Case Study

Fine Spatial Resolution Simulation of Two-Dimensional Modeling of Flow Pulses Discharge into Wetlands: Case Study of Loxahatchee Impoundment Landscape Assessment, the Everglades

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Abstract: Wetland ecosystems are controlled by their hydrology. Recent experimental and numerical investigations have suggested that flow pulses are needed to preserve sediment redistribution in some wetlands. In this study, the authors investigate the effect of pulsed-flow conditions on the hydrologic regime of low-gradient densely vegetated wetlands using a fine-resolution, two-dimensional depth-averaged numerical flow model. The model was applied to simulate flow depth and velocity within the Loxahatchee Impoundment Landscape Assessment (LILA) wetland located in Boynton Beach, Florida. Two pulsed-flow conditions with low-pulse and high-pulse flow magnitude were considered. The simulation results of low-pulse flow conditions reveal the areas within deep sloughs where flow velocities and directions change continuously, creating enhanced mixing areas within the deep slough. These mixing areas may have the potential to affect processes such as sediment redistribution and nutrient transport. Simulation of high-pulse flow magnitude, however, results in more uniform flow velocity inside deep slough. It also indicates that a pulse can only be detected when inflow discharge is at least 3.0 m^3/s. Lower inflow discharge values are too weak in magnitude to generate substantial changes in water surface elevation and velocity and they may not exhibit a flow wave propagation into the study area. **DOI: 10.1061/(ASCE)HE.1943-5584.0001206.** © *2015 American Society of Civil Engineers.*

Author keywords: Hydrology; Numerical model; Wetlands; Ecosystem; Pulsed-flow conditions; Everglades; Ridge and slough landscape; Mixing area.

Introduction

Wetlands are heterogeneous ecosystems characterized by unique biodiversity, hydrology, spatial variability of vegetation types and densities, and landscape patterns (Bolster and Saiers 2002). The Everglades in South Florida is one the largest subtropical wetlands in the world. Its landscape patterns range from hammocks-and-hollows to ridges and sloughs to tree islands. Because of rapid population growth and urbanization and increase in flood control and agricultural land use in South Florida, degradation of natural landscape features such as ridges in areas exposed to changes in hydrology driven by water management practices has been observed.

Previous studies found that hydrology is one of the key factors controlling wetland landscape patterning (Swanson and Grigal 1988; Rietkerk et al. 2004; Noe et al. 2007; Lago et al. 2010). Therefore, an improved understanding of wetland hydrology is key in determining conditions for landscape morphology sustainability. Larsen et al. (2009) have shown that increasing flow velocity by management decisions alone cannot provide the necessary hydrologic conditions to stabilize landscape patterning and that induced pulsed-flow loading is necessary. The effect of natural and induced pulsed-flow conditions on a wetland's hydrology received limited attention by previous studies.

The objective of this study is to investigate the effect of induced pulsed-flow conditions on the hydrology regime in wetlands. In this study, a two-dimensional vertically averaged (FLO-2D) model formulation (Garcia and Kahawita 1986; O'Brien et al. 1993) was adopted and applied to simulate the spatiotemporal variation of flow depth and velocity in a study area located within the Loxahatchee Impoundment Landscape Assessment (LILA) in Boynton Beach, Florida (Fig. 1).

The model development and numerical simulations provide an improved understanding of how wetland surficial (sheet) flow may respond to various inflow conditions and whether creating pulsed-flow scenarios through water management can improve ridge and slough restoration. These modeling results can further be used to simulate transport of suspended sediments in the study area and investigate the effect of suspended sediment transport on spatial and temporal distribution of bed elevation in the areas

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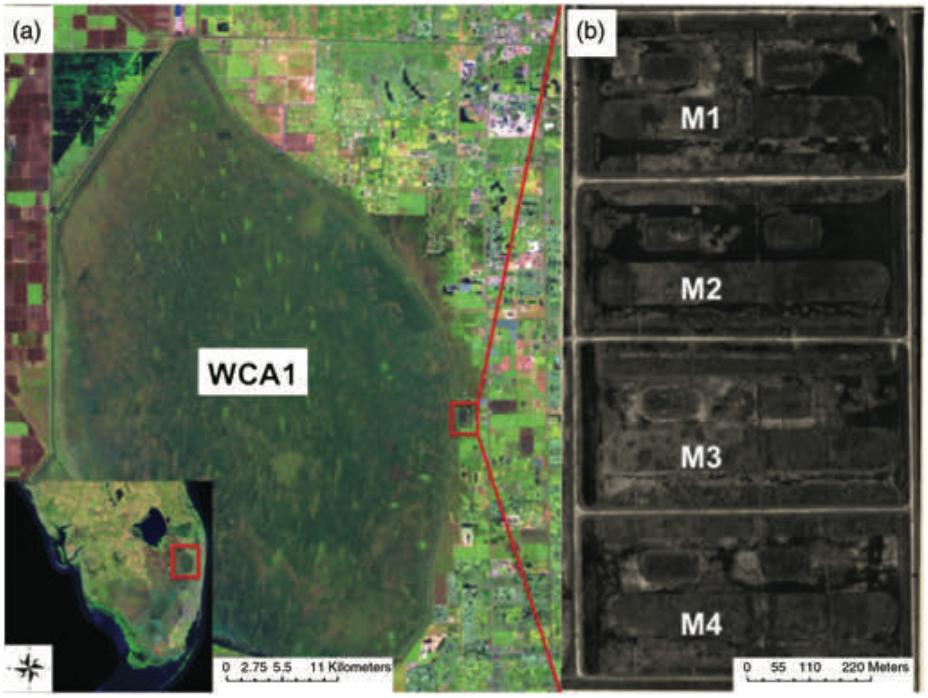

Fig. 1. (Color) (a) LILA location at the eastern boundary of WCA-1; (b) four macrocosms of LILA [(a) and (b) base maps courtesy of the U.S. Geological Survey]

dominated by landscape patterns such as ridge and slough of the Everglades.

Hydrological models of wetland surface flow fall into two categories: they are either used as water inventory (budgeting) tools, such as in the case of ecological and regional ecosystem models, or used to simulate runoff and stream flow as input to hydrodynamic transport models for water quality applications (Hammer and Kadlec 1986). A few high-resolution, two-dimensional (2D) (areal) models have been developed to simulate surficial water flow in wetlands where flow depth and velocity are highly affected by dense vegetation coverage and low topographic gradients. Hammer and Kadlec (1986) developed a one-dimensional surface hydrology model that can be used to predict wetland water depth when short-term rainfall events occur. Their model was tested in a constructed wetland with coarse grids and estimated ground surface elevation. Their findings show that topography and ground surface gradients of the study area have significant influence on modeling results and predicting flow velocity and water depth. However, their findings only covered the comparison between simulated and measured results of water depth and elevation and no comparison was made on flow velocity.

The receiving water quantity (RWQ) model is part of the U.S. EPA Storm Water Management Model (SWMM) (Singh 1995), which was modified to describe the flow regime in water conservation areas (WCAs) in South Florida when additional inflow under back-pumping scenarios occurs (Lin and Shih 1979). It combines Monte Carlo techniques with RWQ and uses the concept of dual elevation in a network of hypothetical channels. The model discretizes the study domain (WCAs) into nodes and triangular grids and then generates a time series of flow depth and velocity at any selected locations inside the study domain.

The South Florida Water Management Model (SFWMM) is a regional-scale hydrologic model developed specifically for South Florida in the early 1970s (MacVicar et al. 1984). It is based on the diffusive wave approximation and Manning's equation on 3.2 by 3.2 km (2 by 2 mi) square grids that cover 19,684 km^2 (7,600 mi^2) of South Florida from Lake Okeechobee to Florida Bay. The SFWMM is coupled with a groundwater model that accounts for a two-dimensional single-layer aquifer. The model is vastly used to predict the long-term response of the Everglades system to changes in hydraulic structures, operational scenarios, and management decisions.

The natural system model (NSM) is a two-dimensional model that was developed by the South Florida Water Management District. It simulates integrated surface water and groundwater hydrology and estimates surface flow for a hypothetical and more natural system of the Everglades National Park (ENP) and WCAs with no hydraulic control structures (e.g., canals, levees, pumps) by using calibrated data and parameters from the SFWMM developed for today's managed system in order to evaluate the efficacy of restoration plans.

The hydrologic simulation engine (HSE) is a finite-volume model that was developed to simulate groundwater and overland flow in the Everglades National Park (Lal et al. 1998). This model solves the diffusion wave and Manning's equations for surface flow and Darcy's equation for groundwater flow. Bolster and Saiers (2002) suggest that the diffusion model is appropriate for describing sheet flow over vegetated surfaces. They developed a two-dimensional nonlinear diffusive model that relates flow velocity and water depth with a simplified power-law equation. Their model predicts large-scale spatial and temporal changes in surface water levels and it was tested in Shark River, a portion of the Everglades that contains ridge and slough patterning.

The U.S. Geological Survey has developed the Tides and Inflows in the Mangroves Ecotone (TIME) model to investigate the interaction between freshwater inflows and tidal forces in mangrove ecotone in South Florida (Schaffranek 2001). This model is used to simulate flow and salinity through a coupled surface water–groundwater model in transition areas such as coastal zones. This model, however, is uniquely developed to serve in coastal zones and it may not be applicable to wetlands that are located further inland away from tidal effects.

Kazezyılmaz-Alhan et al. (2007) developed a wetland solute transport dynamics (WETSAND) model, which has both water quantity and water quality components and incorporates the effects of surface water–groundwater interaction. The model was applied to a restored wetland at Duke University to quantify changes in groundwater depth and distribution of nutrients such as phosphorus and nitrogen into the wetland. Although their results demonstrate the model capability to estimate both recharge and discharge into groundwater and nutrient distribution into the wetland over the long term, they did not report the effect of short-term effect of pulsed inflow discharge.

These previous hydrologic modeling studies focused on spatial scales ranging from large areas (a few square kilometers) to regional; their framework requires numerical grid sizes larger than 300 m, which limits their ability to be used for high-resolution assessments in a smaller areas such as LILA. These models also require a large number of input parameters that may not be always feasible to obtain. To overcome these limitations, the authors have applied the FLO-2D model, which is capable of modeling hydrology for detailed analyses where fine grid sizes are required (such as LILA). In a future paper, the authors will use the results of this flow analysis to simulate sediment transport and bed elevation changes in the study area.

Study Area

Established in 2003, LILA is an area of 34 ha (80 acres) located at the Arthur R. Marshall Loxahatchee National Wildlife Refuge (LNWR) in Boynton Beach, Florida (Fig. 1). It is an enclosed area divided into four subsections called macrocosms M1 through M4 with dimension of 200 by 400 m (Science Coordination Team 2003).

Each macrocosm consists of one ridge, one deep slough, two tree islands located inside the deep slough, and one shallow slough built to resemble the ridge and slough and tree island landscape features of the Everglades (Fig. 2). LILA also refers to the living laboratory of the Everglades and it is a model of the Everglades ecosystem that gives researchers the opportunity to apply and test their restoration techniques in a smaller and controlled area before applying it in the Everglades.

Culverts are installed at each inflow and outflow location, which allows controlling stage and flow at each macrocosm. Flow through LILA macrocosms is generated by a 1.1-m diameter electric axial flow submersible pump and is controlled by 0.9-m gated culverts at the inflows (western end) and 0.9-m culverts with stop logs at the outflows (eastern end). Two of the macrocosms are constant flowing systems (M2 and M4), whereas the other two are nonflowing cells (M1 and M3). Water depth and velocity in each macrocosm can be controlled independently to mimic the Everglades flow system and also makes it possible to conduct pulsed-flow studies. For the purpose of this study, the flowing cell, M2, was selected as the study area to conduct pulsed-flow experiments (Fig. 2).

Dye Study

A tracer study was conducted on October 3, 2007, at LILA macrocosms M1 and M2. In both macrocosms, Intracid rhodamine WT fluorescent dye was used to assess water flow patterns (Scinto et al. 2009). Approximately 19 L (5 gal.) of rhodamine WT was injected over 20 min from 9:30 to 9:55 a.m. into the M2 through the headwater inlet culvert at inflow location (Fig. 3). Aerial photos were taken approximately every hour to provide a visual record of the dye transport during this 8-h study. Flow through the culvert was registered at 0.38 m^3/s (6,000 gal./min). However, an average flow rate of 0.34 m^3/s was registered by the inlet acoustic doppler velocimeter (ADV). The inflow hydrograph (water discharge as a function of time) was reconstructed based on inflow conditions as well as the outflow hydrograph, which was registered by the ADV located at the M2 outlet. The reconstructed hydrographs were used as inflow and outflow hydrographs in the FLO-2D simulation. Fig. 4 illustrates the hydrographs used to simulate the conditions during the dye study.

A total of eight areal photos were taken during the dye study (Scinto et al. 2009). These images were used to validate the hydrology model. The images were georeferenced and prepared in a geographic information system (GIS) (Fig. 5). Each image was taken at a specific time. Within each image, the distance between dye head locations and injection point were measured and then the local velocities were calculated by dividing distance over time. The dye traveling distance was measured by finding the distance form injection point to the dye leading edge of each snapshot in both sides of the tree islands. Fig. 6 shows the estimated locations of dye leading edge during the tracer experiment. Four additional ADVs were installed inside M2 at the north and south of each tree island to register flow velocity during this experiment (Fig. 6). These registered flow velocities were used to calibrate the model.

Fig. 2. (Color) Landscape features in M2 (base map courtesy of the U.S. Geological Survey)

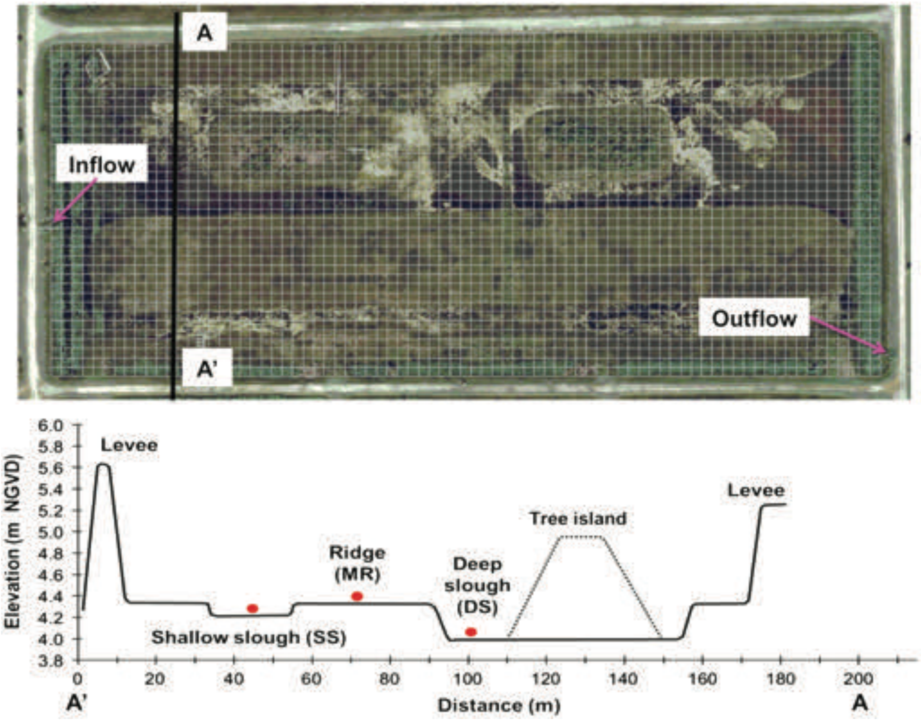

Fig. 3. (Color) M2 grid system, cross section, and inflow and outflow locations (base map courtesy of the U.S. Geological Survey)

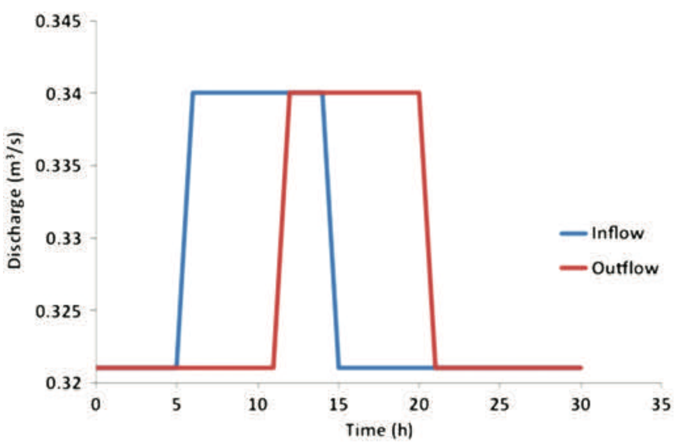

Fig. 4. (Color) M2 inflow and outflow hydrograph

FLO-2D Model Description

FLO-2D is a quasi-two-dimensional physically based flood-routing model that simulates surface flow depth and velocity on a variety of land surfaces from floodplains to urban areas including the presence of hydraulic structures and their operation (O'Brien et al. 1993). FLO-2D discretizes a domain into uniform square grid cells and computes the discharge across eight flow directions (four compass and four diagonal) as shown in Fig. 7. It models the progress of a flow hydrograph through the topographic domain both as channel flow and overland flow. FLO-2D solves the depth-averaged shallow-water equations using an explicit central finite-difference (CFD) numerical scheme and calculates flow depth at each grid element and velocity for eight directions on each grid edge using the following equations:

$$S_f = S_0 - \frac{\partial h}{\partial x} - \frac{V}{g}\frac{\partial V}{\partial x} - \frac{1}{g}\frac{\partial V}{\partial t} \quad (1)$$

$$\frac{\partial h}{\partial t} + \sum_{i=1}^{8} \frac{\partial h V_i}{\partial x} = I \quad (2)$$

where V = flow velocity; x = horizontal distance; V_i = one-dimensional velocity for each flow direction (i); h = depth, which assumed constant over the grid element; S_f and S_0 = friction slope and bed slope, respectively; I = function accounting for water sources and sinks; g = gravitational acceleration constant; and t = time.

FLO-2D is one of the few inundation models approved by the Federal Emergency Management Agency (FEMA 2014) for flood insurance studies and has been used worldwide in multiple applications ranging from volcanic debris flow inundation (Canuti et al. 2002) to dam breaks in river basins (Chen et al. 2004), assessing impact of extreme flow events on mountainous watersheds (Li et al. 2005), flood delineation (Hosseinipour et al. 2012), and flooding events in alluvial fans (Hübl and Steinwendtner 2001). The simplicity of the data requirement to set up a FLO-2D simulation made this model particularly suitable for the application sought in this study. The digital elevation model, Manning's roughness coefficients, and an inflow hydrograph are the only input data required to set up simulation. This appears to be the first application of FLO-2D to model free-surface wetland sheet flow.

Modeling Input

Digital Terrain Model

The first step to set up FLO-2D simulations is to define the computational domain starting from a digital terrain model (DTM) and developing the grid system for the study area. In this study, the area

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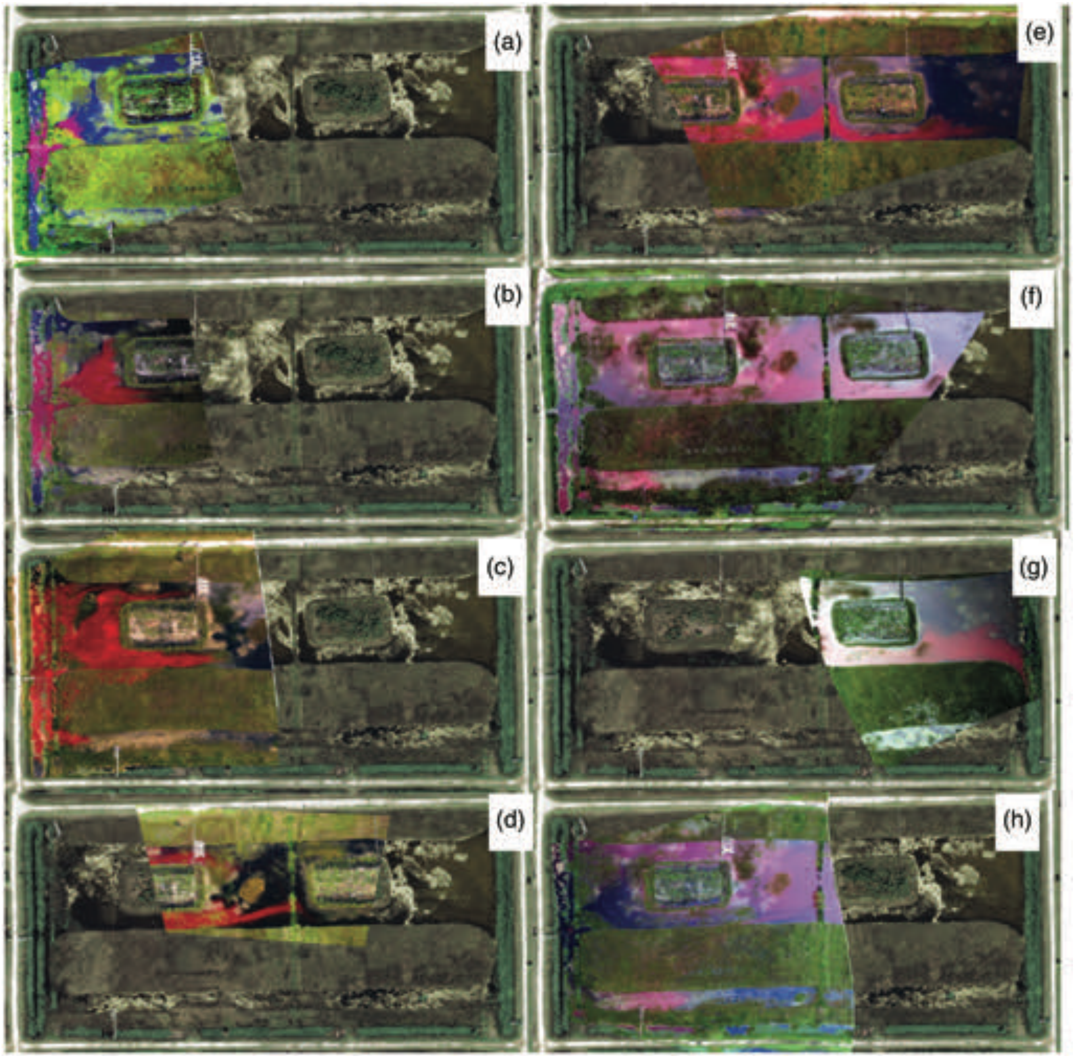

Fig. 5. (Color) Photos of dye experiment overlaid on base map of the study area (base maps courtesy of the U.S. Geological Survey. Dye experiment photos by Eric Cline): (a) 25 min; (b) 1 h; (c) 2 h; (d) 3 h; (e) 4 h; (f) 5 h; (g) 6 h; (h) 7 h; white lines in (a), (c), and (h) are due to the overlaying dye images in *ArcMap*

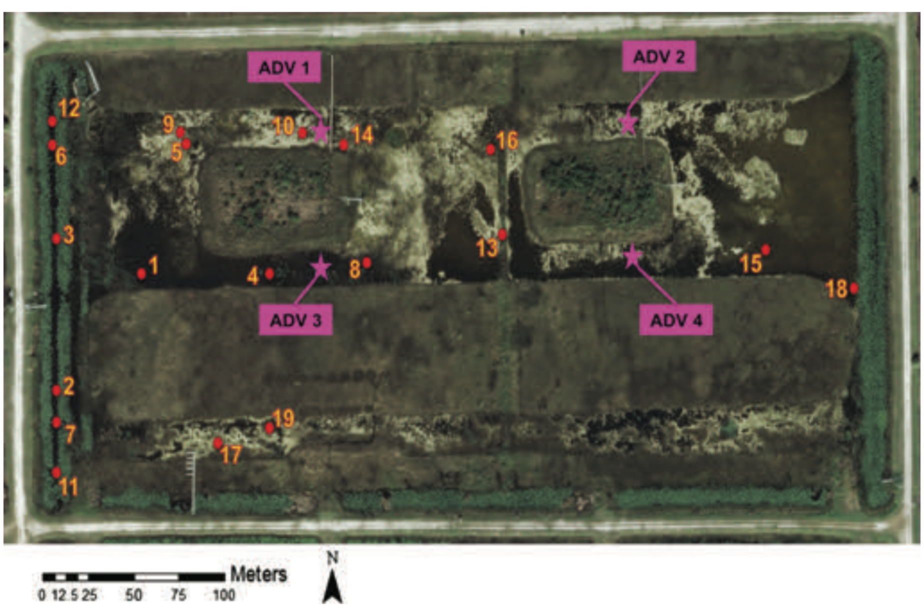

Fig. 6. (Color) Approximate locations of projected dye head and ADVs location; red dots represent dye head (base map courtesy of the U.S. Geological Survey)

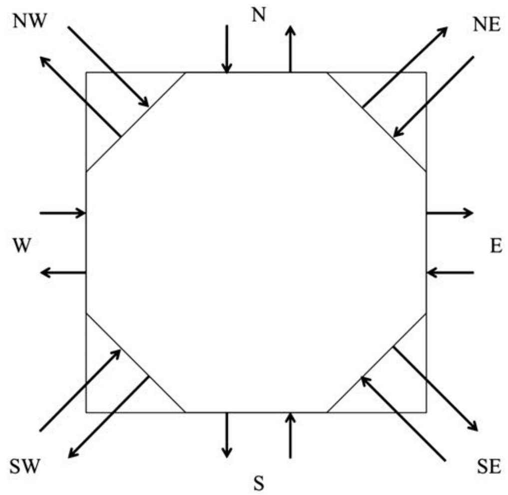

Fig. 7. FLO-2D discharge directions at element

(M2) was first discretized using 5 by 5 m grid elements (Fig. 3), and then original elevation data of LILA (referred to as-built) were used to create the FLO-2D DTM data set (Scinto et al. 2009; Aich et al. 2011). A cross section of the study area is also shown in Fig. 3. These elevation data were processed in GIS and converted into ASCII files containing *x-y* coordinates and elevation data for each point. The elevation data set was processed in FLO-2D's grid developer system (GDS) and was interpolated using the inverse distance weighting method (Fig. 8). Light detection and ranging (LiDAR) data were also considered as the initial elevation data set for the study area. The LiDAR data were acquired in 2010 and were processed by GIS *ArcMap* software. Due to the inaccuracy of LiDAR data, this data set was disregarded.

Pulsed-Flow Conditions

Pulsed-flow events may occur as natural events or induced management decisions. Both events can be characterized by five primary components: magnitude, frequency, duration, timing, and rate of change in flow from beginning to end (Science Advisory Committee 2009). Several tools, such as GIS application, routing application for parallel computation of discharge (RAPID) developed by David et al. (2008), and hydrology-based environmental flow regime (HEFR) (Opdyke et al. 2014), can be used to model high-pulse flow events. Texas Commision on Environmental Quality (TCEQ) (2011) defines a high-pulse flow event as a short-term, high-flow event within the stream channel that occurs during or immediately after a storm event. Although their work demonstrates results of pulsed-flow condition, their conditions are strictly based on a natural storm event with high-flow magnitude and short duration rather than based on a managed pulsed-flow condition. In another study, Karim et al. (2012) used *MIKE 21* to simulate the time history of inundation across a tropical floodplain during a pulsed-flow event. They used three different storm events on wetland to estimate the flood wave propagation.

Two distinct induced-flow conditions are discussed: one with low flow magnitude and long duration (referred to as low pulsed flow), and another with high flow magnitude and short duration (referred to as high pulsed flow). Pulse flow magnitude indicates a managed change to inflow discharge through the operational culvert gate at inflow location during a specific period of time in which the inflow discharge remains unchanged. Low pulsed flow signifies the dye study flow condition with flow magnitude of $0.34\ m^3/s$ and duration of 8 h. High pulsed flow refers to a hypothetical increase to inflow discharge with magnitude of $3.0\ m^3/s$ and duration of 1 h. Because the dye study was an experimental managed event, timing and frequency were neglected. It is assumed that the flow discharge remains constant for the duration in both low and high pulsed flow conditions, therefore the rate of changes is zero. ADV records show an average daily flow discharge of $0.32\ m^3/s$ into M2 at the inflow location. In this study, the inflow discharge was increased to $0.34\ m^3/s$ for duration of 8 h. This condition indicates a low pulsed flow condition that may not be as strong as a pulsed-flow scenario created by naturally occurring extreme events or other pulsed condition that occurs in areas where flow discharge is high or topography is steep. The focus of this paper is in very low-gradient wetlands with high vegetation density with water velocity between 0.005 and 0.01 m/s. Often in these environments slight changes in velocity may be considered important to alter the flow hydraulics of the ridge and slow patters. It may even be enough to create disturbance in the wetland.

Fig. 4 shows the hydrograph of inflow and outflow during the pulsed-flow condition. Both hydrographs were used as inflow and outflow hydrographs. The outflow hydrograph was applied to control and maintain the initial depth of water inside the study area. Several other outflow conditions were explored, including the

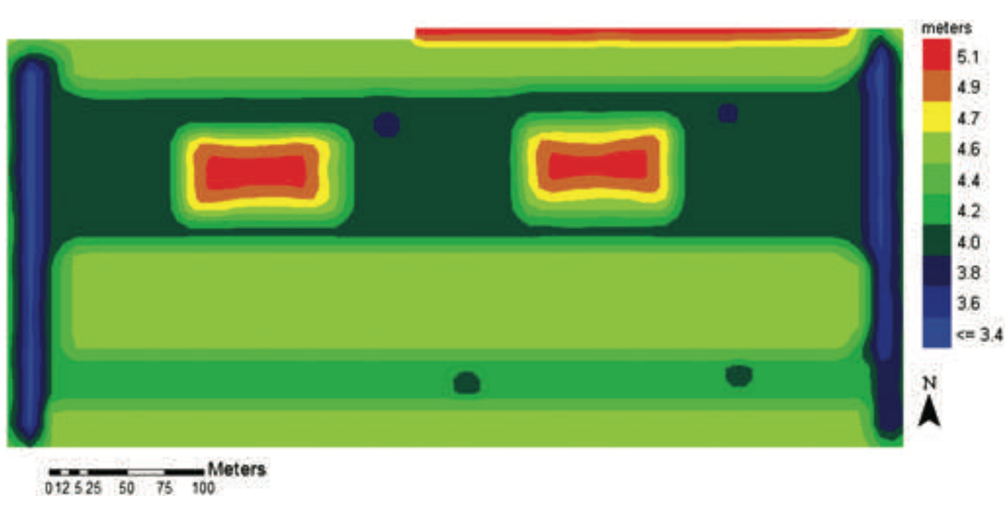

Fig. 8. (Color) M2 ground surface elevation contours

default FLO-2D condition where outflow is obtained assuming uniform flow based on the local bed slope. Due to the low bed gradients in the outflow area, this condition was found to generate instabilities that resulted in unrealistic velocity distributions. After several numerical experimentations it was found that using an outflow hydrograph as the boundary condition generated the least instabilities in the model results.

This hydrograph was obtained from ADVs located at outlet culverts within the M2 cell. ADV was set to register flow rate every 15 min. These flow rate data were collected for pulsed-flow conditions, which were generated on October 3, 2007. Hydrographs were modified and converted into text files according to FLO-2D requirements and then used as inflow and outflow hydrographs in FLO-2D.

Manning's Roughness

An aerial image of the study area for 2006 was obtained from the National Map Viewer site and it was used to specify M2 boundaries. The image was later digitized in GIS to create a vegetation map. Min et al. (2010) determined Manning's value for ridge and slough of Water Conservation Area 3 (WCA3) to be 0.42 and 0.28, respectively, in the wet season, and increased to 0.81 and 0.41 in dry season. These values are considerably higher than the Manning's values reported in classic Manning tables (Chow 1959), which are 0.15 for ridge and 0.025 for slough. This may be due to the fact that Manning's values reported in tables are based on roughness of channels and rivers while Min et al. (2010) estimated Manning's coefficient based on an open water body wetland with sheet flow. The Manning's value of Min et al. (2010) was used for the dry season as the initial Manning's value because the original image of the area obtained from National Map Viewer was taken in the dry season. Initial Manning's values of 0.3 and 0.04 were assigned to patchy vegetation and tree islands, respectively. The Manning's n value over tree islands of $n = 0.04$ is actually very small for flow over vegetated ground, but the fact that tree islands have higher elevation than the ridge and slough and they remain dry during the entire simulation means their n values have no effect on the simulations. Fig. 9 illustrates the distribution of Manning's n values in LILA-M2.

Model Setup

The computational domain boundary was set around levees surrounding the M2 macrocosm. This domain was then discretized using 5 by 5 m grid elements (Fig. 3). As-built elevation data (Fig. 8) were imposed into the domain and interpolated. A no-flow boundary condition was imposed on all sides of the domain. Inflow and outflow elements were identified at the inflow and outflow culverts locations. To improve flow conditions at inflow and outflow boundaries, the reconstructed inflow and outflow hydrographs of the dye test were assigned to both inflow and outflow elements. It is assumed that the area was initially flooded with constant water elevation that corresponds to depths up to 0.5 m. The FLO-2D simulation was initiated with report time intervals of 1 h and continued for total of 30 h including 6 h warm up with flow of $0.32\ m^3/s$, 8 h high-flow pulse of $0.34\ m^3/s$, and then 6 h of normal $0.32\ m^3/s$ flow.

Model Calibration

In this study, the October 3, 2007, inlet hydrograph and Manning's value of 2006 vegetation coverage were used to simulate the dye test hydrologic conditions assuming that vegetation coverage had not changed significantly; therefore Manning's values for 2006 can be used for 2007. Manning's value here is an empirical parameter referring to vegetation roughness in the friction stresses and it encompasses a number of factors including not only bed roughness but also internal stresses.

The model calibration was performed by modifying Manning's values until the simulated velocities at the elements representing approximate location of ADVs inside the M2 (Fig. 6) were roughly matched to the velocities registered by those ADVs. Table 1 shows the initial guess and calibrated value of Manning's coefficient. Average velocities registered by ADV 2, 3, and 4 (Fig. 6) during the dye experiments were 0.019, 0.02, and 0.032 m/s, respectively. ADV 1 data were disregarded because of the inconsistency in the measurement in that location. Simulated velocities after calibration of Manning's at those locations (ADV 2, 3, and 4) were approximately 0.02, 0.02, and 0.03 m/s.

Model Application 1: Dye Study Flow Conditions

The model was applied to the dye study flow conditions in the study area. Fig. 10 illustrates simulation results of water surface elevation before and 5, 15, and 30 min after inflow culvert was opened and water flowed into the study area in full capacity. No significant changes in water surface elevation is detected in these series of results except some minor local changes (2–3 mm) along the western side close to the inflow location. This may be due to the low pulse flow magnitude. As is shown in the inflow hydrograph (Fig. 4), the discharge has increase from 0.32 to $0.34\ m^3/s$, which roughly translates into 6% increase in inflow discharge and pulse

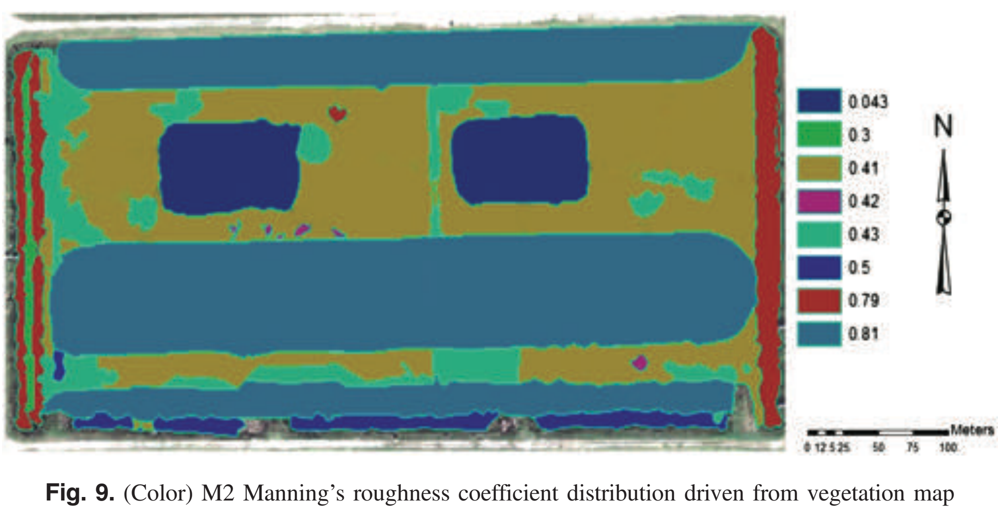

Fig. 9. (Color) M2 Manning's roughness coefficient distribution driven from vegetation map

Table 1. Calibrated Vegetation Roughness Coefficient: *n* Values

Land cover	Initial guess	Calibrated values
Ridge	0.81	0.1
Slough	0.41	0.02
Patchy vegetation	0.3	0.02
Tree islands	0.04	0.04

magnitude of approximately 0.02 m^3/s. Fig. 11 shows the results of simulated water surface elevation and velocity vectors after 1, 3, 5, and 7 h. Changes in water surface elevation are observed 1 h after change in inflow conditions [Fig. 11(a)] along the western side near the inflow location and they continue to progress into both deep and shallow sloughs as time passes within the next 6 h [Figs. 11(b–d)]. However, these changes are very small and only up to 1.00 cm in deep and shallow sloughs and dissipate quickly afterward. Some in situ water depth measurements inside deep slough where ADV 1 was installed (Fig. 6) also confirmed that water level only changed by 1.00 cm. Because the pulsed flow is low magnitude, the pulse has only propagated up to the eastern tree island and it has dissipated faster than a pulsed flow condition with higher magnitude may show (Fig. 12). Figs. 11(e–h) also illustrate simulated velocity vectors over time. This image indicates that velocity does not change during the dye experiment. It is mainly due to the fact that increase in inflow discharge is too small to affect velocity inside the study area, but it is enough to create disturbance. Therefore, the velocity vectors remained almost constant during the experiment. These results also show that velocities are more uniform toward the downstream inside the shallow slough, while deep slough experiences areas between tree islands and downstream where the flow direction varies constantly. This nonuniformity in flow velocity regime creates enhanced mixing areas within the deep sloughs that may affect nutrient and solute transport inside the study area (Fig. 11).

Model Application 2: High-Intensity Pulsed-Flow Conditions

In order to understand the model behavior when a pulsed condition is implemented, the model was applied to various pulsed-flow conditions scenarios with inflow discharge magnitudes as high as 1.5 and 3.0 m^3/s over 1-h duration with total simulation time of 4 h. These amounts of discharges are 5 and 10 times higher than daily discharge into M2 under operational procedure. The results show that the pulse behavior only when inflow discharge is at least 3.0 m^3/s. Lower inflow discharge values are too weak in magnitude to generate substantial changes in water surface elevation and velocity and they may not exhibit a flow wave propagation into the study area. The results of water surface elevations and velocities of a high pulse value of 3.0 m^3/s are presented in Figs. 12 and 13, respectively. These series of images show how water surface elevation increases as the water flows downstream and out of the macrocosm. These results also reveal that water depth is increasing on top of the ridge faster than inside the slough. Fig. 12 shows that areas near the inflow and upstream of the western tree island experience maximum water surface elevations up to 5.0 m. As displayed in Fig. 13, maximum velocities up to 2.0 m/s occur at outflow location.

Discussion

The results of calibration for Manning's value for ridge and slough (Table 1) indicate that there are significant differences between modified Manning's values from model and initial value from Min et al. (2010). Initial guesses of *n* values for ridge and slough were set to be 0.81 and 0.41, respectively, while the calibrated values are 0.1 and 0.02. It appears that calibrated *n* results are closer to the values reported in classical Manning's coefficient for mountain streams with and without vegetation channel reported in Chow (1959). This may be due to the fact that the macrocosms in LILA actually act as open channels rather than open water body in wetlands. The surrounded levees create boundaries that are similar to the bank of streams, and therefore Manning's coefficients are closer to the values reported for open channel table. To explore the validity of low Manning's value, the simulation was repeated with higher values of Manning's coefficient up to 0.1 inside the slough. The results show a slight difference (up to 0.01 m/s) between simulated velocities inside the slough and the velocities registered by the ADVs at the same locations. Simulated velocities were lower than registered velocities at those locations. Manning's values higher

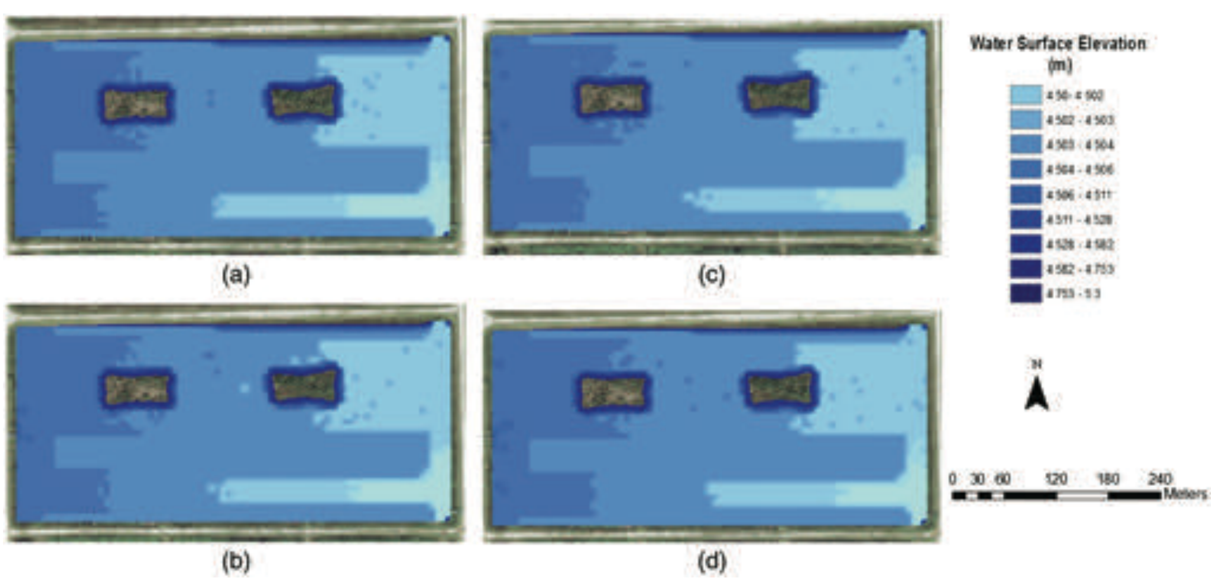

Fig. 10. (Color) FLO-2D simulation results of water surface elevation for dye experiment at (a) before pulse and dye release; (b) 5 min after opening culvert; (c) 12 min after pulse; (d) 30 min after pulse; no change in water surface elevation is detected at the area near the inflow discharge

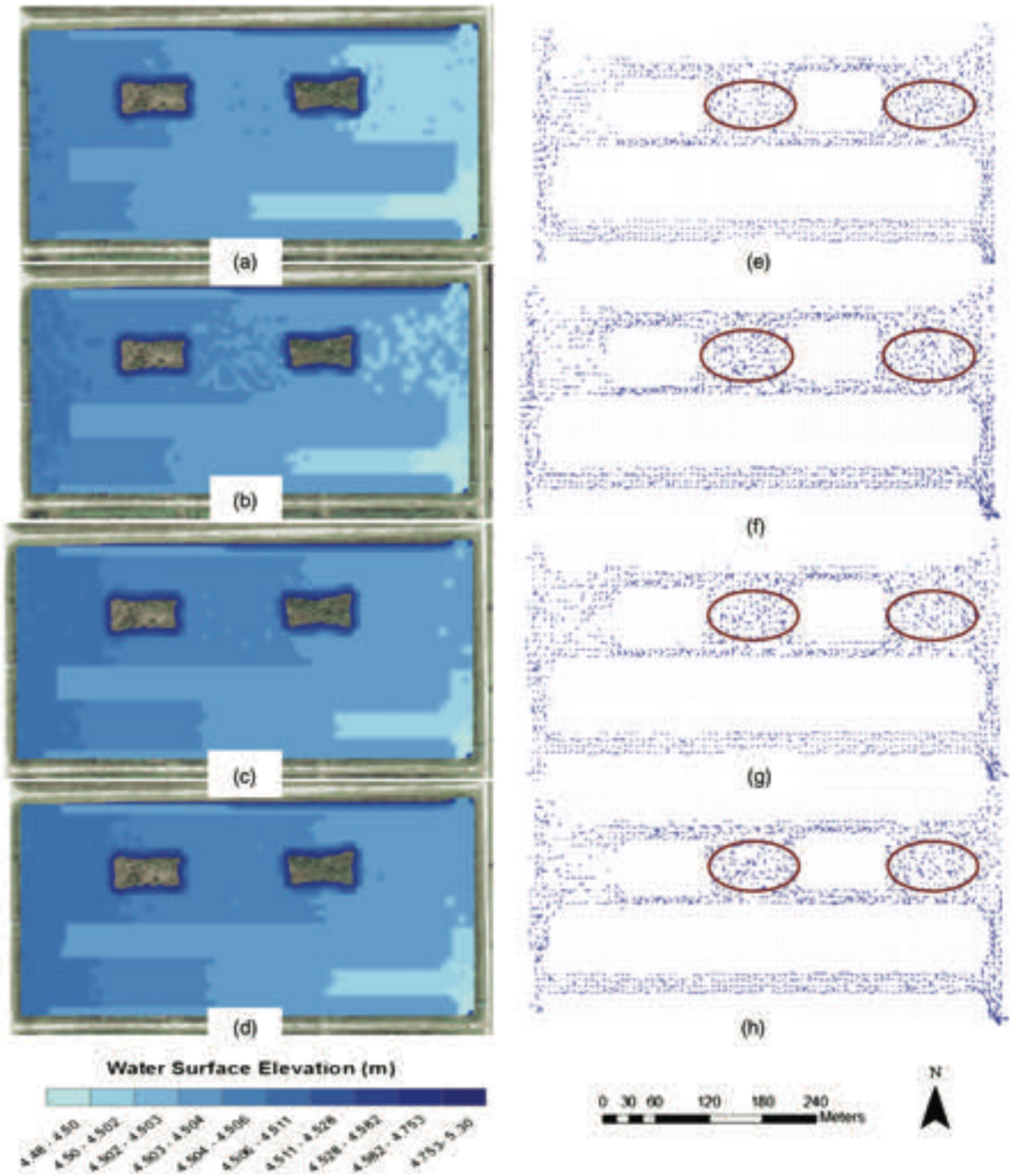

Fig. 11. (Color) FLO-2D simulation results of dye experiment; water surface elevation after (base maps courtesy of the U.S. Geological Survey: (a) 1 h; (b) 3 h; (c) 5 h; (d) 7 h; velocity vectors after (e) 1 h; (f) 3 h; (g) 5 h; (h) 7 h; red circles indicate the mixing zones within the deep slough

than 0.1 result in simulated velocities as low as 0.003 m/s inside the slough.

For the purpose of the comparison between simulation results and observation from each areal image, velocity was calculated by dividing the distance between the injection point and the dye leading edge in the areal image. These images approximate a uniform flow velocity of 0.02 m/s during the pulse condition. Table 2 presents a comparison between observed and simulated velocity results and Fig. 6 shows approximate locations of dye leading edge at each areal photo every hour. Total of 19 points (locations) were marked from areal photos. Average velocities (distance from the injection over time) at locations 1, 2, and 3 are 0.03, 0.03, and 0.02 m/s, while simulated velocities are 0.02, 0.03, and 0.02 m/s, respectively. Locations 4, 5, 6, and 7 experience average velocity of 0.02 m/s and simulated velocity of 0.015 m/s. Simulated results are in agreement with dye results for locations 8, 10, 11, and 14, but are lower than observations for locations 9 and 13 (0.01 m/s) and higher for location 12 (0.02 m/s). Results at 244 through 422 min indicate faster flow in the shallow slough, while images show that the dye flow in the shallow slough is much slower than what simulation has predicted. This may be due to accuracy of elevation data inside the shallow slough. The overall results show very good agreement between observed data of dye study and simulated results (Table 2).

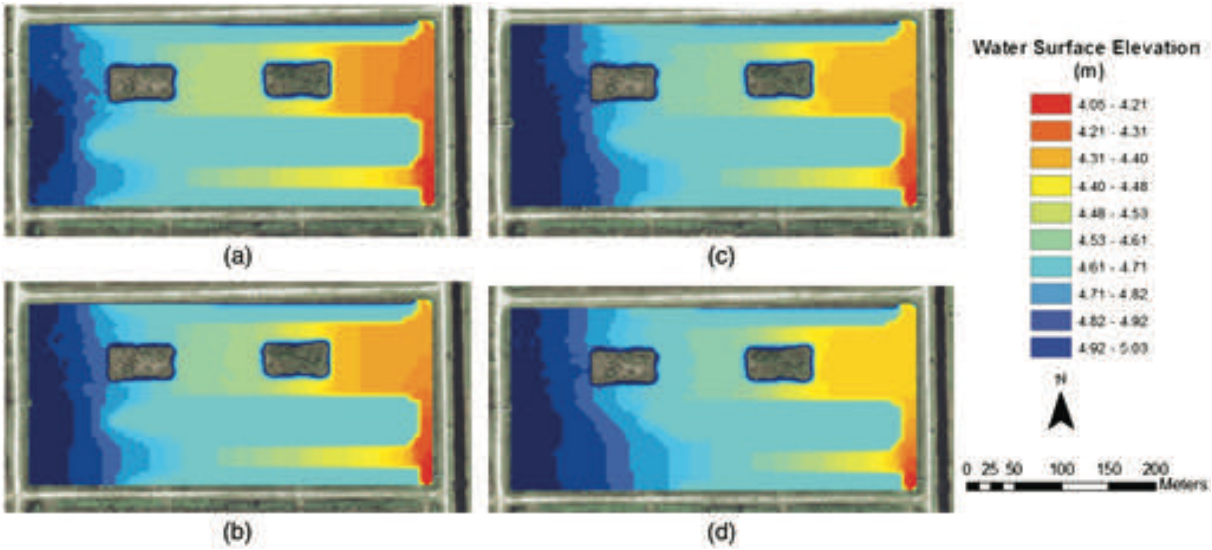

Fig. 12. (Color) Increase in depth of water when 1-h pulsed-flow condition of $3\,m^3/s$ is applied at the inflow culvert; each image shows how water flows after (a) 2 min; (b) 10 min; (c) 15 min; (d) 30 min of pulse implementation

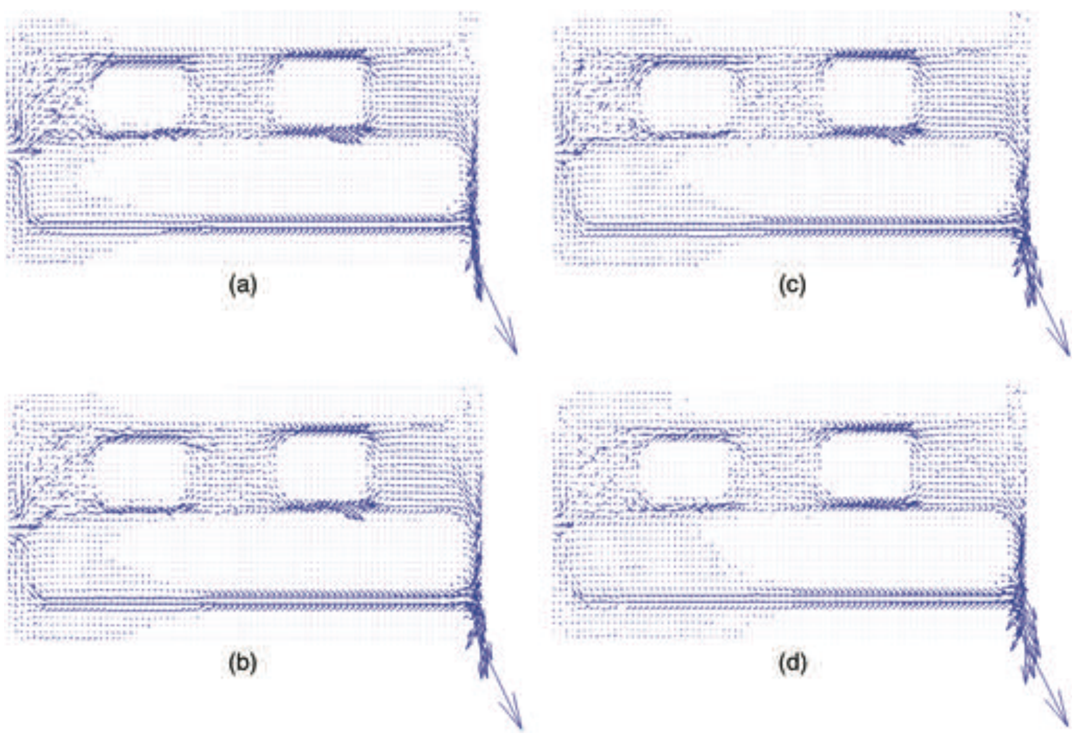

Fig. 13. (Color) Velocity vector when pulse flow condition with $3\,m^3/s$ discharge magnitude and duration of 1.0 h is applied after (a) 2 min; (b) 10 min; (c) 15 min; (d) 30 min

Fig. 14 illustrates simulated results of water depth over time in a few locations inside the study area. These graphs show that the water depth increased by approximately 1.0 cm during the pulse and then decreased to the original depth after flow discharge reached to operational flow (nonpulse) conditions. However, because depth was not measured during the tracer experiment, there are no data to compare with the simulated depth.

The nonuniformity in flow direction within the deep slough creates zones of high mixing capacity [Figs. 11(e–h)]. These zones are bound to affect transport mechanisms within deep sloughs and cause delay in transporting solutes or particles toward downstream. These mixing zones were confirmed by in situ flow measurements, which were conducted during the tracer test using a handheld flow tracker (Scinto et al. 2009).

The results of high pulsed flow condition (Figs. 12 and 13) reveal strong uniform flow behavior inside the entire study area. Uniform flow velocity ranges between 0.2 and 0.7 m/s inside both shallow and deep sloughs and inside the spreading channels in the east and west. This amount is 10 times higher than the operational flow velocity of 0.01–0.02 m/s inside the deep slough. High-flow

Table 2. Comparison between Observed Velocity from Dye Images and Simulated with FLO-2D

Locations	Distance from inflow (m)	Time (minimum)	Velocity observed (m/s)	Velocity simulated (m/s)
1	48	25	0.03	0.02
2	25		0.02	0.03
3	26		0.03	0.02
4	105	71	0.02	0.02
5	120		0.02	0.01
6	65		0.02	0.01
7	60		0.02	0.01
8	150	128	0.02	0.02
9	105		0.02	0.01
10	130		0.02	0.02
11	70		0.01	0.01
12	75		0.01	0.02
13	220	182	0.02	0.02
14	225		0.02	0.02
15	330	244	0.02	0.01
16	270		0.02	0.01
17	147	313	0.01	0.02
18	382	360	0.02	0.02
19	167	422	0.01	0.04

Note: Distance from inflow refers to how far the dye leading head has traveled from inflow location; observed velocities refer to average velocity (distance over time).

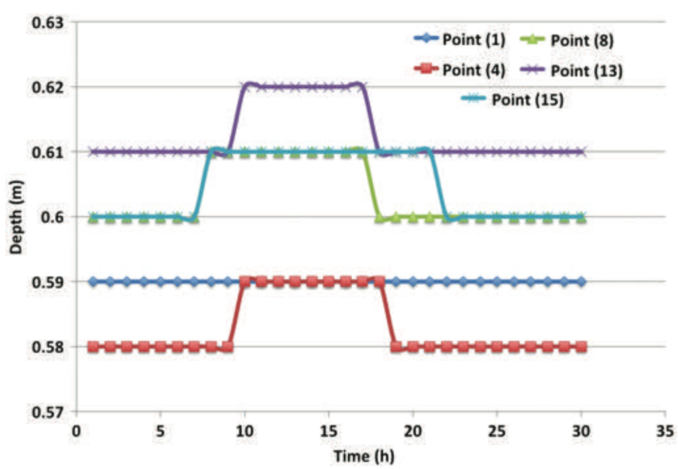

Fig. 14. (Color) Depth results from FLO-2D at locations 1, 4, 13, and 15 in Fig. 6; there is a slight increase of 1.0 cm in water depth at these locations during low pulsed flow condition

velocity of 2.0 m/s can be observed at outflow location. Surface water elevation reaches as high as 4.8 m at locations 1, 5, and 9 of Fig. 6.

Visual comparison between simulated velocity results under high pulsed flow condition (Fig. 13) and dye study flow (low pulsed flow) condition (Fig. 11) may conclude that these distinct areas exist because of the low flow velocity under dye study flow conditions. As inflow discharge increases, water flows faster and more uniformly inside the deep slough toward downstream. Further numerical modeling and field investigations are necessary to evaluate these zones' existence and the hydrologic conditions in which they may exist.

There are also limitations to this modeling attempt. FLO-2D input data are sensitive and require following a certain detailed procedure to prepare input data such as elevation, flow hydrograph, and Manning's value, which may lengthen the initial modeling setup if not followed carefully. It also has limited visualization capability. FLO-2D reports final results as text files, which requires using other software programs to visualize. In this study, the effect of floating mat of periphyton was considered in Manning's calibration. Due to mobility of these floating mats with flow, it may not be possible to assign spatially fixed roughness value to the areas where they cover the surface of slough. Leonard et al. (2006) have shown that floating plants and periphyton affect velocity magnitude and the shape of vertical profiles, especially in slough where they are most abundant. The presence of these periphyton mats on the surface of water inside a slough may also affect the dispersion and diffusion, which have not been considered. Lack of enough flow velocity and water depth data during the tracer study and limited areal images of dye transport are other limited factors in this study. In this study, the interaction between groundwater and surface water is neglected. No change in groundwater head elevation was detected from nearby groundwater monitoring wells during the dye study and pulsed condition. Eight hours for pulsed-flow condition during the dye experiment is too short to cause any interaction between groundwater and surface water.

Conclusions

The purpose of this study was to develop a high-resolution hydrologic model in FLO-2D and evaluate whether the model could simulate the effect of pulsed-flow conditions on sheet flow in low-gradient wetlands with high vegetation density. This study presented the results of two different pulsed-flow conditions: low inflow discharge with magnitude of 0.34 m^3/s and duration of 8.0 h, which represents hydrologic condition during a dye study conducted on October 2007, and high inflow discharge with magnitude of 3.0 m^3/s and duration of 1.0 h. The results reveal that the low pulsed flow condition produces flow velocity values that are low (0.02 m/s) and vary in direction and do not follow the east-west flow direction, creating areas of mixing inside deep slough. Under high pulsed flow, simulated flow velocity values are high (0.1 m/s) but they are uniform indicating east-to-west flow direction toward downstream inside deep slough. The high spatial resolution of this modeling effort may be another reason to reveal mixing zones inside deep slough where flow direction varies. This may affect transport of sediments and nutrients and cause accumulation of substances within these areas. Further investigations are needed to support the existence of these mixing zones and whether they may significantly alter transport mechanisms.

This modeling investigation indicates that the proposed model is capable of estimating flow depth and velocity in wetlands with realistic accuracy. The hydrologic model was developed using FLO-2D, a vertically averaged numerical model for surface water flow. This model was calibrated using flow velocity measurements obtained from ADVs installed inside the study area during a field test with generated pulsed-flow condition. The calibrated model was used to simulate water flow in an experimental wetland system (LILA) where a dye study was conducted. Simulated values of water velocity were found to compare favorably with those derived from dye test observations. This study also provides a platform for further application of FLO-2D to simulate flow velocity and water depth in regional areas such as WCAs and the Everglades.

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