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Effects of hydraulic resistance by vegetation on stage dynamics of a stormwater treatment wetland

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SUMMARY

This work examined the potential effects of large-scale thinning of emergent vegetation on the stage dynamics in a very large (33.3 km^2) constructed treatment wetland in South Florida. Dense vegetative biomass in treatment wetlands may restrict water flow and increase water levels, which may in turn have adverse effects on vegetative community structure. Here, we developed a physically-based, spatially-distributed hydrodynamic model of Stormwater Treatment Area 2, Cell 2 (STA2C2) to investigate the spatio-temporal variability of water level (stage) in response to management for thinning of emergent macrophytes (e.g., burning and/or herbicide treatments). The model was calibrated against stage measured at six monitoring stations for 1 year, and subsequently validated against 2 years of stage data from eight stations. Finally, the validated model was extended to simulate various vegetation management scenarios. The model provided an excellent fit to observed stage data in both calibration and validation periods (median model efficiency indices of 0.82 and 0.83, respectively). Higher stages in the treatment cell were dominantly associated with peak inflow magnitude and the timing of event intervals. Prolonged periods of sustained deep water conditions were observed when one flow peak was followed by consecutive peaks. A gradual stage gradient from the inlet to outlet was observed during peak flow periods, with a shift to a sharp gradient at approximately two-thirds distance from the inlet. Stages in the wetland were found to be controlled less by the hydraulic resistance, as indicated by a low sensitivity of simulated water levels for a ±50% perturbation in flow resistance parameter. Water depths were reduced by a maximum of 12 cm at the inlet region by thoroughly thinning the remaining emergent vegetation in STA2C2. Similarly, a maximum of only 2% of the total STA2C2 area was prevented from exceeding a water depth believed to be detrimental to *Typha* sp. (1.22 m) after the highest peak inflow. Collectively, our findings suggested that vegetation thinning may not be effective for minimizing deep water conditions in STA2C2.

1. Introduction

Emergent macrophytes are the dominant form of aquatic plants in treatment wetlands (Kadlec and Wallace, 2008); they are often established in dense stands to reduce contaminants and nutrient concentrations in drainage water through physical, chemical and biological mechanisms (Thullen et al., 2005; Kadlec and Wallace, 2008). Pollutant reduction in a treatment wetland is considerably influenced by a variety of hydraulic features of the wetland such as water depth, velocity, and flow distribution (Kusler and Kentula, 1990; Dierberg et al., 2005), which are often critical variables to nutrient/sediment transport, evolution of vegetative communities, and vegetation survival (Kadlec and Wallace, 2008). Hydraulic resistance induced by the macrophyte stem/leaf drag holds considerable importance in understanding the hydrodynamic behavior of wetlands since it controls the flow distribution and residence time of the water within the wetland (Nepf, 1999; Harvey et al., 2009; Chin, 2011). Generally, increased resistance to flow results in a decrease in mean velocity, increased water levels and longer retention times (Kadlec, 1990; Jadhav and Buchberger, 1995). The composition of emergent macrophytes in surface-flow wetlands is profoundly influenced by the depth of flooding (Grace, 1989; Squires and Vandervalk, 1992). Extended duration of deep water conditions can cause physiological stress in emergent communities, and adversely influence growth, seed germination, and reproduction of vegetation species (Grace, 1989; Chen et al., 2010); therefore, emergent macrophytes are often constrained to shallow depths to minimize negative ecological impacts (Kalff, 2002).

Constructed treatment wetlands have been increasingly used to treat stormwater and agricultural runoff (Kadlec and Wallace, 2008). In South Florida, large-scale (18,000 ha effective treatment

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area) constructed treatment wetlands, known as Stormwater Treatment Areas (STAs), have been built and operated by the South Florida Water Management District (SFWMD) to reduce phosphorus (P) concentrations in agricultural drainage waters before entering the P-sensitive Everglades ecosystem (Chimney and Goforth, 2001; Noe et al., 2001; Sklar et al., 2005). Management and manipulation of vegetation communities in STAs is an important component of efforts to improve the P removal performance (Toth, 2007). A significant portion of the STAs contains emergent aquatic vegetation (EAV), dominated by cattail (*Typha domingensis* and *Typha latifolia*) (Ivanoff et al., 2012). In recent years, SFWMD has been actively engaged in large-scale vegetation conversion from EAV to submerged aquatic vegetation (SAV) in some of the EAV-dominated back-end treatment cells (Pietro et al., 2010) because SAV communities were found to be effective for P sequestrations at low P concentrations (Dierberg et al., 2002). During vegetation conversion, EAV are generally controlled through periodic and selective use of herbicides to suppress EAV establishment while facilitating the establishment of SAV (Ivanoff et al., 2012). These conversion efforts reduce the biomass density of macrophytes and influence the hydraulic behaviors of the wetland.

Characterizing the variability in hydraulic regimes as a function of vegetation community type/density is crucial for the sustainability of STA vegetation communities, and, therefore, the treatment performance of the wetland. At high flows, the hydraulic resistance induced by dense vegetation can contribute to greater water depths due to reduced flow cross-sectional area (Jadhav and Buchberger, 1995; Bal et al., 2011). This condition has often been observed at the front-end of many of the STA flow-ways. From over a decade of STA operations, it has been recognized that excessive water depths for a long period of time have considerable adverse impacts on cattail communities (Chimney et al., 2000; Pietro et al., 2010). For example, the death of approximately 40% of the cattail standing crop in Cell 2 of STA 1 West (STA-1W) between May 1997 and November 1998 was coincident with frequent high water levels that may have exceeded the tolerance range for the cattail (Chimney and Moustafa, 1999). Such remarkable cattail mortality highlights the need for well-informed hydraulic operations to sustain desired plant communities. Chen et al. (2010) found 1.37 m water depth to be sufficient to cause physiological stress on cattail, harming both growth and reproduction. Water depths >1.2 m have been observed in some areas within STA2. Although efforts have been made to determine the cattail tolerance and stress patterns in the STAs as a result of water depths (Chen et al., 2010), the cattail sustainability in these systems remains unknown. Managers of the STAs and other constructed wetlands would benefit from the ability to minimize prolonged deep water conditions.

Macrophytes creating hydraulic resistance in surface flow wetlands can range from dense mats of emergent vegetation in shallow water, to sparse populations of SAV or floating plants in deeper (1–2 m) areas. Converting EAV to SAV in portions of a wetland flow path may reduce hydraulic resistance enough to avoid excessive water depths in remaining areas supporting EAV communities. The authors are aware of only one field study that evaluated the potential impacts of rapid vegetation change on sheet flow in wetlands. Schaffranek et al. (2003) studied the effects of a fire that burned a dense stand of emergent vegetation (Sawgrass; *Cladium jamaicense*) in the Everglades National Park (ENP). Velocity profiles indicated higher flow velocities in the burned area, relative to nearby unburned sites.

Since it is difficult to physically test these large field-scale operations that require enormous efforts and time, numerical modeling can provide a quantitative evaluation of different management alternatives. In this study, we developed and applied a physically-based, spatially distributed dynamic flow model of Stormwater Treatment Area 2, Cell 2 (STA2C2) to investigate the impacts of large-scale vegetation management (conversion from EAV to SAV) scenarios on stage dynamics. While the conversion in STA2C2 was initiated to achieve water quality goals, it provided the opportunity to improve our understanding of how these management activities affect the internal flow dynamics. We assumed that the thinning of emergent macrophytes through herbicide treatments or burning during the conversion process decreases the hydraulic roughness induced by emergent vegetation.

Because deep water conditions generally occur during high flow periods, we explore these scenarios in relation to designated peak inflows. These simulations are particularly designed to address the following questions:

1. How does stage vary internally within STA2C2, especially under peak inflows?
2. What is the spatio-temporal extent of water depths greater than 1.22 m (4 ft) and 1.07 m (3.5 ft) for designated peak-inflows in relation to vegetation management scenarios, and can we use these estimates to evaluate the benefits of management approaches to minimize hydraulic resistance?
3. What is the sensitivity of the model output (i.e., stage) to changes in hydraulic resistance parameter in the model?

In order to address these questions, we first developed the STA2C2 flow dynamics model including model parameterization. Next, the model was validated using 2 years of independent stage data from eight monitoring sites, and the effects of thinning emergent macrophytes on water depth were evaluated. The implications for STA vegetation management approaches to minimize deep water conditions were discussed. This modeling study was designed to help understand internal flow behavior varies in response to vegetation management (i.e., thinning biomass by herbicide and/or burning; conversion of cattail to SAV) in treatment wetlands.

2. Study site

STA-2 is a large (33.3 km^2) constructed freshwater wetland designed to remove P from stormwater and agricultural runoff before entering the Water Conservation Area 2A (WCA-2A). STA-2 is located in southern Palm Beach County (Florida, USA) along the northwestern boundary of WCA-2A and on the southeastern boundary of the Everglades Agricultural Area (EAA) in South Florida (26°24′N, 80°31′W, Fig. 1). This treatment wetland was built by SFWMD on former agricultural land and wildlife management areas (Huebner, 2008), and originally consisted of three parallel treatment flow-ways, where the flow-through operation began in 2000.

STA-2 primarily receives stormwater runoff and agricultural runoff from EAA. A series of inflow culverts distributes flows from the inflow canal to the respective treatment cells. STA2C2 is one of the treatment cells of STA-2 and is located between treatment cells 1 and 3, which receives inflows through G331A-G gated culverts (Fig. 1). Flows then move southward through the treatment cell into the Discharge Canal through G-332 gated spillway, and eventually exit STA-2 through outflow pump station G-335.

In STA2C2, the major vegetation coverage types include cattail (*Typha* sp.), open water with or without SAV, and emergent sawgrass (*Cladium jamaicense*). Of the total areal coverage, these three vegetation types covered approximately 89% (53% cattail, 19% open water with or without SAV, and 17% emergent sawgrass). In April 2009, vegetation in the southern section was reconfigured, in which EAV was converted to SAV in approximately 162 ha, referred to as “Conversion Area” (Fig. 1) (Germain and