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# Spatially distributed modeling of surface water flow dynamics in the Everglades ridge and slough landscape

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SUMMARY

A two-dimensional, spatially distributed flow dynamics model was developed and tested for a 1.5 by 4 km area of the patterned ridge and slough landscape of the Florida Everglades. This model is intended to support a deepened understanding of the system ecohydrological dynamics, and provide a useful tool for management decision support. The model was constructed with a fine enough mesh structure to ensure proper representation of ridge and slough topographic detail as well as capture local hydrologic influences. Upstream and downstream stage data collected near the study area in central Water Conservation Area 3A were used to establish the initial and boundary conditions. Water velocities measured in the ridges and sloughs over a 3-year period were used to calibrate and verify the model. Hydraulic resistance was computed using a power-law relationship with water depth. The simulated water levels, water depths, and flow velocities showed good agreement with the 3-year field-monitored data with percent model errors of approximately 4%, 12%, and 10%, respectively. Computed differences in hydraulic resistance between ridge and slough were reduced significantly during the storm season compared to the dry season. This suggests that more solute and suspended solid mass can be redistributed from the sloughs to the ridges in particular during wet seasons, due to the weakened heterogeneity of hydraulic resistance during high flows.



## 1. Introduction

Spatially distributed flow dynamics models can be used by aquatic ecosystem scientists and managers to help understand or predict hydrological, biogeochemical, or ecological changes over various time scales. In aquatic systems such as wetlands where key ecological processes are strong functions of the spatio-temporal changes in hydrodynamic parameters (i.e. water depth and flow velocity), integrating reactive transport models with ecosystem models enables testing of environmentally critical hypotheses through both hind- and forecasting scenarios. However, to obtain meaningful simulation or prediction results, one cannot overemphasize the importance of a robust flow dynamics model developed at a spatial scale consistent with the modeling purpose.

Human intervention to the Everglades during the last century has caused the loss of historic surface flow. The disturbed hydrology has been suspected as a trigger of the partial loss of the unique ridge and slough landscape pattern in the central Everglades. Currently, temporal variation of hydrodynamic features in the remnant Everglades is mainly controlled by water management practices regulating flow (usually stormwater) from upstream hydraulic structures (Harvey et al., 2009). For the recent and proposed future restoration efforts, the role of surface water flow and organic-rich sediment (flocculent materials) transport as well as spatio-temporal change in hydroperiod has been highlighted due to the importance of physical and ecological impacts on the landscape formation, maintenance, and degradation (SCT, 2003; Leonard et al., 2006; Larsen et al., 2007, 2009; Noe et al., 2007). Restoring a more natural hydropattern and improving water quality in this ecosystem are critical components of the Comprehensive Everglades Restoration Plan (CERP) (Perry, 2004), including decompartmentalization – removal of canals and levees to restore the historic sheetflow through the remnant Everglades (i.e. to increase hydrologic connectivity of the system). While simple water balance models may be adequate for broad water resource management, a well developed flow dynamics model can play a foundational role in developing more advanced modeling tools to understand current hydrological and ecological effects on the wetland ecosystem and predict the future changes from the wetland ecosystem restoration.

Compared to recent systematic monitoring efforts on water flow and solute/particle transport in the patterned landscape of the Everglades (Saiers et al., 2003; Harvey et al., 2005b, 2009; Bazante et al., 2006; Leonard et al., 2006; Noe et al., 2007; Huang et al., 2008), physically based, spatially distributed modeling

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studies with local- or intermediate-scale (i.e. beyond pilot or mesocosm scales) have been rarely reported in this unique wetland ecosystem. The primary reason may be due to the difficulties in obtaining high resolution spatial data for model development (bathymetry, peat depth, vegetation type and density) and spatio-temporally distributed hydrologic data necessary for model setting, calibration, and validation, including field observations in both ridges and sloughs. Model grids in regional-scale models are too coarse to represent the topographic and vegetative heterogeneities effectively. The physical differences between ridges and sloughs form different flow characteristics. The average ponding depths, hydroperiods, flow velocities, and the transported water and solute fluxes are all different between the ridge and slough habitats (Noe and Childers, 2007). The different surface water flow characteristics regulate the formation and distribution of bimodal vegetative habitat, which impacts the flow again by creating different hydraulic resistances, ultimately controlling the landscape stability directly or indirectly.

The significance of heterogeneous topography and vegetation for understanding and modeling wetland flow characteristics have been well documented (Martinez and Wise, 2003; Dierberg et al., 2005; Jenkins and Greenway, 2005; Min and Wise, 2009). However, these impacts were not fully considered in previous spatially distributed regional modeling efforts for the bimodal ridge and slough landscape (SFWMD, 1994; Bolster and Saiers, 2002; SFWMD, 2005a) despite the acknowledged differences in hydrologic/hydraulic characteristics of ridges and sloughs. The objective of the present study was to examine the significance of topographic and the associated vegetative (in terms of hydraulic resistance) bimodality on the ridge and slough flow dynamics, which have not been considered in previous flow dynamics modeling efforts. The South Florida wetland ecosystem may be one of the best study areas in the world to develop and test such a model due to decades of continuous and extensive hydrologic monitoring.

In this study, a two-dimensional (2-D), spatially distributed flow dynamics model was developed for the ridge and slough landscape and tested against hydrologic data, such as water level ($h$), depth ($d$), and flow velocity ($v$), collected from a typical ridge and slough area that is considered well-conserved. The modeling framework was the Regional Simulation Model (RSM) developed by the South Florida Water Management District (SFWMD). The RSM has been applied mainly for a large-scale (>$10^3$ km$^2$) basin with complex hydrology (Lal et al., 2005), but rarely used for relatively smaller-scale ($\sim$10 km$^2$) natural wetland systems. Hence, the second objective was to evaluate the usefulness of the RSM framework in predicting local- or intermediate-scale hydrology of the landscape accurately. The final objective was to evaluate the effect of limited spatial information on the ability to predict hydroperiods (seasonal pattern of water level in wetlands) and $v$ in the Everglades ridge and slough landscape. Ultimately, this model can serve as the hydrodynamic foundation of a hydro-ecosystem model through linking with a transport and a reaction algorithm (RSM WQ; James and Jawitz, 2007) including both sediment transport and net peat accretion processes that may be different between ridge and slough habitats.

## 2. Site description

The selected model domain is a 1.5 by 4 km rectangle located approximately 4 km south of Alligator Alley (I-75) in Water Conservation Area 3A (WCA-3A, Fig. 1A and B). In this area the historic ridge and slough landscape pattern is considered to be well preserved (SCT, 2003; Harvey et al., 2009). The ratio of ridge and slough landscape is about 1:1 (Wu et al., 2006). Relatively higher-elevation ridge areas dominated by dense stands of sawgrass (*Cladium jamaicense*) have shallower $d$ and shorter hydroperiod compared to adjacent lower-elevation sloughs, open water areas with plants accustomed to deeper $d$, such as *Nymphaea odorata*, *Eleocharis* spp., *Utricularia* spp., and *Panicum repens* (Fig. 1C). Jorczak (2006) reported that site J-1 located 2.4 km west of the model domain had an average topographic difference of 16 cm between ridge and slough and the difference increased toward

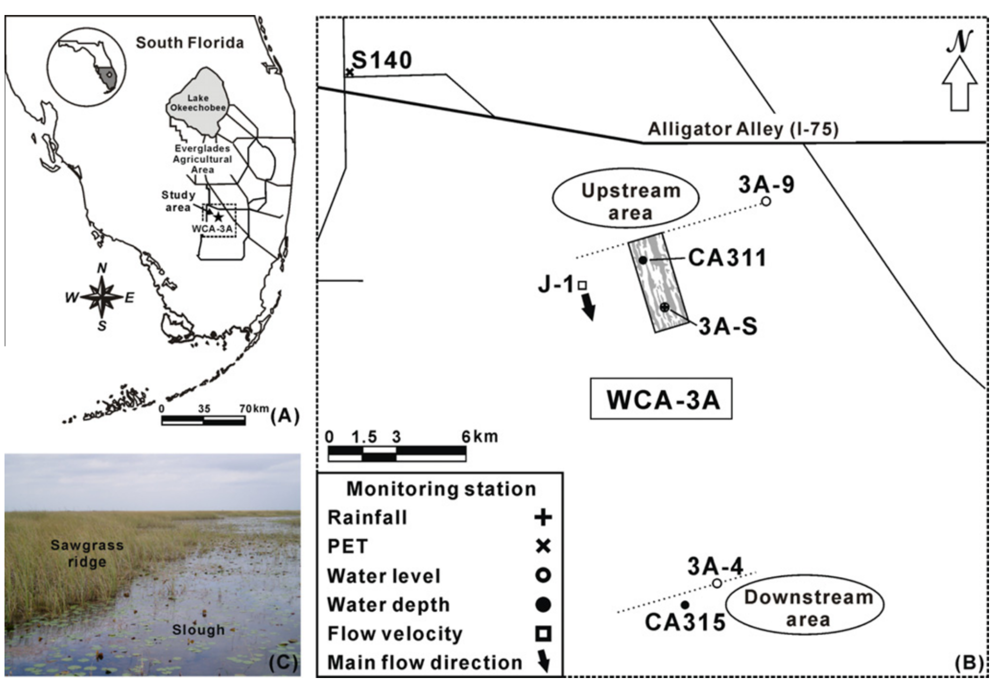


**Fig. 1.** Location maps of model domain and hydrometeorologic data monitoring stations: (A) regional map of study area in Water Conservation Area 3A, (B) enlarged view of study area (dotted rectangle in panel A) showing the location of model domain and hydrometeorologic data monitoring stations used for model development and calibration. The station numbers are from the SFWMD online database DBHYDRO, except station J-1, from Jorczak (2006), and (C) photograph showing the typical sawgrass-dominant ridge and open slough landscape in study area.

downstream area of WCA-3A (elevation difference at the downstream area in Fig. 1B: 25 cm).

## 3. Methods

### 3.1. Modeling framework

A physically based, spatially distributed numerical model for landscape flow dynamics was developed based on the Hydrologic Simulation Engine (HSE) of the SFWMD RSM. This finite volume based model was developed to comprehensively simulate various surface (overland flow in wetlands, hydraulic structure flow, and canal flow) and subsurface flows and their interactions principally for application to the complex regional hydrologic system of South Florida (Lal et al., 2005; SFWMD, 2007).

The HSE governing equations for mass and momentum conservation (St. Venant equations) are consistent with traditional surface flow dynamics models. The inertia terms of the momentum equation were neglected for diffusion flow assumption (Feng and Molz, 1997; Bolster and Saiers, 2002), which has been shown to be valid for most regional flows in the south Florida Everglades (Lal, 1998, 2000). The modified governing equations in integral form, based on Reynolds' transport theorem, are combined to generate a diffusion flow equation and solved using an implicit finite volume method. The model is implemented with two basic abstractions – "waterbodies" and "watermovers", which are used to represent the state within a control volume and the flux between the volumes, respectively (SFWMD, 2007). This allows multi-dimensional calculation of the storage in various waterbodies (overland, subsurface, canal and lake) and the flow between the waterbodies. Detailed descriptions of the RSM HSE modeling framework can be found elsewhere (Lal et al., 2005; SFWMD, 2005b, 2007).

### 3.2. Model setup

#### 3.2.1. Model domain

The model domain size (1.5 km by 4 km) was selected to be large enough to capture the bimodal features typical of the ridge and slough landscape and yet small enough that model effectiveness would not be compromised by the number of calculations and the corresponding model running time. It was desired to employ a fine enough mesh structure to represent ridge and slough topographic detail, and the domain size was thus limited to approximately 10 $km^2$, rather than the approximately $10^3$ $km^2$-scale of the entire hydrologic basin (WCA-3A). A 2004 Digital Ortho Quarter Quad (DOQQ) map of this study area and the selected model domain are illustrated in Fig. 2A. The rectangular model domain with the major axis parallel to the elongated ridge direction (i.e. main flow direction) comprises approximately four major ridges separated by three sloughs. No flow boundaries were assigned to the directions parallel to the main flow direction (Bolster and Saiers, 2002) as shown in Fig. 2B. The upper and lower boundaries were set based on long-term *h* data measured at nearby monitoring stations. The borders between the ridges and sloughs within the model domain followed the landscape boundary delineated by Cowardin et al. (1979) (Fig. 2B) and there were no major discrepancies when compared to the recent pattern shown in the DOQQ map. For the model grid, an irregular triangular mesh, which is suitable to delineate the complex bimodal landscape boundaries, was generated with Groundwater Modeling System (GMS) v5.1 (Brigham Young University, 2004) (Fig. 2C). The number of discretized grid cells was 962 (ridge: 486 and slough: 476). An enlarged portion of the model grid, shown in Fig. 2D, illustrates specific grid cell location of simulation output points for *d* and *v* at ridges (R1–3) and sloughs (S1–3), respectively. For comparison with the measurement data at J-1, these points were selected arbitrarily along the direction perpendicular to the main flow direction, considering the location of J-1. The simulation period was 3 years (January 1, 2002–December 31, 2004) and the simulation time step was 6 h.

#### 3.2.2. Model bathymetry

The Everglades Depth Estimation Network (EDEN) is an active *h* and ground-elevation monitoring/modeling effort in the Everglades that enables scientists and managers to access current *h*, *d*, and topographic information (Chartier and Jones, 2007; Jones and Price, 2007; Pearlstine et al., 2007; Palaseanu and Pearlstine, 2008). However, the elevation model source data vertical resolution of ±0.15 m and cross-validation error of 0.07–0.17 m (Chartier and Jones, 2007) were not sufficient to differentiate the subtle topographic difference between the ridges and sloughs (about 0.16 m) in the model domain. The average topographic difference between 14 EDEN DEM ridge points and 24 slough points was only 0.01 m ($p = 0.52$). Hence, the model bathymetry was constructed independently using available hydrologic monitoring data and a geostatistical interpolation scheme and then confirmed with the EDEN data.

The average landscape slope was determined as follows. First, the upstream and downstream (see the locations in Fig. 1B) slough bottom elevations were estimated from the differences between 3 year average *h* at 3A-9 and *d* at CA311 and 3 year average *h* at 3A-4 and *d* at CA315: upstream/downstream slough 2.94/2.56 m NGVD29; slope = 0.0025%. With the assumption that the lateral bathymetric variation was negligible, a 2-D regional slough topographic map was created using spline interpolation method. The gently sloping landscape was set to be slightly steeper in the slough than the ridges according to the field observations of Jorczak (2006). Ridge bottom elevations were estimated by adding topographic differences measured by Jorczak (2006) in the upstream and downstream areas (0.16 and 0.25 m) to the slough bathymetry estimates: upstream/downstream ridge 3.10/2.81 m NGVD29; slope = 0.0019%. A regional ridge map was made using the same interpolation scheme. These two regional maps were cut along the ridge and slough boundary and merged into a final bathymetry map using ArcGIS 9.2, illustrated in Fig. 2E. The upper/lower boundary ridge and slough topographic elevations were determined to be 3.10 and 2.94 m/3.02 and 2.84 m, respectively. The average ridge topographic elevation over the entire model domain (3.06 ± 0.02 m) was 0.17 m greater than in sloughs (2.89 ± 0.03 m), generating topographic differences between the bimodal landscapes that increased from 0.16 to 0.18 m along the main flow direction. These ridge/slough topographic differences are very close to the average difference (0.15 m) reported by Givnish et al. (2008) across the study regions (WCA-3A/3B). Differences between the calculated slough bathymetry and the EDEN DEM data near the model boundaries were only 0.03–0.05 m. Also, the estimated regional topographic slope of 0.0025% was comparable to those reported by Kushlan (1990; 0.0030%) and Harvey et al. (2009; 0.0033%). Peat soil depth of 0.8 m was assumed to be constant throughout the entire model domain (Jorczak, 2006).

#### 3.2.3. Boundary and initial conditions

In systems with intensive hydraulic manipulation, such as the Florida Everglades, local processes such as rainfall and ET may not be sufficient to predict local hydrologic response. The hydrodynamic simulations of Bolster and Saiers (2002) were more sensitive to the upstream boundary conditions than rainfall or ET. Here, daily averaged *h* measured at 3A-9 were used for the upper boundary during the simulation period and the lower boundary was set through linear interpolation between *h* measured at 3A-9 and at 3A-4. This lower boundary was consistent with the average *h* mea-

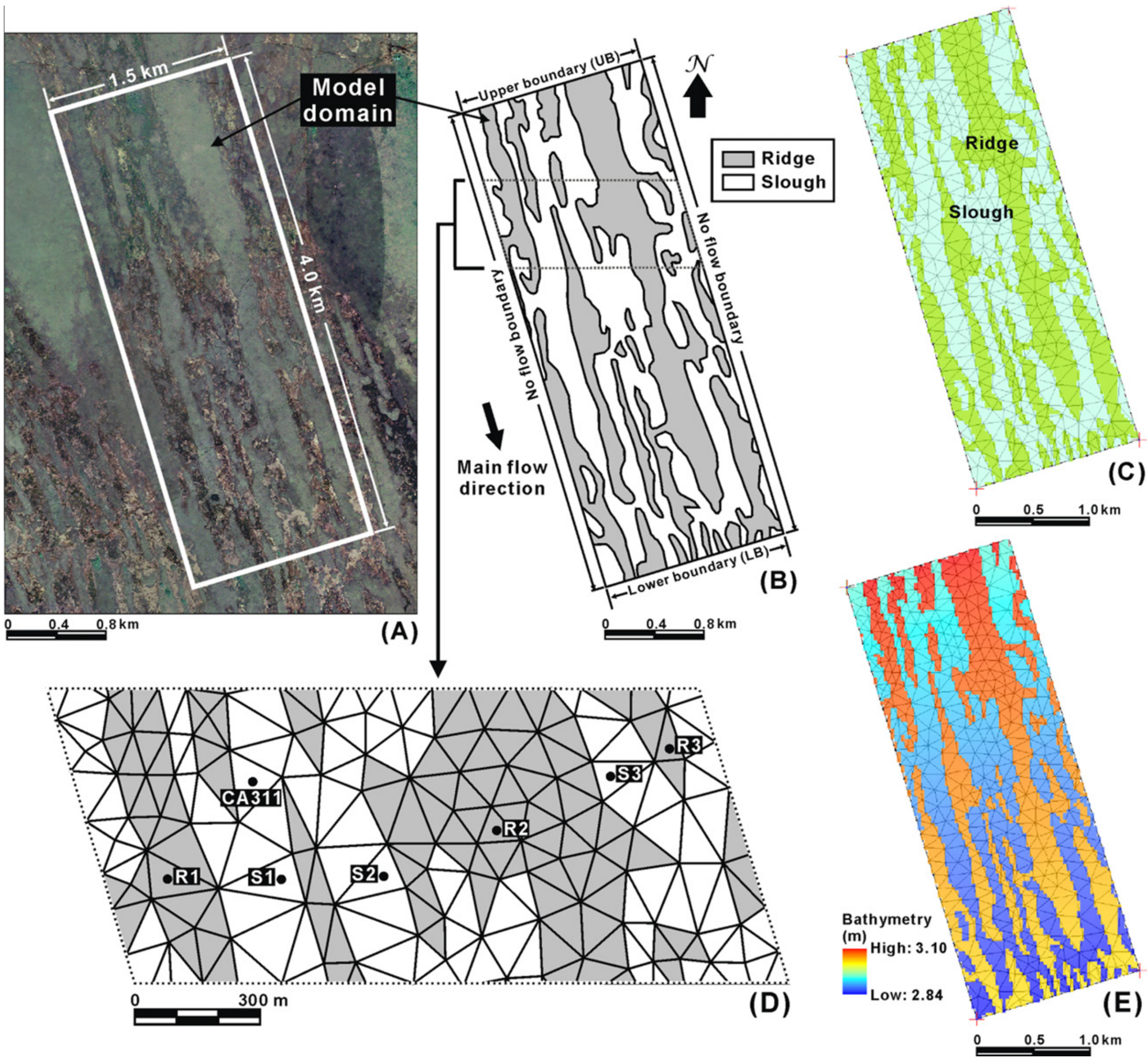


**Fig. 2.** Model domain – the bimodal landscape and the spatially distributed key model input data: (A) the selected 1.5 by 4.0 km rectangular model domain, parallel to the elongated axis of the ridges, (B) the model domain classified into two dominant aquatic habitats (ridge and slough) according to the bimodal landscape pattern delineated by Cowardin et al. (1979) and the assigned model boundary conditions (note that no flow boundary was assumed for both directions perpendicular to the main flow direction), (C) 2-D, irregular triangular grid mesh overlapped onto the bimodal landscape pattern, (D) specific grid cell location of simulation output points for $d$ and $v$, and (E) model bathymetry prediction map interpolated using spline.

sured at nearby EDEN monitoring stations (average difference 0.01–0.03 m). For the initial $h$ condition, the average $h$ value (3.32 m) of the upper and lower ones measured on the simulation starting date (January 1, 2002) was assigned throughout the model domain.

### 3.3. Hydrologic data

To develop and test a 2-D, spatially distributed flow dynamics model, hydrometeorological data collected from the central portion of WCA-3A were used. Spatially uniform rates of daily based rainfall and potential ET (PET) were applied throughout the entire model domain. Daily based rainfall and PET data were collected by SFWMD at 3A-S and S140, respectively (Fig. 1B). Approximately 10% missing values in the S140 PET data during the simulation period were substituted with PET measured at 3AS3WX, a monitoring station located in the southern WCA-3A (the median value of absolute differences between the remnant comparable PET data monitored at these two stations was 0.38 mm; correlation coefficient = 0.79). These data are publically available through the SFWMD online database, DBHYDRO (http://my.sfwmd.gov/dbhydroplsql/show_dbkey_info.main_menu). Actual ET was calculated using the ET crop correction coefficient ($K_c$) which was determined as a function of $h$ (SFWMD, 2005b). When $h$ was greater than the ponding depth (fixed to 2.0 m in this study, considering the maximum height of sawgrass), $K_c = 1.0$ (open water condition). The $K_c$ value linearly decreased as $h$ decreased to the ground surface ($d = 0$). When $d = 0$, the $K_c$ value corresponded to the root zone ET coefficient ($K_{veg}$). To assign the temporally variable $K_{veg}$ values, the monthly averaged values (0.88 ± 0.05) calibrated in South Florida Water Management Model (SFWMM) v5.5 for sawgrass plains (SFWMD, 2005a) were used in this study. When $h$ was in the shallow root zone (top 0.5 m of soil), $K_c = K_{veg}$ and then again the $K_c$ value was linearly decreased from the point $d = -0.5$ m to the extinction depth (fixed to a depth of 1 m below ground surface) where $K_c = 0$. In this modeling study, the $K_{veg}$ coefficients were assumed to be homogeneous regardless of the ridges and sloughs due to the lack of reliable information at finer scales.

Long-term hydrologic data, such as $h$, $d$, and $v$, monitored around the study area were also used for model setup and testing. Daily averaged $h$ and biweekly measured $d$ data were monitored by SFWMD or USGS (available from EDEN: http://sofia.usgs.gov/eden/) at the locations shown in Fig. 1B. Jorczak (2006) independently measured $v$ (and $d$) at the ridge and slough site of J-1 over a period of 16 months (November 2002–February 2004).

Groundwater–surface water interaction was not modeled in this study because groundwater exchanges determined by Harvey et al. (2004, 2005a) in WCA-3A (Site 3A-15, near our study site) were the smallest in the central Everglades. These authors concluded that the interior area of WCA-3A (our study area), which is far from levees and canals, may be the best modern analog for pre-drainage conditions with net groundwater exchange <1% (Harvey and McCormick, 2009). This is in contrast to the present-day managed condition of the central Everglades that is heavily influenced by drainage and control structures with net groundwater recharge as high as 16% (Harvey and McCormick, 2009).

Wind effects were also not included in this study. Although wind sometimes plays an important role in solute transport in shallow aquatic bodies (Langevin et al., 2005; Swain, 2005), this impact can be minimized in densely vegetated wetlands like the sawgrass ridges since the emergent vegetation dampens wave energy and shelters the water surface from wind stress (Nepf, 1999; Braskerud, 2001). Also, submerged aquatic vegetation such as found in sloughs has been reported to be effective in limiting wind-driven sediment/nutrient resuspension (Barko and James, 1997; Horppila and Nurminen, 2003). Therefore, wind effects were considered to be relatively less dominant compared to gravitational forces in controlling flow in the low gradient, patterned bimodal landscape.

### 3.4. Hydraulic resistance

A general power law form of frictional equations used for overland flow in wetlands was suggested by Kadlec and Knight (1996):

$$v = ad^{b-1}S^{c} \tag{1}$$

where $v$, $d$, and $S$ are surface water flow velocity, water depth, and water surface slope, respectively. For the friction parameters ($a$, $b$, and $c$), Kadlec and Knight (1996) recommended $a = 10^7/5 \times 10^7$ $\mathrm{m}^{-1}\,\mathrm{d}^{-1}$ (densely/sparsely vegetated), $b = 3.0$, and $c = 1.0$ (Table 1). Also, Bolster and Saiers (2002) estimated $a = 5.1 \times 10^6\ \mathrm{m}^{0.46}\,\mathrm{d}^{-1}$, $b = 1.54$, and $c = 1.0$ through model calibration to $h$ measured at Shark River Slough (Table 1). Eq. (1) is equivalent to Manning's equation when $a = 1/n$, $b = 1.67$, and $c = 0.5$. The Manning's roughness coefficient, $n$, has been widely used to represent a lumped hydraulic resistance in wetlands in spite of the theoretical inappropriateness indicated by Kadlec and Knight (1996). Considering a general trend that Manning's $n$ decreases as $d$ increases (Kadlec and Knight, 1996), SFWMD (1994, 2005a,b) suggested an empirical relationship between Manning's $n$ and $d$ as follows:

$$n = Ad^{B} \tag{2}$$

where the empirical coefficients, $A$ and $B$, are usually determined through model calibration. The magnitudes of $A$ and $B$ probably depend on wetland habitat (vegetation type) or vegetation density (given a wetland type) and the vertically non-linear characteristics of a $d$-dependent resistance curve (i.e. given a wetland type, a vertical $v$ profile), respectively. According to SFWMD (1994, 2005a), the value of $B = -0.77$ was satisfactory in most wetland habitats. Hence, a modified Manning's equation with the relationship of Eq. (2) can be arranged as:

$$v = \frac{1}{Ad^{-0.77}} d^{0.67} S^{0.5} \tag{3}$$

In this framework, a spatio-temporally variable Manning's $n$ is determined from the calculated $d$ at each grid cell every simulation time step. This $d$-dependent Manning's equation cannot be directly expressed in the form of Eq. (1) because $a$ would not be temporally constant.

We tested the above cases through model calibration of the resistance parameters, $a$ or $A$, to measured $v$ and $h$ profiles at the ridge and slough area, respectively (Table 1). Uniform vegetation density within each bimodal habitat was assumed in this study due to the lack of spatial distribution data in vegetative cover. A surface water detention depth of 0.03 m was assigned over the model domain, below which no flow occurred even if a hydraulic gradient was calculated.

## 4. Results

### 4.1. Model calibration

The ridge and slough $v$ profiles measured at J-1 were compared to daily average simulated $v$ profiles at R1–3 and S1–3. The model

**Table 1**
Wetland flow frictional equations tested in this study.

| | R/S[a] | Model parameters | | | $R^2$ | | Bias | | RMSE | | N–S | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $a$ | $b$ | $c$ | $v$ | $h$[b] | $v$ (cm/s) | $h$[b] (m) | $v$ (cm/s) | $h$[b] (m) | $v$ | $h$[b] |
| Kadlec and Knight (1996)[c] | R | $1.0 \times 10^7\ \mathrm{m}^{-1}\mathrm{d}^{-1}$ | 3.0 | 1.0 | 0.78 | 0.98 | −0.42 | 0.030 | 0.508 | 0.039 | −1.22 | 0.96 |
| | S | $5.0 \times 10^7\ \mathrm{m}^{-1}\mathrm{d}^{-1}$ | 3.0 | 1.0 | 0.95 | | −0.28 | | 0.403 | | 0.40 | |
| Bolster and Saiers (2002)[d] | R | $5.1 \times 10^6\ \mathrm{m}^{0.46}\mathrm{d}^{-1}$ | 1.54 | 1.0 | 0.74 | 0.99 | −0.41 | 0.031 | 0.505 | 0.039 | −1.21 | 0.96 |
| | S | $5.1 \times 10^6\ \mathrm{m}^{0.46}\mathrm{d}^{-1}$ | 1.54 | 1.0 | 0.73 | | −0.44 | | 0.650 | | −0.55 | |
| Kadlec-type | R | $1.25 \times 10^8\ \mathrm{m}^{-1}\mathrm{d}^{-1}$[e] | 3.0 | 1.0 | 0.76 | 0.98 | −0.11 | 0.032 | 0.209 | 0.041 | 0.62 | 0.96 |
| | S | $1.04 \times 10^8\ \mathrm{m}^{-1}\mathrm{d}^{-1}$[e] | 3.0 | 1.0 | 0.95 | | 0.02 | | 0.111 | | 0.95 | |
| Modified | R | $3.1 \times 10^4$–$3.5 \times 10^5\ \mathrm{m}^{0.33}\mathrm{d}^{-1}$[e] | 1.67 | 0.5 | 0.86 | 0.98 | −0.05 | 0.030 | 0.139 | 0.039 | 0.83 | 0.96 |
| Manning ($d$-dependent $n$)[f] | S | $4.4 \times 10^4$–$4.6 \times 10^5\ \mathrm{m}^{0.33}\mathrm{d}^{-1}$[e] | 1.67 | 0.5 | 0.90 | | 0.07 | | 0.143 | | 0.93 | |
| Manning[g] | R | $6.9 \times 10^5\ \mathrm{m}^{0.33}\mathrm{d}^{-1}$[e] | 1.67 | 0.5 | 0.62 | 0.98 | 0.05 | 0.030 | 0.171 | 0.038 | 0.75 | 0.96 |
| | S | $7.8 \times 10^5\ \mathrm{m}^{0.33}\mathrm{d}^{-1}$[e] | 1.67 | 0.5 | 0.51 | | 0.10 | | 0.245 | | 0.78 | |

[a] R = ridge/S = Slough.
[b] Calibrated to $h$ measured at 3A-S (this study).
[c] Recommended values (R: densely/S: sparsely vegetated).
[d] Calibrated to Shark River Slough $h$.
[e] Calibrated to $v$ measured at J-1 (this study).
[f] $A = 0.19$ (R)/0.17 (S).
[g] $n = 0.13$ (R)/0.11 s/m$^{1/3}$ (S).

calibration process was not finalized until the RMSE between the measured $v$ ($N = 7$) and the averaged value of $v$ simulated at the three points was minimized. First, the values recommended by Kadlec and Knight (1996) and estimated by Bolster and Saiers (2002) were tested, but the results were not satisfactory (Table 1). Subsequently, the resistance parameters, $a$ or $A$, were estimated by model fitting with the other parameters fixed: (1) Kadlec-type: $a$ = calibration parameter, $b = 3.0$ and $c = 1.0$, (2) Modified Manning: $A$ = calibration parameter, $b = 1.67$ and $c = 0.5$, (3) Manning: $a$ ($1/n$) = calibration parameter, $b = 1.67$ and $c = 0.5$. As summarized in Table 1, the $v$ model calibration results reveal that the average RMSE was lowest when the modified Manning's equation was used. For ridge $v$, the RMSE was lowest (0.139 cm/s) when $A = 0.19$ ($R^2 = 0.86$). For slough $v$ the RMSE was lowest (0.143 cm/s) when $A = 0.17$ ($R^2 = 0.90$). Also note that the model calibration to $h$ was much less sensitive compared to the $v$ model calibration (Table 1). For hydraulic resistance in this study, the depth-dependent Manning's approach ($A = 0.19$ (ridge)/0.17 (slough), $b = 1.67$, and $c = 0.5$) was therefore applied to each ridge and slough finite element at each simulation time step. This was also supported by comparison to other common metrics of model performance: $R^2$, Bias, and Nash–Sutcliffe model efficiency coefficient (N–S) (Table 1). Although the field $v$ observations were limited (e.g., there was only one wet season field measurement), the model predicted the temporal fluctuation and spatial difference of each $v$ profile in the bimodal landscape reasonably (discussed further below). More systematic flow velocity data collection efforts (at least nine monitoring stations longitudinally and transversely – three by three in future monitoring efforts) are necessary to reduce the uncertainties associated with the low frequency of observations and confirm the calibration accuracy.

### 4.2. Spatio-temporal variation of hydraulic head

Daily averaged $h$ and biweekly measured $d$ were monitored by USGS and SFWMD at the two interior slough points of the model domain (3A-S and CA311). Hydraulic heads simulated at the corresponding model grid cells were compared to the field measurements (Table 2). The average $d$ (±1 SD) measured at CA311 (slough) and simulated at the corresponding grid cell (see the location in Fig. 2D) were 0.43 ± 0.20 m and 0.41 ± 0.19 m, respectively ($p = 0.36$). Fig. 3 also shows that the simulated hydraulic heads closely match the spatial and temporal variations in field observations for 3 years. Simulation error for $d$ ($R^2 = 0.74$; RMSE = 0.09 m) was greater than for $h$ ($R^2 = 0.98$; RMSE = 0.04 m). This is likely due to the higher uncertainties of manually measured $d$ including the local difference of microtopography (Sutron Corp., 2004). The percent model errors (PME), defined as RMSE divided by the range of the measured data, were about 4% and 12% for $h$ and $d$, respectively. Conrads and Roehl (2007) reported PME less than 6% for estimating $h$ at 25 new Everglades gauging stations using EDEN. Our hydraulic head simulation RMSE (0.04 m) was slightly higher than the EDEN water surface model RMSE (about 0.025 m) in WCA-3A reported by Liu et al. (2009).

**Table 2**
Comparison between measured and simulated hydraulic heads ($h$ and $d$).

| | *N* | Mean | SD | Max. | Min. | Note |
|---|---|---|---|---|---|---|
| *h (m)* | | | | | | |
| Measured | 1096 | 3.27 | 0.19 | 3.72 | 2.80 | 3A-S (slough: USGS, EDEN) |
| Simulated | 1096 | 3.30 | 0.19 | 3.75 | 2.92 | |
| *d (m)* | | | | | | |
| Measured | 67 | 0.43 | 0.20 | 0.92 | 0.14 | CA311 (slough: SFWMD, DBHYDRO) |
| Simulated | 1096 | 0.41 | 0.19 | 0.87 | 0.04 | |

The average (±1 SD) $d$ ($N = 6$) monitored by Jorczak (2006) in both the ridge (0.23 m ± 0.10 m) and slough (0.39 m ± 0.10 m) of J-1 were compared to averages of the daily based $d$ simulated at R1–3 (0.27 m ± 0.16 m) and S1–3 (0.44 m ± 0.16 m) (see the specific grid cell location in Fig. 2D) during the same time period. These simulation output points were selected arbitrarily along the direction perpendicular to the main flow direction based on the location of station J-1. The topographic and hydrologic conditions at J-1 were assumed to be similar to those at the R1–3/S1–3. The average simulated $d$ values were slightly higher than the measured values (0.04–0.05 m on average).

### 4.3. Hydroperiod

Hydroperiod plays a key role on vegetation dynamics and the biogeochemistry of organic rich soil in wetland ecosystems; thus, it is important to accurately predict the spatio-temporal pattern of this parameter in ecohydrological modeling efforts (Townsend, 2001). The simulated 3-year $d$ at R1–3/S1–3 were used to calculate ridge and slough hydroperiods in the study area. For the slough, there were no days when $d$ was less than 0.01 m (i.e. 100% hydroperiod under current flow regime controlling the $h$ boundaries). The ridge was dry for less than 1 month per year (6%), with $d < 0.01$ m 9% of the time, for ridge and slough hydroperiod of 91–94%. The spatio-temporal extent of hydroperiod simulated in this study is very close to the general patterns reported by other investigators in multiple locations of the patterned landscape (Ross et al., 2006; Givnish et al., 2008), which also supports appropriateness of the model setting based on the limited spatial data.

### 4.4. Flow velocity

The best model fits to the $v$ profiles measured by Jorczak (2006) at site J-1 are shown in Fig. 4. Note the several intermittent discrepancies in correlation between rainfall and flow velocity peaks denoted in Fig. 4, highlighting the importance of upstream water management practices in controlling the regional hydrology (Harvey et al., 2009). Although the current flow regime does not fully follow the historic rainfall-driven sheetflow pattern, the temporally fluctuating hydrologic pattern is still distinct as shown in the field observations of hydraulic head and $v$ (Figs. 4 and 5). During the dry season (November–May), the modeled $v$ did not usually exceed 0.5 cm/s in either ridges or sloughs. In the wet season (June–October) $v$ was much faster, with short-duration peaks greater than 2 cm/s in sloughs (Fig. 4). Although the pattern of seasonal variation of simulated $v$ was well captured, additional wet-season $v$ measurements are needed to confirm the magnitudes of predicted wet-season $v$. Note that Harvey et al. (2009) reported seasonal ranges of measured $v$ of 0.02–0.79 cm/s. Typical snapshots of dry and wet season simulated flow pattern are illustrated in Fig. 5. In addition to the overall trend of faster/sluggish velocities in the wet/dry seasons, $v$ was always higher in sloughs compared to adjacent ridges. The simulated 3 year average $v$ at the three slough grid cells (S1–3) was approximately 40% higher than at the ridge cells (R1–3) (Table 3). These results are consistent with long term field measurements reported by Harvey et al. (2009), that average ambient $v$ measured in central WCA-3A were typically on the order of 0.3 cm/s and the average $v$ was 29% higher in sloughs compared to ridges over a 3 year monitoring period.

### 4.5. Hydraulic resistance

Several types of frictional equations (Manning's and Kadlec-type) were tested in this study. Direct use of previously reported

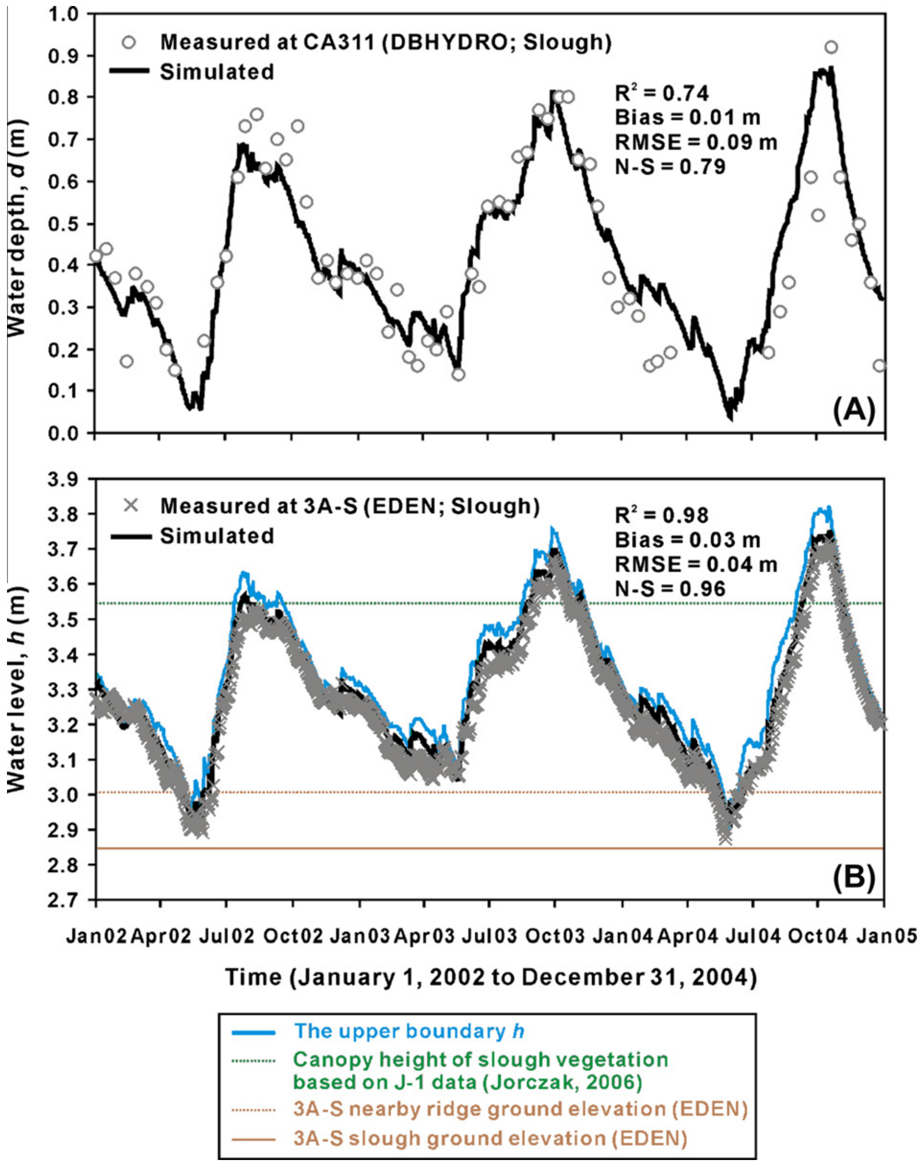


**Fig. 3.** Model fit of time series hydraulic head measured at two interior points of the model domain: (A) $d$ at CA311 and (B) $h$ at 3A-S. The canopy height of ridge vegetation (sawgrass: about 2 m above the ridge ground elevation) is not marked (out of range of $y$ axis).

parameter values for the general form of the wetland flow frictional equation was not suitable in simulating $v$ in the ridge and slough area (Table 1). When calibrated to $v$ measured in the study area, the simulation results from the modified Manning's approach were slightly better than those from the Kadlec-type and traditional Manning's approaches (Table 1). Also, compared to $v$, $h$ was not sensitive to the friction parameters (Table 1). This may be related to setting the boundary condition based on $h$. Hence, for models assigned by $h$ boundaries, using $h$ may be inappropriate to calibrate the hydraulic resistance.

Manning's roughness coefficients ($n$) were determined for ridges and sloughs as a function of $d$ using Eq. (2) and the model-calibrated hydraulic resistance parameter, $A$ (Fig. 6A). For the 3 year averaged $d$ simulated at the model grid corresponding to CA311 (ridge: 0.24 m and slough: 0.41 m), Manning's $n$ values of 0.57 and 0.34 s/m$^{1/3}$ were calculated for the ridges and sloughs, respectively. During the wet season, as $d$ increased, the lumped hydraulic resistances were reduced to 0.42 and 0.28 s/m$^{1/3}$, respectively. During the dry season, the shallow $d$ increased the roughness coefficients to 0.81 and 0.41 s/m$^{1/3}$.

The average Manning's roughness coefficient values calculated here were compared to the values calibrated in various south Florida landuse patterns under the same hydraulic resistance modeling framework, SFWMM v5.5. For the central/southern WCA-3A wetland area (categorized as "Ridge and Slough II" in SFWMM), which includes the model domain of this study, the average ridge and slough Manning's values were 0.62 and 0.41 s/m$^{1/3}$ ($A = 1.25$/$B = -0.77$ SFWMD, 2005a). These estimates were close to those determined in this study (ridge: 0.57 and slough: 0.34 s/m$^{1/3}$). In addition, those values were 3–5 times greater than the $n$ values (ridge: 0.13 and slough: 0.11 s/m$^{1/3}$) calibrated with the traditional Manning's equation (Table 1). This shows that a simple application of model-calibrated constant Manning's $n$ in wetlands with highly transient flow regime should be done with caution because it may cause a significant underestimation of hydraulic resistance, particularly during dry seasons.

To evaluate the impact of change in topographic slope on the relationship between $d$ and Manning's coefficients, only the model topographic slope was doubled/halved under the same model condition and then the non-linear relationships were reconstructed

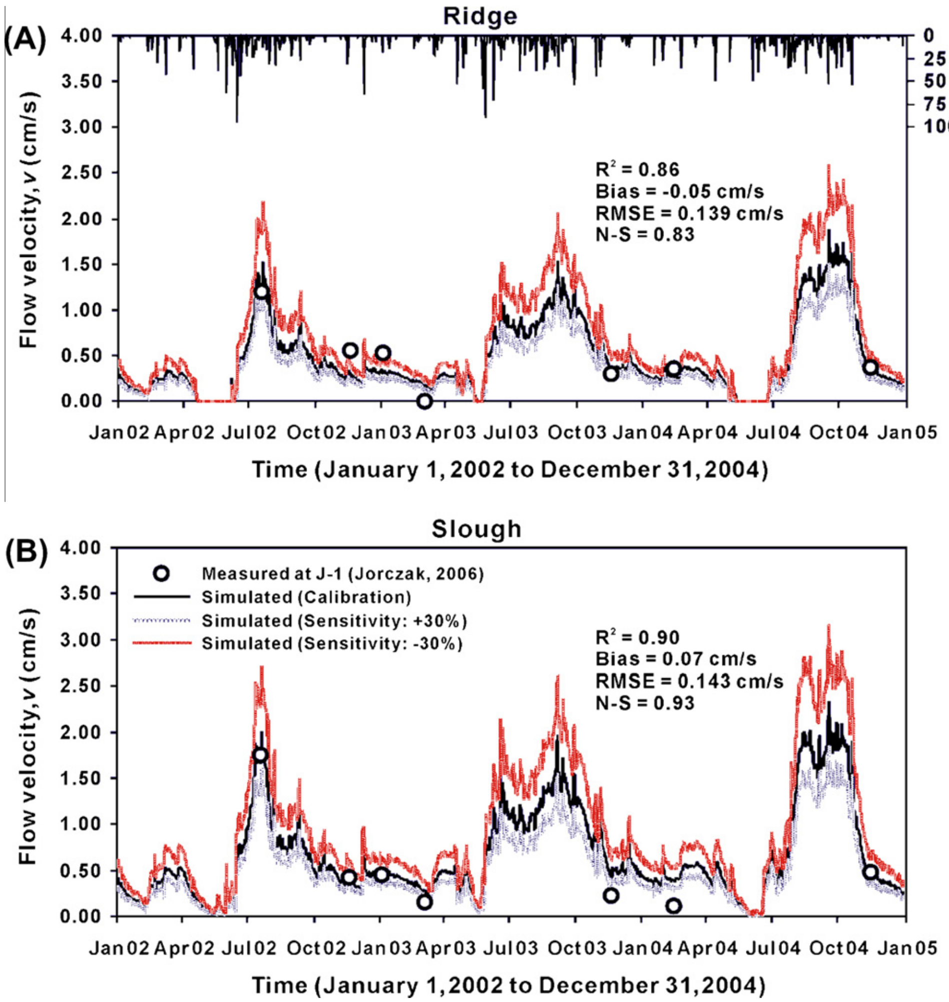


**Fig. 4.** Model fit of $v$ measured at J-1 by Jorczak (2006) and sensitivities of model-calculated flow velocities to change in hydraulic resistance coefficient, $A$ (±30%): (A) ridge and (B) slough. For model calibration, average of $v$ profiles simulated at R1–3 and S1–3 was used, respectively.

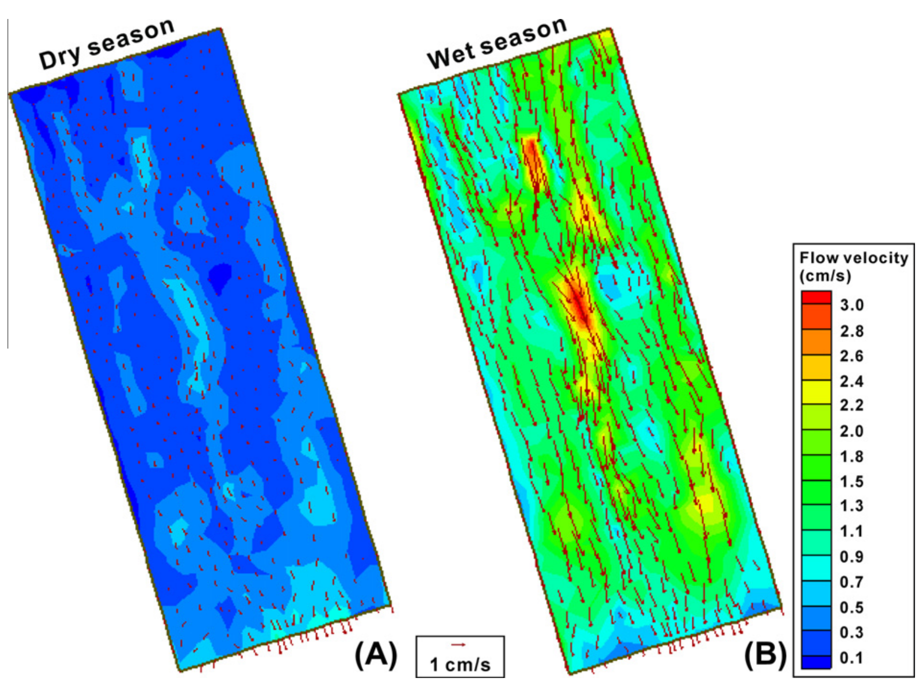


**Fig. 5.** Snapshots of computed $v$ in the model domain: (A) dry season (April 20, 2004) and (B) wet season (August 24, 2004).

**Table 3**
Sensitivity of modeled $v$ in the ridges and sloughs to change in hydraulic resistance coefficient, $A$ (±30%).

| | Model calibration | | | 30% Increase in $A$ | | | 30% Decrease in $A$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | $A$ | Avg. $v$ ± 1 SD (cm/s) | RMSE (cm/s) | $A$ | RMSE (cm/s) | $S_{v,A}$[a] | $A$ | RMSE (cm/s) | $S_{v,A}$[a] |
| Ridge | 0.19 | 0.47 ± 0.40 | 0.139 | 0.25 | 0.198 | −0.73 | 0.13 | 0.272 | −1.34 |
| Slough | 0.17 | 0.66 ± 0.49 | 0.143 | 0.22 | 0.201 | −0.74 | 0.12 | 0.325 | −1.30 |

[a] Sensitivity coefficients defined as the ratio of the change of 3 year-averaged simulated $v$ to the change of hydraulic resistance coefficient, $A$ for ±30% change in the coefficient.

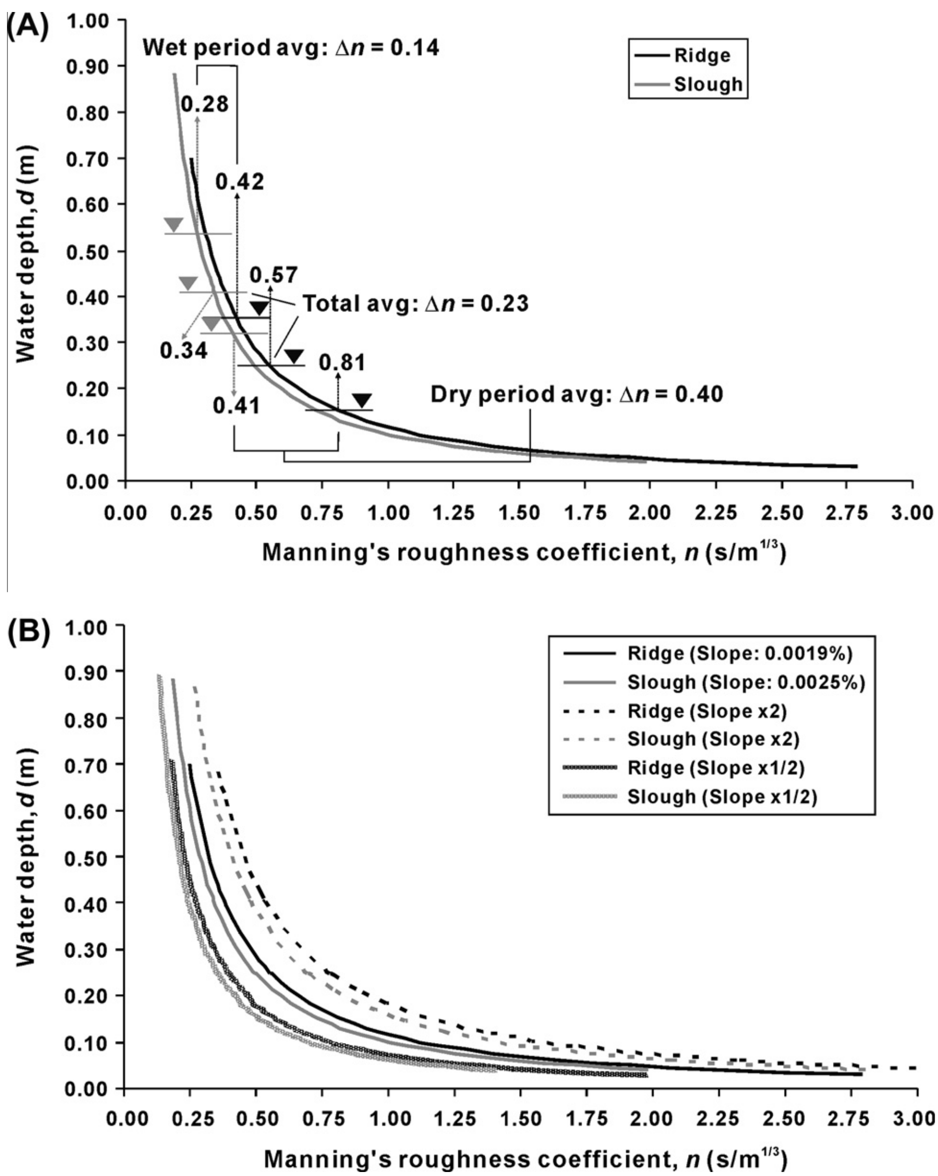


**Fig. 6.** Relationship between Manning's roughness coefficient and $d$ in the ridges and sloughs: (A) model calibration result and (B) the impact of changes in topographic slopes (2× and 0.5×).

(Fig. 6B). This figure shows that if the topographic slope of the study area were steepened/flattened by a factor of two, the hydraulic resistances estimated here should be increased/decreased by about 40%/30%, respectively.

*4.6. Sensitivity test*

Sensitivity test results of model-calculated $v$ profiles to changes in the empirical hydraulic resistance coefficient, $A$ (±30%) are illustrated in Fig. 4. The sensitivity of $v$ to the changes in $A$ was evaluated using the sensitivity coefficient $S_{v,A} = \frac{\Delta v/v}{\Delta A/A}$. For example, a sensitivity coefficient of −0.5 indicates that a 10% increase of $A$ would decrease $v$ by 5%. Table 3 shows the resulting $A$ values, RMSEs, and sensitivity coefficients. When the model-calibrated coefficient values were increased/decreased by 30% in the ridges and sloughs simultaneously, 3 year-averaged $v$ simulated in the bimodal landscape (R1–3/S1–3) decreased/increased by approximately 22%/40%.

## 5. Discussion

### 5.1. Hydraulic resistance modeling in the patterned wetlands

In view of traditional open channel hydraulics, the Manning's coefficient ($d$-independent, constant $n$) has been primarily focused on frictional resistance due to drag by a channel bottom; however, the hydraulic resistance on surface flow in vegetation-covered wetlands is predominantly dependent on the depth-specific vegetation stem/litter density and morphology (Kadlec, 1990; Kadlec and Knight, 1996; Nepf, 1999; Lightbody and Nepf, 2006). The non-linear relationship between $d$ and lumped hydraulic resistance used in this study was based on the assumption of high resistance for shallow flow due to high stem density, undergrowth and non-decomposed organic debris (litter) near the ground surface. In this framework, it is similarly assumed that flow resistance decreases with flow depth. However, some previous observations have not fully supported the exponential relationship between resistance and ponding depth. For example, Lightbody and Nepf (2006) reported that in a Massachusetts *Spartina alterniflora* salt marsh, vegetation volumetric frontal area and $v$ are maximal and minimal, respectively, near 0.10 m from the bed, not the bottom elevation, but above the critical $d$, stem density decreased exponentially. Also, Schaffranek et al. (2003) reported vertically constant $v$ profiles above around 0.10 m from the bed in an unburned, medium dense sawgrass area in Everglades National Park and an approximately linear increase of $v$ with $d$ at a burned, sparsely dense site.

In this study, the empirical approach shown in Eq. (2) was used under the assumption that the modified Manning's coefficient represented the overall lumped depth-variable resistance exerted by the ridge and slough vegetation as well as the sediment layer. The method employed here is consistent with the form suggested by Kadlec and Knight (1996) and applied by Bolster and Saiers (2002) and Kazezyilmaz-Alhan et al. (2007), with the notable difference that the resistance parameter, $a$, is expressed as a range rather than a constant (Table 1). The power-law relationship between $d$ and hydraulic resistance resulted in the lowest RMSE (Table 1) compared to measured $v$ profiles in ridges and sloughs, and provided values consistent with previous regional modeling efforts in the Everglades (SFWMD 1994, 2005a).

Accurately modeling vegetative cover hydraulic resistance in wetlands is one of the most challenging topics in wetland flow dynamics modeling. Vegetation cover and associated hydraulic resistance changes horizontally, vertically, and temporally as a function of many factors, such as vegetation type, density, and morphology, and wind. A more complex mathematical description of the spatio-temporal variation of hydraulic resistance in wetlands would contribute to accurately simulating the complex natural phenomena, but may also increase the complexity of numerical models and decrease the ease of model application, requiring additional, systematic field surveys (Bolster and Saiers, 2002). Therefore, it is suggested that future improvements in hydraulic resistance modeling efforts in these patterned wetlands should be based on higher density spatio-temporal field measurements of $v$ and vegetation community characteristics in both ridges and sloughs.

### 5.2. Implication on mass transfer between ridges and sloughs

It has recently been acknowledged that flow and mass transport play a critical role in the formation, maintenance, and degradation of the Everglades ridge and slough landscape (SCT, 2003; Ross et al., 2006; Larsen et al., 2007, 2009). Despite recent monitoring efforts on the characteristics of organic-rich sediment and critical $v$ regulating sedimentation and resuspension in the water column, our understanding of the flow dynamics and mass transport is still limited in this unique wetland ecosystem.

The calculated relationships between $d$ and Manning's $n$ (Fig. 6A) indicate a significant seasonal difference in hydraulic resistance for the ridges and sloughs. The average difference of the lumped coefficient between ridges and sloughs was 0.14 as a Manning's coefficient unit during the wet season. However, this difference was nearly tripled (0.40) during the dry season (Fig. 6A). This phenomenon is even more pronounced over shorter durations. For example, in one of driest months, April, the 3 year average difference (1.11) was almost an order of magnitude higher than the average difference in August (0.12). The average slough to ridge $v$ ratio was 1.9 in April, but only 1.4 in August.

One may conclude that such differences in the depth-dependent hydraulic resistance relationships between the ridges and sloughs are not significant, and that the separation into a bimodal landscape is not necessary in terms of hydraulic resistance. However, it is emphasized that the utility of this discretization is fully dependent on the modeling purpose. For long term, regional scale water management, a single hydraulic resistance value relationship is likely sufficient. However, the subtle seasonal differences in velocity between ridge and slough may be of overriding importance in developing and applying a hydro-ecosystem model to simulate mass transport and peat accretion processes that may be different between ridges and sloughs.

Temporally variable characteristics of hydraulic resistance between ridges and sloughs are likely to regulate the interconnectivity of mass transport between these habitats. Ridges may act as barriers to flow and mass transfer during the dry season, but the degree of restriction is likely to be significantly reduced during wet seasons. In view of sediment redistribution between ridges and sloughs, the smaller wet season difference of flow resistance between ridges and sloughs and faster $v$ conditions are favorable for floc entrainment, increased allochtonous sediment input and greater transport of organic-rich particles from sloughs to ridges that eventually accumulate due to the relatively shallower $d$ and slower $v$. Larsen et al. (2009) hypothesized that net transport of organic floc from open to vegetated areas during high flows is critical for forming and maintaining the patterned landscape in the Everglades. This study shows that the weakened heterogeneity in hydraulic resistance in the bimodal landscape during high flows facilitates such mass redistribution.

## 6. Summary

Despite the simplifying assumptions of uniform rainfall and ET, linear topographic slope and uniform vegetation density within each bimodal habitat, and a power-law relationship between $d$ and hydraulic resistance, the simulated $h$, $d$, and $v$ showed good agreement with the 3-year field-monitored data. Our simulation results also suggest that the RSM HSE can be used to accurately predict the relatively smaller-scale hydrology of the patterned wetland area in the Everglades. Temporally averaged Manning's $n$ values of 0.57 and 0.34 s/m$^{1/3}$ were obtained through model calibration for the ridge and slough zones, respectively. According to the $d$-dependent hydraulic resistance relationship, the ridge and slough hydraulic resistance differences were reduced significantly during the storm season compared to the dry season. This result supports a hypothesis that more dissolved or suspended mass transported from the upstream slough or resuspended from the slough bottom can be redistributed into the ridge area, in particular during wet seasons, due to the weakened heterogeneity of hydraulic resistance during high flows.

The flow dynamics model developed here ultimately can be linked with an optimized ecosystem model to determine key mechanisms of landscape degradation and evaluate restoration scenarios. For this, more systematic field monitoring efforts on the depth-specific $v$ and vegetation stem/litter densities as well as hydroperiod in the ridges and sloughs are required to confirm the values and hypothesis suggested in this modeling study. For example, development of more advanced ridge and slough coupled flow dynamics and ecosystem models that allow simulation of eco-hydrological and biogeochemical feedbacks may require finer horizontal and vertical resolution spatial data, perhaps to the level of grid cell used in this study.

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