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Compartment-based hydrodynamics and water quality modeling of a Northern Everglades Wetland, Florida, USA☆

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ABSTRACT

The last remaining large remnant of softwater wetlands in the US Florida Everglades lies within the Arthur R. Marshall Loxahatchee National Wildlife Refuge. However, Refuge water quality today is impacted by pumped stormwater inflows to the eutrophic and mineral-enriched 100-km canal, which circumscribes the wetland. Optimal management is a challenge and requires scientifically based predictive tools to assess and forecast the impacts of water management on Refuge water quality. In this research, we developed a compartment-based numerical model of hydrodynamics and water quality for the Refuge. Using the numerical model, we examined the dynamics in stage, water depth, discharge from hydraulic structures along the canal, and exchange flow among canal and marsh compartments. We also investigated the transport of chloride, sulfate and total phosphorus from the canal to the marsh interior driven by hydraulic gradients as well as biological removal of sulfate and total phosphorus. The model was calibrated and validated using long-term stage and water quality data (1995–2007). Statistical analysis indicates that the model is capable of capturing the spatial (from canal to interior marsh) gradients of constituents across the Refuge. Simulations demonstrate that flow from the eutrophic and mineral-enriched canal impacts chloride and sulfate in the interior marsh. In contrast, total phosphorus in the interior marsh shows low sensitivity to intrusion and dispersive transport. We conducted a rainfall-driven scenario test in which the pumped inflow concentrations of chloride, sulfate and total phosphorus were equal to rainfall concentrations (wet deposition). This test shows that pumped inflow is the dominant factor responsible for the substantially increased chloride and sulfate concentrations in the interior marsh. Therefore, the present day Refuge should not be classified as solely a rainfall-driven or ombrotrophic wetland. The model provides an effective screening tool for studying the impacts of various water management alternatives on water quality across the Refuge, and demonstrates the practicality of similarly modeling other wetland systems. As a general rule, modeling provides one component of a multi-faceted effort to provide technical support for ecosystem management decisions.

1. Introduction

The Arthur R. Marshall Loxahatchee National Wildlife Refuge (Refuge), which overlays Water Conservation Area 1 (WCA1), is an impounded freshwater marsh established in the 1950s for protection of wildlife habitat (e.g., the endangered Everglade snail kite) as well as sources of water supply to croplands, water storage across the dry and wet seasons, and flood protection to the neighboring urban environment (Brandt et al., 2004; USFWS, 2007). The Refuge is a remnant of the once contiguous Everglades that extended from the Kissimmee Chain of Lakes south to Florida Bay. In the historic Everglades, water generally flowed from north to south following the natural elevation gradient as sheet flow. Presently, the Refuge marsh is encircled by a 100-km levee and its associated borrow

Abbreviations: CA, cluster analysis; CL, chloride; DMSTA, dynamic model for storm water treatment; EAA, everglades agricultural area; ET, evapotranspiration; SFWMD, South Florida Water Management District; STA, stormwater treatment area; SO_4, sulfate; SRSM, simple refuge screening model; TP, total phosphorus; USACE, U.S. Army Corp of Engineers; USEPA, U.S. Environmental Protection Agency; USFWS, U.S. Fish and Wildlife Service; USGS, U.S. Geological Survey; WCA, water conservation area.

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canal with an average width of 40 m, which was completed by the U.S. Army Corps of Engineers in the early 1960s.

Land use in the drainage basin upstream of the Refuge has changed from historic Everglades marsh to primarily agriculture and some urban use. This change has resulted in substantially elevated nutrient and mineral concentrations in the inflow into the Refuge (USFWS, 2007). Water quality even in the interior marsh of the Refuge has been affected by intrusion of eutrophic and mineral-enriched waters in the canal that surrounds the Refuge (Gilmour et al., 2008; Harwell et al., 2008; Surratt et al., 2008; Wang et al., 2009; Chen et al., 2012). There are two major mechanisms responsible for the increase in nutrient and mineral concentrations in the Refuge, inflow and intrusion. First, inflows into the Refuge from pumped agricultural stormwater runoff (USFWS, 2007) bring agricultural nutrients and elevated mineral concentrations to the Refuge. Nearly half of the average annual water inputs to the Refuge originate in these inflows, with direct rainfall accounting for the remainder (Arceneaux et al., 2007; Meselhe et al., 2010). Constructed wetlands, termed Stormwater Treatment Areas (STAs), bordering the northern part of the Refuge were created to remove total phosphorus (TP), often removing over 80% of TP, but they remove less than 20% of sulfate (SO_4) (He, 2007). Second, rather than being discharged from the Refuge rim canal through outflow structures that discharge to WCA2, much of the inflow enters the Refuge interior marsh as overbank flows from the canals, similar to a floodplain wetland, resulting in elevated concentrations of nutrient and minerals in marsh interior (Harwell et al., 2008; Surratt et al., 2008). Modeling presented here quantifies these mechanisms and their impacts.

Degradation of water quality in the Refuge could greatly affect the structure, function, and health of the Refuge ecosystem. Phosphorus enrichment is a major driving factor responsible for vegetation and landscape changes within the Refuge and across WCA2A (McCormick et al., 2009). Most of the ecological responses to phosphorus enrichment ultimately occur within a relatively narrow range of water-column TP concentration between approximately 0.01 and 0.03 $mg\,l^{-1}$ (10 and 30 $\mu g\,l^{-1}$) (McCormick et al., 2002). Therefore, even a small change in TP concentration may cause substantial shifts in native biological populations (McCormick et al., 2002). Recognizing this sensitivity, the State of Florida set the numerical criterion for TP in the Refuge at a geometric mean of 0.01 $mg\,l^{-1}$ (10 $\mu g\,l^{-1}$, Walker and Kadlec, 2011). As for the ecological impact of SO_4, previous studies (Bates et al., 1998; Gilmour et al., 1998, 2008; Orem et al., 2002) indicated that high levels of SO_4 entering the Everglades marsh could stimulate microbial sulfate reduction, causing buildup of sulfide in pore water, and production of methylmercury (a neurotoxin to fish and other wildlife).

It is a challenge for the Refuge to identify management alternatives that maximize benefits for wildlife while meeting constraints of flood control and water supply. The optimal management requires physical-based predictive tools to assess and forecast the impacts of water management on Refuge water quality. Integrated hydrodynamic and water quality models provide such predictive capability. Previously, there have been limited modeling efforts that link hydrodynamics and water quality in the Refuge. The Everglades Landscape Model (ELM) (Fitz and Trimble, 2006; Fitz et al., 2011), which imports part of its flow simulation from the South Florida Water Management Model (SFWMM) (South Florida Water Management District, 2005), simulates hydrology and water quality in a large area of South Florida including the Refuge but at a coarse resolution (2-mile × 2-mile) with consideration of discharge only for major hydraulic structures within the model grid. The commercial MIKE-FLOOD model combined with ECOLab (DHI, http://www.mikebydhi.com/Products/ECOLab.aspx) has also been used to simulate Refuge stage and water quality at a high spatial resolution (400-m × 400 m; Chen et al., 2010, 2012). While this model performs well, it is computational costly. It requires very long run time relative to the model presented here, and requires a significant level of user training and sophistication. Arceneaux et al. (2007) conducted water budget and water quality modeling for the Refuge using concentric four-compartment delineation (one canal compartment, and three inner marsh compartments) termed the Simple Refuge Screening Model (SRSM). Such delineation was not sufficient to capture the large spatial variations in hydrodynamics and constituent transport among different areas where the characteristics of soil, topography, and vegetation show spatial heterogeneity within the Refuge (e.g., variations in water quality parameters in marsh areas along the east and west of the rim canal). Development of the SRSM has continued (Meselhe et al., 2010; Roth and Meselhe, 2010), and it has been applied in a number of management applications where Refuge-wide aggregated results are of interest. The model described herein evolved from the concept of the SRSM, and was conceived to provide a compartmental model, which combines ease-of-use and computational efficiency, similar to that of the SRSM, but with improved spatial resolution. It should be noted that each of these Refuge models has particular applications for which they are useful, and no model meets all needs.

Identification of superior management strategies requires answering questions such as what conditions (e.g., timing and location of structure inflows) would cause canal water intrusion into the marsh interior, and what inflow amount and concentrations would lead to spikes of TP and SO_4 in the marsh interior? In this research, our objectives are to: (1) develop a spatially-lumped model to examine the spatial and temporal variations in water quantity and water quality parameters (CL, TP and SO_4) in the Refuge; and (2) examine the influence of canal water on marsh water quality in the Refuge through scenario analyses in a fast and computationally efficient way.

2. Methods

2.1. Study site

The Arthur R. Marshall Loxahatchee National Wildlife Refuge is located in the subtropical region of South Florida (latitude 26°21.36′ to 26°41.04′N; longitude 80°13.32′ to 80°26.7′W; Fig. 1). It is bordered on the northwest by drained wetlands converted to

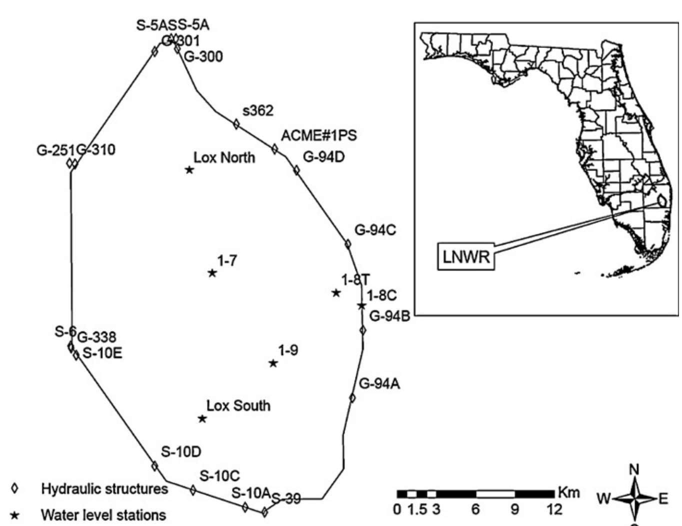

Fig. 1. Location of the A.R.M. Loxahatchee National Wildlife Refuge (LNWR), Florida (inset) and distribution of hydraulic structures and water level stations in the Refuge.