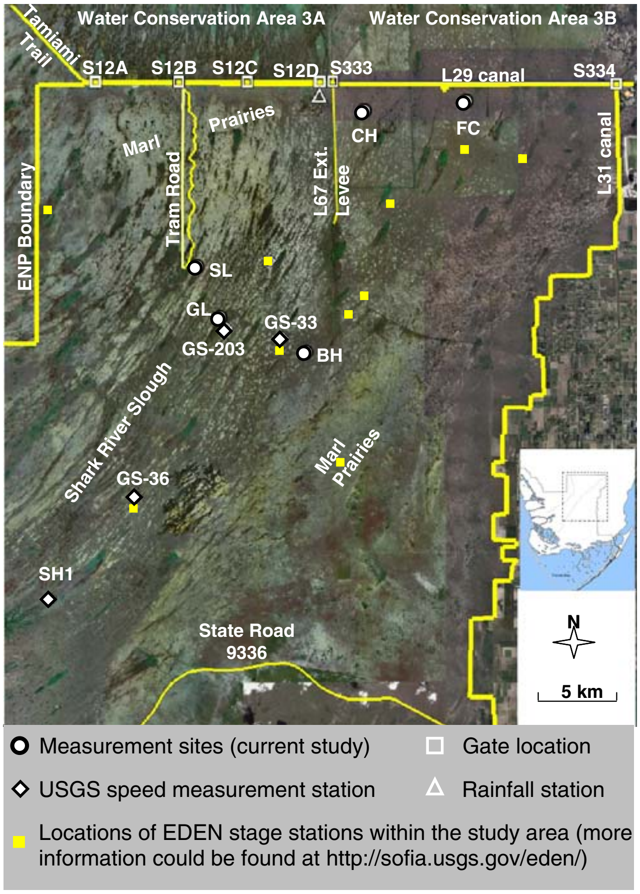


Fig. 1 The five study sites (CH = Chekika, FC = Frog City, GL = Gumbo Limbo, SL = Satin Leaf, and BH = Black Hammock) are located in Shark River Slough within Everglades National Park. Stations GS-33, GS-203, GS-36, and SH1 were stations corresponding to Riscassi and Schaffranek (2002, 2003, 2004)

25.75180 N, long 80.59053 W). Both CH and FC were on the east side of the L67-Ext. and had vegetation types similar to those at the other three sites. The ground elevations to the west of the levee (1.5 to 2.3 m, relative to North America Vertical Datum 88, or NAVD 88) are in general higher than those to the east (1.0 to 1.5 m).

Methods

Water velocity was measured every 15 min using “side-looking” Acoustical Doppler Velocity (ADV) meters (SonTek Argonaut-ADV, San Diego, CA, firmware version 11.6). The ADV units are capable of measuring water speeds in the range of 0.001 to 600 cm s^{-1} in water depths as shallow as 15 cm. The ADV units were installed so that one sample reflected an average of 3,000 individual measurements within a 5-minute interval. The corresponding instrument-generated noise level is approximately 0.006 cm s^{-1} for the range of speeds (up to 3 cm s^{-1}) observed in the Everglades. During each maintenance trip the ADV units were adjusted vertically so that velocity measurements were collected at or near 6/10 of the water depth. More details about the settings and maintenance of the sites are described by Bazante et al. (2006).

Data were considered erroneous and removed from the analysis when the signal strength was outside the normal range (30 to 60 counts per minute) and when the signal to noise ratio (SNR) was less than 5. Low SNR was caused by low water levels, entanglement of vegetation in the probe, low battery voltage, or low concentrations of suspended solids. Measurements were also affected by other disturbances such as vibration from aquatic animals and strong winds. To address these effects, water speed data with a standard error greater than 20 cm s^{-1} were not included in the analysis.

Gate discharge and rainfall data were obtained from the SFWMD website (DBHYDRO at http://www.sfwmd.gov/). Water surface elevations or stages (NAVD 88) at our sites were obtained from the Everglades Depth Estimate Network (EDEN) maintained by the U.S. Geological Survey (http://sofia.usgs.gov/Eden/). The EDEN stage data are based upon spatial interpolations among 253 monitoring stations distributed throughout the Greater Everglades area, including ENP and water conservation areas. The accuracy of the interpolated stage could be compromised close to levees and canals (Palaseanu and Pearlstine 2008). A visual comparison between time series of daily averaged stage data with water depth data collected on site in this study using pressure water level data loggers (Infinities USA, Inc., Port Orange, FL, resolution of 0.0254 cm) at GL, CH, and FC revealed that only CH displayed noticeable discrepancies (Fig. 2). Therefore, EDEN stages were reliable at GL and FC. Because SL and BH were inside the SRS and were close to GL, we assume that the EDEN model was reliable at these two sites as well.

Correlations at five sites between water speed and upstream gate discharges, stage, stage gradient, and local rainfall were evaluated to identify the relative importance of these variables on water speed at our stations. Forward stepwise regression was used to evaluate the overall performance of these variables in explaining the water speed. Discharge from each of the S12s, the S333, and the S334 was treated as a single variable. All stage data for these calculations were obtained from the EDEN network. Stage gradient was calculated as the difference in stage between each site and its corresponding reference site located 1 km upstream along the streamline defined by the predominant flow direction. Only significant variables ($p<0.05$) were included in the regression models.

The relationship between water speed (U), water depth (h), and the hydraulic gradient (or surface slope, S_f) was

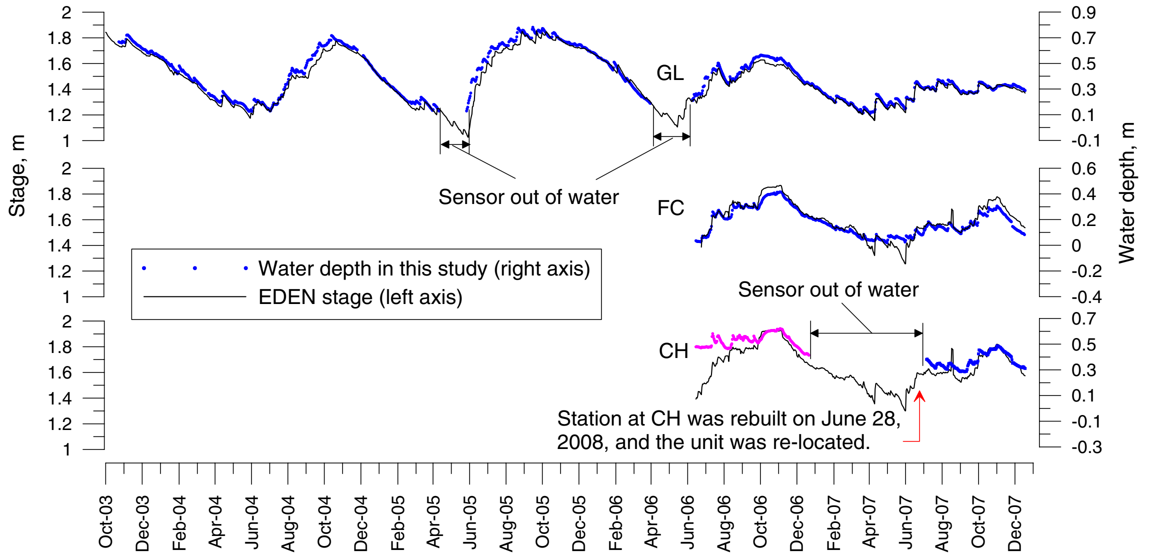


Fig. 2 Water depth measured in this study and stage data derived from EDEN network. Note that the station at CH was damaged and was rebuilt on June 28, 2007. The water level recorder was relocated during the reconstruction; therefore, the unit lost a consistent ground elevation for water depth estimate before and after the construction. Water levels before June 28, 2007 were readjusted by adding an additional 0.27 m for comparison purposes only. CH data between December 22, 2006 and June 28, 2007 and GL data during May 2007 and May 2006 were discarded because the sensor was out of water

evaluated through two simple models. These models assume two dimensional sheet flow without constriction or broadening. Such an assumption is considered reasonable given the distance of the monitoring stations from nearby tree islands and the relatively shallow depth of flow. The first model is Manning's equation:

$$U = \frac{1}{n} * h^{2/3} * S_f^{1/2} \tag{1}$$

where n is the Manning's roughness. This model was developed for turbulent open-channel flows but also has been used by several studies in vegetated flows (Voinov et al. 1998; Sklar et al. 2001b). The second model utilizes a more general form of Manning's equation and has been used to simulate speeds within highly vegetated areas (Kadlec 1990):

$$U = K_f * h^{\beta} * S_f^{\lambda} \tag{2}$$

The values K_f, β, and λ are usually obtained through experiments and calibration. The constant K_f is related to vegetative resistance and is site specific. Values of λ are assumed to depend on the flow regime: 0.5 for turbulent flow and 1 for laminar flow. For most wetlands, flow is neither turbulent nor laminar, but often in the transitional regime between them, for which λ ranges from 0.7 to 1 (Kadlec and Knight 1996). The value of β is thought to be associated with the microtopography and stem density distribution. Earlier studies have found a range of 0.5 to 3 for several types of vegetated flow (Kadlec 1990; Bolster and Saiers 2002). In this study, we calibrated K_f, β, and λ using least-squares regression with daily averaged water speed measurements, stage gradients, and water depth data. Water speeds were measured directly in this study. Both stage gradient and water depth were obtained based on the EDEN stage. Water depths measured at GL, FC, and CH in this study were used to estimate the ground elevations by comparing the depths with the stage. GL, BH, and SL were assumed to have the same ground elevation. Water depth measured in this study was not used directly in the calibration due to periods of missing data when the sensor of the water level logger was out of the water column and because depth measurements were not available at SL and BH. For model calibration, only U values equal to or greater than 0.1 cm s^{-1} were used to avoid large measurement errors at low water speeds. In addition, the model was evaluated only during those periods when speeds were greater than 0.5 cm s^{-1} and flow directions were within 10 degrees of the average.

Results

General Characteristics of Water Speed, Stage, Gate Discharge, and Precipitation

Average daily water speeds at all five study sites showed seasonal trends between 2003 and 2005 and lower water speed during 2006 and 2007 (Fig. 3). Between 2003 and

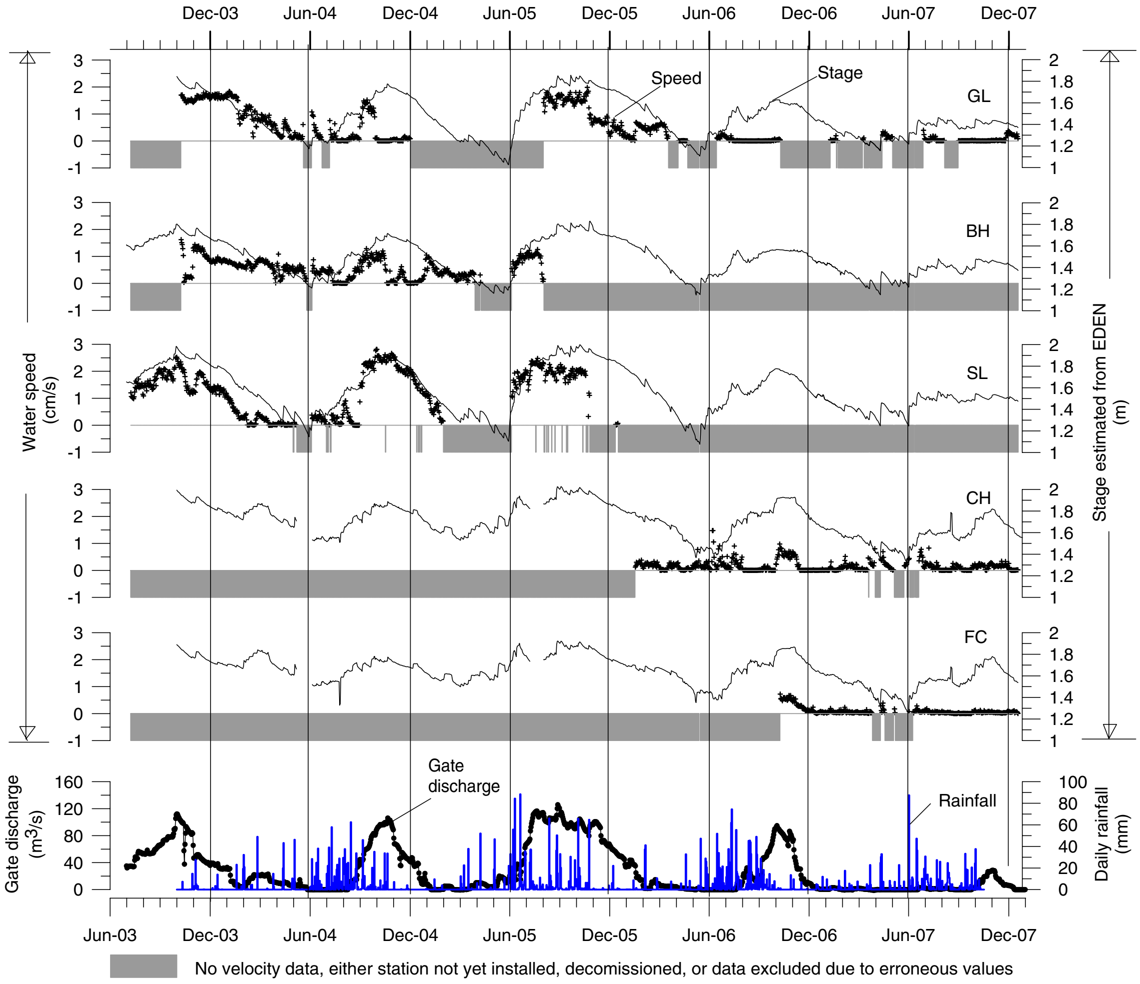


Fig. 3 Daily water speed (symbol) and stage (solid line) at the five study sites. Gate discharge (line+symbol: S12A+S12B+S12C+S12D+S333-S334) and rainfall (vertical bar: at station S12D) are provided in bottom panel for reference. Stage at the five study sites were interpolated based on the EDEN estimated stage, which were downloaded from USGS EDEN network. Note that the EDEN stage prior to October 1, 2006 were designated as final, and the stage after October 1, 2006 were designated as provisional and subjected to review at the time of this study

2005, seasonally-averaged daily water speed ranged from 0.29 to 1.90 cm s^{-1} during the wet season and ranged from 0.33 to 1.03 cm s^{-1} during the dry season (Table 1). During 2007, flow speeds were generally slow and averaged less than 0.25 cm s^{-1}. Over the course of the 5-year study, daily-averaged water speeds did not exceed 3 cm s^{-1} at any of the sites. The highest flow speeds occurred at SL, the station closest to the S12s on the western side of SRS. The lowest average speeds were recorded in the northeastern portion of SRS at FC and CH, just south of Tamiami Trail. The stations located in central SRS (GL and BH) exhibited intermediate flow speeds, but generally closer to those observed at SL than either FC or CH.

Rainfall and gate discharge fluctuated seasonally over the course of the study except that high gate discharge was not observed during the wet season in 2007 (Fig. 3). Rainfall peaks were most closely correlated to peaks in gate discharge when lagged by 11 weeks, but the relation between these two variables was weak (R^2=0.19 between 2000 and 2007).

Water surface elevations at the five study sites varied seasonally. The highest water level (1.8 to 2.0 m) occurred between September and November and the lowest water level (1.1 to 1.5 m) occurred between April and June (Fig. 3). In response to low gate discharges, wet season stages at all sites were lower during 2007 compared to average values from the previous four years. Stage variations were greatest between seasons at SL (up to 0.8 m), and least at FC and CH (0.4 and 0.5 m, respectively). Interestingly, the stage at BH was lower than that at GL during the wet season but was higher during the dry season. The relative stage difference between these two sites suggests that different flow directions occurred during these two seasons. The average

Table 1 Mean values for daily water speed measured at five study sites along with total rainfall (S12D) and gate discharge (S12A+S12B+S12C+S12D+S333-S334), grouped by dry (June to November) and wet seasons (December to May). Numbers in the parenthesis correspond to the standard deviation and number of daily observations

Site	Water speed (cms^{-1})								
	2003 Wet	2003–2004 Dry	2004 Wet	2004–2005 Dry	2005 Wet	2005–2006 Dry	2006 Wet	2006–2007 Dry	2007 Wet
BH	0.89 (0.49, 53)	0.64 (0.20, 177)	0.41 (0.36, 179)	0.33 (0.23, 122)	0.84 (0.26, 59)	N	N	N	N
GL	1.59 (0.09, 53)	0.91 (0.58, 171)	0.29 (0.44, 166)	N[b]	1.29 (0.41, 121)	0.35 (0.23, 127)	0.04 (0.07, 117)	0.21 (0.39, 42)	0.04 (0.13, 133)
SL	1.67 (0.35, 145)	0.44 (0.50, 157)	1.29 (1.05, 174)	1.03 (0.53, 61)	1.90 (0.34, 140)	0.03 (0.02, 5)	N	N	N
CH	N[a]	N	N	N	N	0.14 (0.09, 133)	0.21 (0.24, 183)	0.11 (0.14, 149)	0.24 (0.42, 176)
FC	N	N	N	N	N	N	0.40 (0.18, 53)	0.07 (0.06, 126)	0.05 (0.04, 176)
Rainfall (m)	17.70	8.41	25.03	7.07	27.12	8.56	27.28	7.33	20.03
Discharge (m^3/s)	62.75	15.53	38.22	8.83	85.91	15.93	30.80	0.89	5.76

[a] "N" means no data collected.

[b] Only data for one day was collected. The value was 0.08 cm s^{-1}.

stage gradients (cm/km) with their standard deviation at the five sites were 4.47±0.80 (GL), 3.88±1.13 (BH), 5.07±0.83 (SL), 0.41±1.25 (FC), and −3.23±2.64 (CH). The negative sign at CH was either due to the effects of completely dry conditions or deviation of the flow from the primary flow direction.

The primary direction of water flow at the five sites appeared to be constant at higher water speeds (Fig. 4). The average directions (clockwise from magnetic north) for water speeds equal to or greater than 0.5 cm s^{-1} were 208° (standard deviation: 4°) at GL, 194° (4°) at SL, 194° (4°) at BH, 206° (4°) at FC, and 157° (5°) at CH. The general flow direction of about 200° indicates a dominant southwestward flow, which is consistent with the historic flow direction in the slough. The exception occurred at CH, the site located southeast of the intersection of the L67 Ext. and Tamiami Trail. When flow speed was below 0.5 cm s^{-1}, flow direction tended to turn more to the south or southeast. For speeds between 0.1 to 0.5 cm s^{-1}, flow direction was more variable and the average directions were 192° (GL), 173° (SL), 180° (BH), 170° (FC), and 151° (CH).

The EDEN stage contours indicated flow directions that were generally consistent with our observations (206°, 199°, and 190° at GL, SL, and BH, respectively). Larger-scale flow directions derived from EDEN show that for a typical day during the wet season (Fig. 5), the dominant flow direction in the area to the south of Tamiami Trail and west of L67 extension levee was south (180°). This flow expands towards the east as well as towards the west at the southern terminus of the L67 Ext., generating a southwestern direction at BH.

Statistical Description

Gate discharge was an important factor affecting flow speed at all sites (Table 2). Correlations between stage and flow speed were strong at all sites except at CH. A high correlation between stage gradient and speed was also observed at SL and FC, but less so at GL and BH. Stage gradient and flow speed were only weakly correlated at CH. The correlation between local rainfall and speed was minimal at all stations. Including all the variables together in a multivariate, stepwise regression ($p<0.05$) explained 78 and 90% of the variation in speed at SL and FC, respectively. At GL, BH, and CH, these variables accounted for 58, 52, and 10% of the variance. Because there was collinearity among gate discharge, stage, and gradients, the model coefficients were not reported. The lack of explanatory power using the stepwise regression at CH was probably related to the more variable flow directions (Fig. 4) and the uncertainties in EDEN stages at this site.

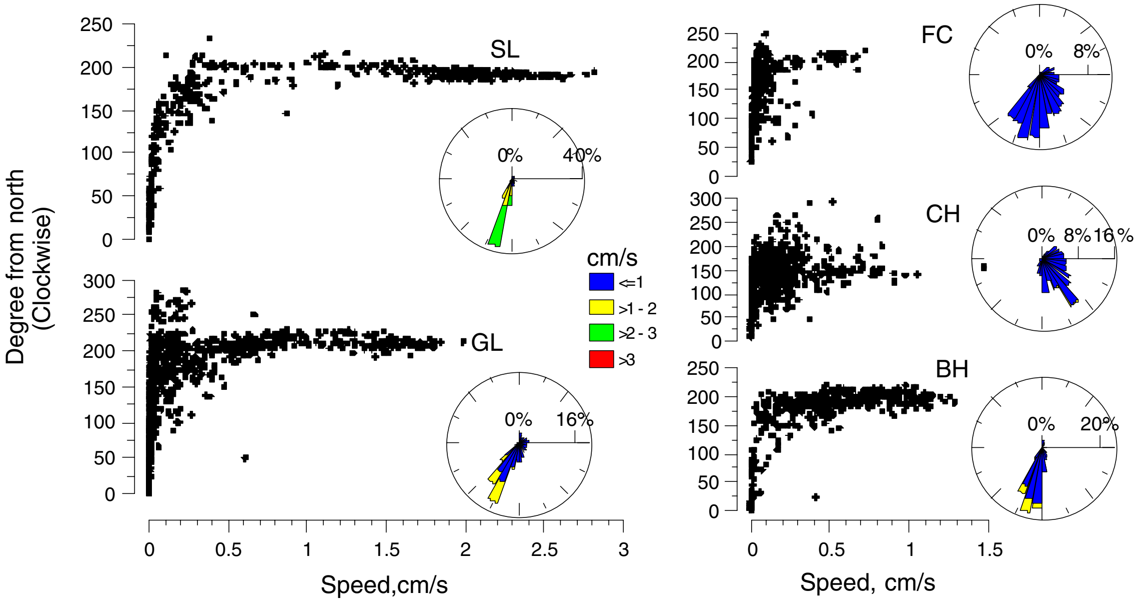


Fig. 4 Flow directions vs. water speed plot as well as "wind rose" plot for water velocity at five sites. In the "wind rose" plot, the length of the "spoke" represents frequency of the water speed in the corresponding direction. The magnitude of speed is sorted and differentiated by color. Both types of plots show that the flow directions are relatively constant particularly when water speeds are above 0.5 cm/s. The less obvious are at CH and FC where water speeds are relatively low. Only data collected after February 9, 2004 are shown due to a malfunction in the internal compass of the sensor which affected measurements prior to this date

Model Calibration

The Chekika site was excluded from this analysis because of our reduced confidence in the EDEN model at this site. Depth-averaged velocities modeled with Manning's equation showed the closest match to our measurements using a roughness coefficient (n) of 0.46 $m^{-1/3}$ s (0.28 to 0.75, 95% confidence interval). The best-fit values for the three

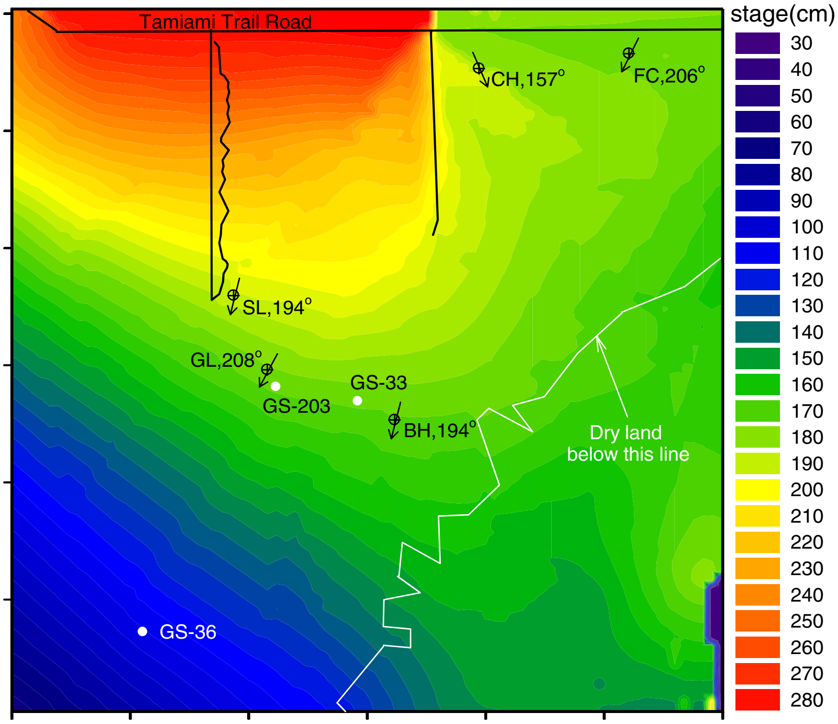


Fig. 5 EDEN stage contour plot (NAVD88, cm) on September 15, 2004 for the 30×30 km^2 area that covers the five study sites. The directions labeled for the five sites are the average flow directions for water speeds >0.5 cm s^{-1}. The length of the arrow is not proportional to the speed

Table 2 Correlation coefficients between water speed and eight variables. Variables examined included discharge at flow control structures (S12A-D and S333-334), stage, hydraulic gradient and rainfall. Each variable was evaluated independently for its correlation with water speed. Only water speeds greater than or equal to 0.1 cm s^{-1} were used in these analyses

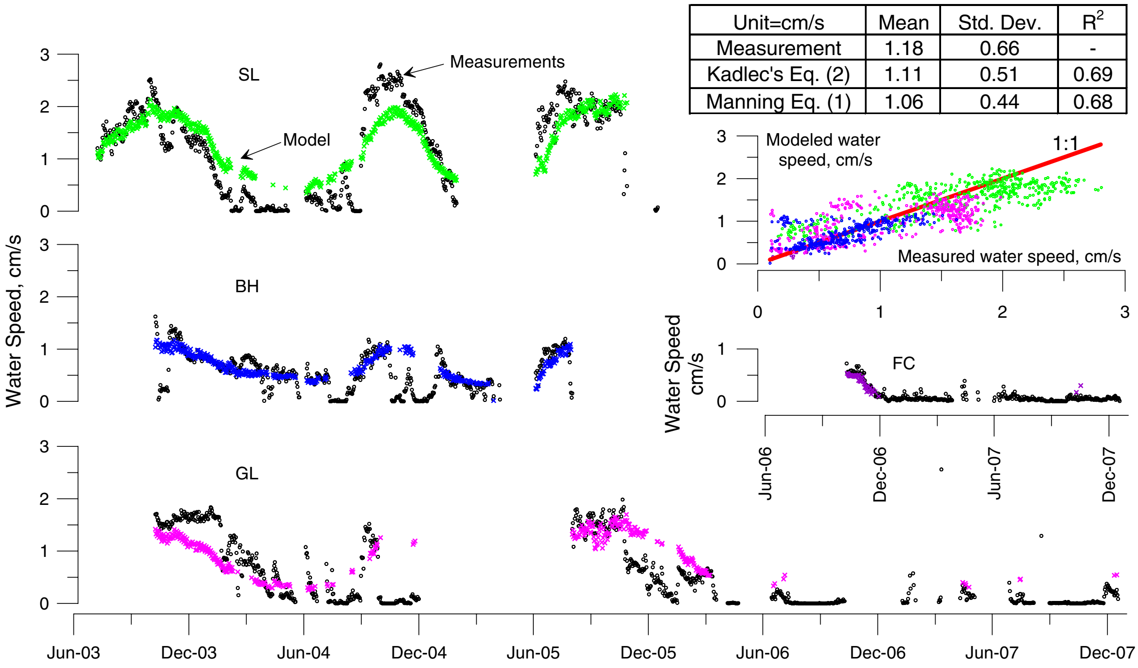
	S12A	S12B	S12C	S12D	S333-S334	Stage	Gradient	Rainfall
GL	0.50	0.38	0.58	0.62	−0.11	0.65	0.18	−0.03
BH	0.33	0.24	0.53	0.54	−0.01	0.56	−0.22	−0.02
SL	0.68	0.75	0.79	0.87	−0.23	0.79	0.72	−0.05
CH	0.22	0.23	0.21	0.15	0.20	0.03	0.02	0.07
FC	0.79	0.84	0.91	0.88	0.91	0.74	0.80	−0.23

parameters in Kadlec's version of this model with their 95% confidence intervals were λ=0.66±0.09, β=1.12±0.07, and K_f=14.4 (5.8 to 35.7) $m^{-1.67}$ s^{-1}. Comparison of the residuals from these two models with stage, discharge, or rainfall showed no significant relationship and thus the models were not refined beyond the basic empirical relationships.

Both models explained approximately 70% of the variation in speed. In general, low flow speeds were overestimated, while high flow speeds were underestimated using Kadlec's equation (Fig. 6). However, overall deviations between the model and observations were slightly but significantly less (signed-rank test, p<0.01) when using Kadlec's model instead of Manning's equation. Both the mean and standard deviation of U predicted using Kadlec's model were closer to our observations than those predicted using Manning's equation (see top right inset in Fig. 6). Therefore, we suggest that Kadlec's equation is more appropriate for simulating flow speed in the ridge and slough habitat.

Discussion

Our speed measurements from 2003 to 2005 are consistent with earlier studies conducted in 2002 and 2003 that measured water speed along transects that bisected multiple ridges and sloughs (Leonard et al. 2006) as well as transects that crossed the GL tree island (Bazante et al. 2006). The peak speeds during the wet seasons at GL and BH were



Unit=cm/s	Mean	Std. Dev.	R^2
Measurement	1.18	0.66	-
Kadlec's Eq. (2)	1.11	0.51	0.69
Manning Eq. (1)	1.06	0.44	0.68

Fig. 6 Measured (open circle) and modeled (cross) flow speeds predicted using Kadlec's model (λ=0.66, β=1.12, and K_f=14.44 $m^{-1.67}$ s^{-1}) at four of the five study sites. Site CH was excluded from the calibration because of unreliable stage estimated by the EDEN network. There is no distinguishable difference between predictions by Kadlec's model and by Manning's model if they were plotted together in the graph. Therefore, only predictions by Kadlec's model are shown while statistics for both models are given in the inset table. Also shown below the inset table is a plot of measured versus modeled flow speeds

also consistent with those measured by Riscassi and Schaffranek (2002, 2003, 2004) at two neighboring sites (GS-203 and GS-33) during the 1999 to 2003 wet seasons, when similar gate discharges (44.7 m^3 s^{-1}) to the current study (Table 1) were observed. These speeds were smaller than those observed at two downstream sites (GS-36 and SH1), which were either located at the narrow portion of SRS (GS-36) or was in a region tidally influenced and impacted by coastal ground-water discharge (SH1, Price et al. 2006).

Flow directions from the EDEN network were consistent with the measured values at GL, SL, and BH; however, the direction did not match at CH and FC, which is likely due to the effects of nearby canals and levees (Palaseanu and Pearlstine 2008). On a larger spatial scale, the EDEN stage contours east of the L67 Ext. showed a dominant southeastward flow. This is in contrast to the historic southwest flow direction in this area as suggested by the orientation of the ridge-slough and tree island formations (Sklar et al. 2001a).

Factors Affecting Water Speed in SRS

Despite the differences in conditions at the monitoring sites, we found that one set of parameters each for Manning's and Kadlec's equations was sufficient to explain 70% of the variability in marsh flow speeds when the datasets were combined (Fig. 6). Our estimate of Manning's roughness coefficient (n) appeared to be in line with those for other vegetated wetlands, which range from 0.3 to 5.0 depending on the type of vegetation and its density (Jenter and Schaffranek 1996). Values of n between 0.27 and 1.1 have been suggested for south Florida constructed wetlands (Brown and Caldwell 1996). Our estimates of both λ (0.66 ± 0.09) and β (1.12 ± 0.07) in Kadlec's model also fell within expected ranges of 0.7 to 1 for λ and 0.5 to 3 for β (Kadlec 1990; Kadlec and Knight 1996; Tsihrintzis 2001). We attribute the differences between predicted and observed flow speeds to other local factors not explicitly represented in these models, such as vertical variations in water column biomass (Nepf 1999; Leonard et al. 2006). To account for this effect, Lee et al. (2004) proposed a resistance model for flows in sawgrass marshes, which included stem spacing as one of the parameters. Other researchers found that Manning's coefficient varied with water depth (Musleh and Cruise 2006; Wilson 2007). These studies suggest that flow resistance is site specific and that analytical models such as Manning's equation should include variable resistance coefficients that take into account changing water levels and seasonal and local changes in vegetation biomass. The shift to the relatively constant flow directions observed at the five sites at high water speeds (Fig. 4) during high water conditions (Fig. 3) also suggests that the effects of vegetation on flow patterns in this habitat are stage dependent. This change in flow pattern may be caused by the changes in the distribution of biomass within the water column, with the immediate effects of water level increases resulting in a net decrease in the fraction of the water column occupied by underwater biomass.

In wetland systems dominated by submerged vegetation, maximum speeds occur above the vegetation (Nepf and Vivoni 2000; Järvelä 2005). In the freshwater sloughs in the Everglades, some of the submerged vegetation floats and thus the location of the maximum speed in the water column in the Everglades' sloughs will therefore depend on the overall distribution of periphyton biomass and other submerged vegetation in the water column (Bazante et al. 2006; Leonard et al. 2006; Variano et al. 2009). Within the sawgrass ridges, and in sloughs containing high densities of emergent species, the depth of the maximum speed will depend on the water depth in relation to the deflection height of the vegetation. As the water level rises close to the deflection height, the vertical velocity profile is likely to shift, with the higher speeds occurring closer to the surface. At three of our sites, when the water reached certain threshold levels (about 1.6 m at GL and BH, and 1.8 m at SL), we observed deviations in the relationships between speed and depth. For example, during August 2005 at SL, July to October 2006 at GL, and August 2005 at BH (Fig. 3), the speed decreased or leveled off while stage was still rising. We speculate that the deflection height of local vegetation was exceeded during these periods and that the maximum velocities moved towards the surface above the ADV. Because the ADV units were fixed at 6/10 of the water depth during each preceding maintenance trip, it is possible that the units may have missed the velocity changes as a majority of the flow moved towards the surface. This hypothesis can be used to explain some of the drops in flow speed but not all.

Gate discharges also play a central role in determining the water speed in SRS. As expected, the stations (SL, BH, GL) located in the southwestern portion of SRS were strongly influenced by the S12s, and on the northeastern side of SRS (Fig. 3), flow speeds at both FC and CH exhibited significant correlation with the S333-S334 discharge (Table 2). However, there are some uncertainties. Flow speeds at FC and CH were significantly correlated with one or more of the S12 structures (Table 2), which was surprising given the distance from these two sites to the S12s and the orientation of the hydraulic gradients in these areas (Fig. 5). It is important to recognize that gate discharges, water levels, and regional rainfall patterns all exhibit varying degrees of spatial and temporal correlation in the Everglades, particularly over seasonal or annual time scales. We expect that the relationships between S12 discharges, stages at FC and CH, and flow speeds at these two sites may reflect these synoptic properties of the system, especially for discharge through the control structures that in many cases are operated simultaneously in response to prevailing hydrologic conditions. Together these results emphasize the role of regional water supply and management of hydrologic conditions within the study watershed.

Topographical features of SRS are also recognized to affect spatial variations of the water speed. The slough starts with a wider opening at the northern boundary of ENP and narrows to the southwest, accelerating flow in the downstream direction (Riscassi and Schaffranek 2004). Furthermore, the flows through SRS are analogous to flows through the floodplain of a river. During high water conditions, the water will overflow from SRS into the adjacent western or southeastern marl prairies when the water elevation reaches above the ground elevation of these regions (Tabb 1990). The elevations of the marl prairies that are adjacent to the central portions of the slough are about the same as the observed stage (1.65 to 1.69 m in Fig. 3), at which several sudden decreases in water speed occurred at GL and BH. If overland flow occurs, the dramatic increase in flow area can prevent water speeds from increasing or even causes the water speed in the slough to slow down due to increased frictional resistance. Therefore, an overland scenario could explain the unexpected water speed-stage relations during those high stage periods. This scenario points to the need to include channel morphology in refinements of predictive models of flow patterns in the SRS.

Implications for Everglades Restoration

Sediment resuspension and settling are two processes regulated by flow speed and water depth that are thought to be important in maintaining the ridge and slough ecosystem (Larsen et al. 2007). Based on an open channel flow model, Bazante et al. (2006) proposed 7 cm s^{-1} to be the critical speed for particle (3.3 μm in size) resuspension in the Shark River Slough. Larsen et al. (2009) measured a critical bed shear stress of 0.01 Pa for the resuspension of flocculated particles (100 μm in size) collected from the Everglades. This bed shear stress translates to a flow velocity of 2.5 cm s^{-1}. Water speed measured in this study rarely exceeded that rate suggesting that resuspension of particulates would not occur under current conditions given the Bazante et al. (2006) estimate, and would rarely occur given the Larsen et al. 2009 estimate; these comparisons suggest that resuspension of particulates from the sloughs is almost non-existent. Based on the Kadlec's equation with the coefficients obtained in this study, water needs to be deeper than 1 m to reach 2.5 cm s^{-1} and 2 m to reach 7 cm s^{-1} if the hydraulic gradients remain within 6 cm km^{-1}. For either critical velocity, the required water depth is deeper than the normal values we measured, which indicates more water is needed for resuspension to occur.

Our observations also provide evidence that the surface water flow directions, particularly in the eastern portions of SRS, have changed from the pre-drainage periods (Sklar et al. 2001a). Such changes in flow direction can be expected to lead to alterations in the advection and dispersion of suspended particles in marsh habitats that exhibit anisotropic vegetation patterns. Restoring flow directions to match the orientation of the historic ridge and slough formations will require careful coordination between the timing and location of water deliveries and the operations of the border canals. This type of coordination is necessary to align the landscape-scale flow directions along historic flow paths and is required in all systems (such as SRS), that are characterized by extremely low hydraulic gradients, and in which groundwater-surface water interactions can significantly affect surface water flow patterns. The historic flow pattern will not be generated through local rainfall-runoff dynamics alone and requires the reestablishment of water deliveries as sheet flow from contributing basins. This is typified in the measurements in northeast SRS, which show that the loss of seasonal flow patterns is due primarily to insufficient discharges of surface water across the Tamiami Trail. Such an approach presumes that water deliveries at the borders of the system will permit for the restoration of local landscape features and vegetation structure; however, additional interventions may be necessary to re-establish landscape and vegetation features needed to restore the historic flow regime.

In summary, water speeds and depths in SRS are characterized by a strong seasonal pattern with localized variations. A forward stepwise regression model showed that gate discharge, stage, and stage gradient can explain 50 to 90% of the variance in speed at four of total five sites and only 10% at CH, a site located close to a levee-canal combination. Manning's and Kadlec's equations can explain approximately 70% of the variation in speed. However, a more complete explanation of variation in speed requires knowledge of local-scale channel morphology, vegetative resistance, and ground-water exchange. Nevertheless, seasonal hydropatterns and water speed variations are critical to the sustainability of the Everglades ecosystem and depend on the amount and timing of discharge from the upstream water management control structures. Our observations suggest that discharges through these structures should be increased and flows along the borders of the system must be carefully coordinated to restore the ridge and slough topography in ENP.

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