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Shifting nutrient sink and source functions of stormwater detention areas in sub-tropics

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ABSTRACT

Two-year field measured water and nutrient fluxes from an agricultural stormwater detention area (SDA) in Florida's Everglades region showed that it was a source of phosphorus (P) for the first year (Y1 retention efficiency = −12%) and a sink for the second year (Y2, 54%). The SDA remained a consistent sink of nitrogen (N). Source function was a combined effect of dilution of incoming drainage from a tropical storm and legacy-based soil P saturation. Denitrification was the main biochemical process contributing to N retention (Y1 = 23%, Y2 = 56%). Volume reduction was the main reason for nutrient retention, especially for P because of limited to no remaining soil P sorption capacity. Although a net sink of P for Y2, an event-wise analysis showed the source function for 40% of the outflow events indicating intermittent P release from soil. Because surface P treatment efficiency during both years was either less than or close to the water retention efficiency, volume reduction and not sorption or biological assimilation controlled P treatment. Almost a third of the incoming P was lost through subsurface pathways, highlighting the significance of groundwater P losses from SDAs. Harvesting and removal of biomass can mine P and restore SDA's sink function. For an example sub-basin of Florida Everglades, potentially harvestable P from SDAs was more than the basin P loads. A payment for environmental services project to treat additional P through biomass harvesting is a sustainable approach, especially under future climate projections of more frequent high-intensity storms for the Everglades and beyond.

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1. Introduction

Approximately 2.6 million artificial water features, such as ponds and detention/retention areas, are distributed throughout the continental United States (US) with most of these present in the eastern US. Despite their ubiquitous presence and use in flood management, water supply, and water quality improvement, these features have not been well documented compared to large reservoirs with regards to their hydrology, geochemistry, and ecology (Smith et al., 2002). Collectively, these represent 20% of the total standing water area within US (Smith et al., 2002) making their cumulative impact on water balance and biogeochemistry comparable to larger reservoirs and named lakes (e.g., Lake Okeechobee in Florida).

Agricultural stormwater detention areas (SDAs), a term collectively used for natural/manmade depressions, ponds, reservoirs, etc. in agricultural settings, have historically been used mainly for flood protection and water supply, and are increasingly being used for water quality improvement. At a global scale, SDAs represent up to 6% of the total farmed area with a total area of 77,000 km^2 (Downing et al., 2006). Within continental US, their total area is 21,600 km^2 (Downing et al., 2006). Downing et al. (2006), using a statistical relationship, showed that SDA area as a percent of total agricultural area increases with increase in average annual precipitation. For example, Nebraska with an annual average rainfall of approximately 60 cm was reported to have less than 0.2% of SDA area as percent of total farm area. In contrast, Mississippi with an annual average precipitation of approximately 150 cm was showed to have a SDA coverage of about 4% (Downing et al., 2006). Florida, given the large annual precipitation (130-150 cm) and shal-

Abbreviations: SDA, stormwater detention area; BMP, best management practice; TP, total phosphorus; TN, total nitrogen; STA, stormwater treatment area.

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low water table, has SDAs which account for approximately 10% of the farm area.

In Florida, most SDAs were built for downstream flood protection in shallow water table regions that were prone to higher flooding risk. They also provided flood protection for crops by temporarily storing the drainage from the production fields. Rapid rise in shallow water table (almost 16 times the rainfall; Jaber et al., 2006), necessitates drainage to lower the water table which reaches almost to the surface. The SDAs in Florida have a regulated design capacity to store the first 2.5 cm of drainage from the farm with the goal of reducing downstream flooding (Shukla et al., 2010; SFWMD, 2013). In addition to their flood control features, their biogeochemistry is increasingly becoming important as the state and federal agencies struggle to protect the world renowned ecosystem, the Everglades, a P limited system, which is losing its ecological integrity due to excessive P loads (Corstanje et al., 2016). Apart from the Everglades, other sensitive ecosystems, such as the Lake Okeechobee, have also been adversely impacted by the excessive flows and nutrient (nitrogen (N) and phosphorous (P)) loads (He et al., 2014). Current loads of P (609 metric tons), the limiting nutrient for the Lake Okeechobee, are more than 4 times above the threshold (140 metric tons) to protect the lake (SFWMD, 2015). A P limit of 10 ppb has been set for the water entering the Everglades National Park (FDEP, 2004) to maintain its ecological integrity; however, the flow weighted mean total phosphorus (TP) concentration of the water leaving the stormwater treatment areas (STAs) and entering the Everglades was reported to be 21 ppb in 2014 (SFWMD, 2015).

Global P fertilization is predicted to increase threefold by 2050 (Tilman et al., 2002), making the edge-of-the-farm treatments like SDAs important in retaining nutrient loads from the farms, in addition to in-field source control. End-of-the-farm, transitional location between farmland and waterbodies, makes the SDAs the last segment of the treatment train before agricultural drainage is discharged to the public waters. Assumed to reduce off-site N and P discharges, SDAs are considered one of the most important best management practices (BMPs) (SFWMD, 2009a). However, despite a dominant presence, limited data exist on material fluxes, especially water and nutrients to evaluate their nutrient retention potential. Due to lack of data, literature values for other treatment systems such as constructed wetlands are used for watershed planning purposes.

Several studies have quantified the nutrient transformations and retention in natural and artificial treatment systems (Kovacic et al., 2000; Coveney et al., 2002; Tanner et al., 2005; Eveborn et al., 2012; Kynkäänniemi et al., 2013; Beutel et al., 2014; Pietro and Ivanoff, 2015). These studies have reported the treatment systems to be a sink of nutrients such as N and P, popularizing them as an important BMP. The processes for N and P retention in most treatment systems including SDAs are similar, such as sedimentation, plant uptake, soil adsorption, and microbial conversions (e.g., nitrification–denitrification in case of N). However, due to differences in the land use (nutrient input) in the drainage area, vegetation, soil type, type of inflow (gravity/pumped), and climatic conditions (humid/tropic/arid), the results from these studies cannot be generalized (Shukla, 2014).

Although results from past studies are not directly applicable to SDAs, the fact that detention systems can behave as a source of P is noteworthy. Among the P retention processes, soil adsorption controls the long-term retention (Chen et al., 2015), while plant accumulation of P is a short-term process because plants die and release nutrients back to the water (Álvarez and Bécares, 2006; Beutel et al., 2014). Since long-term loadings of P can saturate the soil P adsorption sites, making the system a source of P; knowing the extent of soil P saturation for its potential for P release is critical. Our study attempts to answer the following questions regarding the N and P treatment potential of SDAs: (1) what are the N, P, and water fluxes associated with SDAs?; (2) are SDAs a net sink or source of N and P?; (3) how does hydrology, biogeochemistry, and climate affect N and P treatment efficiency of SDAs?; and (4) how can the nutrient treatment efficiency of SDAs be enhanced? Specific objectives are: (1) quantify water, N and P fluxes, and nutrient treatment efficiency of a SDA located in a sugarcane farm in south Florida; and (2) identify and evaluate hydraulic and biotechnological management alternatives to enhance nutrient treatment.

2. Methods and materials

2.1. Study area

The study was conducted for two years (Year 1—August, 20, 2008 to August 20, 2009; Year 2—August 21, 2009 to August 20, 2010) at a SDA (area = 14.16 ha) built in 1999. The SDA is located in a sugarcane farm (122 ha) in the C-139 basin, a sub-watershed of the Everglades basin, a P limited system located in warm (minimum temperature = 18.9 °C, maximum = 29.4 °C; Shukla et al., 2010), sub-tropical, south Florida (Fig. 1).

The region annually receives 134 cm of rainfall on an average which varies spatially between 113 and 164 cm (Abtew et al., 2011). Most rainfall (66%) is received in the wet season (June–October) (Abtew et al., 2011). A drainage pump commonly termed as the "throw-out pump" with a capacity of 22.71 m^3/min and discharge pipe diameter of 0.4 m is located on the northwest side of the SDA. The outflow structure is a rectangular orifice. The SDA is surrounded by an embankment and farm drainage is pumped from a borrow ditch surrounding the SDA perimeter on the outside using the throw-out pump (Fig. 1). Once the water level inside the SDA exceeds the crest level of the rectangular orifice, water is discharged to a public canal. A borrow ditch surrounds almost the entire inner perimeter of the SDA (Fig. 1). The inner ditch, irregular in width (9–19 m), was created during SDA construction when material inside the SDA was excavated to provide soil for embankment construction. Almost the entire SDA is covered with Para grass (*Brachiaria mutica*). The dominant soil type is the Holopaw fine sand, a poorly drained soil with approximately 94% sand. The lowest and the highest points of the SDA lie at the bottom of the inner borrow ditch (2.92 m AMSL, NAVD88[1]) and top of the embankment (7.47 m AMSL, NAVD 88), respectively. The floor of the SDA is nearly flat (minimum, maximum, and average elevations = 4.88 m, 5.23 m, and 5.09 m respectively; AMSL, NAVD88).

2.2. Hydrologic monitoring

Surface water fluxes monitored included: (1) inflow; (2) outflow; and (3) storage. The throw-out pump was calibrated to develop flow rate as a function of impeller rotations per minute (RPM) and lift head (h) using an ultrasonic flowmeter (Thermo Polysonics DCT7008). Surface outflow was estimated using a standard orifice discharge equation which uses the measured head from a hydrostatic level transducer (http://www.levelandpressure.com/series500.aspx) connected to a datalogger.

Seepage was estimated by modifying the traditional White's method and using the nocturnal water level changes in conjunction with ecosystem specific yield during low temperature regime (November to March; Shukla et al., 2015). The FAO-56 Penman–Montieth (P–M) equation was used to calculate grass referenced evapotranspiration (ET, referred to as ET_o) which was converted to actual ET using the crop coefficients. Given the

[1] AMSL, NAVD88 is height above mean sea level as per North American Vertical Datum established in 1991.

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