



An innovative solar energy-powered floating media bed reactor for nutrient removal (I): reactor design

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ABSTRACT

Nutrient impairment of Florida's surface waters due to urban stormwater runoff is a growing concern, resulting in the development of new regulatory policies. Several best management practices (BMPs), such as stormwater retention/detention ponds, help reduce the impact of flooding but may not reduce nutrient loadings sufficiently to meet water quality goals. This paper presents the design and implementation of a floating media bed reactor (FMBR) as a supplementary treatment unit for stormwater wet detention ponds to enhance the removal efficiency of total phosphorus (TP) and total nitrogen (TN). This effort mitigates the adverse effects of stormwater runoff on downstream impaired waterbodies. The FMBR was filled with an engineered mixture of adsorption media made of natural and recyclable materials and operates on a 24 h continuous cycle, powered by a small photovoltaic pumping system. Significant reductions in TP and TN were documented across the FMBR achieving varying degree of removal efficiencies for storm and non-storm events with fluctuating temperatures. The outcome expands the state of the art stormwater treatment technology and encourages stormwater reuse as an alternative source of freshwater.

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1. Introduction

The expansion of urban development over the last several decades has increased pollutant loading to surface waterbodies throughout Florida. Several best management practices (BMPs) have been implemented to help reduce pollutant loading from stormwater systems to surface waterbodies for municipal, commercial, and agricultural runoff. Wet detention ponds, originally designed for flood mitigation, are perhaps the most common BMP, operating by the capture and transformation of pollutants through physical, chemical, and biological processes prior to discharging to lakes, rivers, and oceans (USEPA, 1999). According to current Florida regulations, a stormwater pond shall achieve an 80% average annual load reduction of pollutants from the influent stormwater (F.A.C. Chapter 62-40). Currently, regulations pertain to solids removal only; however, recent research indicates that nutrients are the most significant parameters linked to water quality impairment within

the State of Florida (Harper and Baker, 2007) and are ranked the first major source of impairment in Florida lakes (Obreza et al., 2010).

Nutrients are naturally occurring in the environment and a necessity for ecosystems to function. However, when a limiting nutrient, often phosphorus for fresh waterbodies, begins to exceed natural background levels, the ecosystem may be detrimentally impacted by harmful algal blooms (HABs) or dominated by single-species groups because of eutrophic conditions. Note that most impacts associated with water quality pollutants are based on toxicity thresholds, in which a dose–response relationship may address a particular concern with a pollutant's impact on water quality. Nutrients, however, are more complex in nature, whereby a particular concentration may be detrimental to a naturally low-nutrient waterbody yet normal for a waterbody with naturally high nutrient levels in a well-adapted ecosystem. A decrease in nutrients may result in detrimental effects on an ecosystem if particular organisms no longer have sufficient resources to maintain populations. Nutrients therefore require ideal ranges that may vary from one waterbody to another to ensure an efficiently functioning ecosystem.

Curbing the effects of elevated anthropogenic nutrient loading to surface waters, primarily from total phosphorus (TP) and total

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nitrogen (TN), is a complex subject for both scientific quantification and regulatory development. During the last few decades, several efforts including the creation of total maximum daily loads (TMDLs) and the National Pollution Discharge Elimination System (NPDES) have been applied to meet the standard goals outlined in 302.531 F.A.C., which states, “in no case shall nutrient concentrations of a body of water be altered so as to cause an imbalance in the natural population of flora or fauna.” Moreover, the US Environmental Protection Agency’s (USEPA) national strategy for the development of nutrient criteria (USEPA, 1998) resulted in some states creating specific numeric nutrient criteria (NNC) that establish numerical ranges of acceptable nutrient concentrations to meet water quality goals.

One method to meet these goals in stormwater wet detention ponds is implementation of BMPs to enhance the pond’s nutrient removal capacity. According to a summary of 10 studies evaluating wet detention pond performance conducted from 1982 to 2005, ponds in Florida were found to remove a mean value of 37% TN and 69% TP (Harper and Baker, 2007). Clearly, there is an acute need to increase the nutrient removal capacity of stormwater wet detention ponds by integrating additional BMPs.

The use of filtration/adsorption media such as sand, compost, and wood chips for removal of nutrients in stormwater runoff has been increasingly studied during the last decade, typically using column studies (Kim et al., 2000; Hossain et al., 2009; Jones et al., 2015). Such adsorption media are commonly used in infiltration or exfiltration applications and have been included in commercial applications. Adsorption media can be incorporated into multiple filter configurations and have been found to effectively reduce nutrients, suspended solids, and turbidity in stormwater management systems (Khambhammettu et al., 2006; Ryan et al., 2010).

This paper presents the design and implementation of a floating media bed reactor (FMBR) filled with green sorption media to increase the nutrient removal capacity of a stormwater wet detention pond. The FMBR was built to field-scale and installed in a small wet detention pond located in Palatka, Florida. The FMBR utilizes an upflow filtration configuration in the middle of the pond due to a densely vegetated littoral zone and limited space surrounding the pond. Insights into the performance of the green sorption media and reactor design under varying inflow and changing weather conditions were drawn from the study to promote stormwater reuse. To our knowledge, limited work has examined the use of a continuously cycling sorption media filter for inter-event stormwater treatment in a wet detention pond. The use of innovative and environmentally sustainable BMPs, such as a FMBR, is a profound step forward in stormwater management and a valuable tool for achieving desired nutrient removal rates and compliance with newly formed federal and state regulations.

2. Materials and methods

This study aims to (1) establish the removal capacity of the FMBR for TP and TN nutrient species; (2) establish the operability of the FMBR, especially with regard to change in headloss; (3) supplement the limited database on field performance of stormwater green technology using sorption media; (4) examine how this technology may be used in meeting TMDLs and NNC regulations; and (5) explore the temperature effect on nutrient adsorption rates through various isotherms.

2.1. Design of the FMBR

Although stormwater filters show promise for nutrient removal, the current technologies are limited by storm-event driven technologies and consequently may only operate when a hydraulic gradient

develops across the filter, occurring during and shortly following rainfall events. As a result, filter surface areas must be increased to treat significant volumes of stormwater during relatively short run time while keeping hydraulic loading rates within reasonable ranges. Furthermore, wet detention ponds typically do not provide any continuous baseflow treatment and may not discharge for several weeks during dry periods, leading to long durations of filter inactivity. One technique to overcome this deficiency is the incorporation of pumps, enabling the filter to run continuously.

In this study, the FMBR was arranged in an upflow filtration design and incorporated a photovoltaic pumping system to continuously cycle water through the media bed (Table 1, Fig. 1). Incorporation of photovoltaic cells allowed the FMBR to operate free of a power grid. The photovoltaic cells were sized based on calculations of daily joules consumed, battery capacity, and required area of photovoltaic module to recharge the battery supply. Power system designs for the FMBR included the total power draw by the submersible pump, energy loss through the voltage regulator, energy losses charging the battery, energy drain losses through wiring, and output power generated by the photovoltaic module. Several environmental factors were considered in the design of the power system, including sunlight exposure, time of year, local weather conditions and patterns, and photovoltaic module installation angle. The FMBR was operated to run under a 1-h hydraulic retention time (HRT) based on the following equation:

$$\text{HRT} = \frac{V \cdot \eta}{Q} \quad (1)$$

where:

HRT = hydraulic residence time (min);

V = volume occupied by media (L);

η = media porosity (%);

Q = flow rate through the FMBR (L min^{-1}).

2.2. Biosorption activated media

The mixture utilized in this study extends from a family of green media mixtures tested at the University of Central Florida (UCF),

Table 1
FMBR design information.

Component	Parameter	FMBR
Hydraulics	Bed volume (L)	340
	Flow rate (L min^{-1})	1.5
	Loading rate ($\text{L min}^{-1} \text{ m}^{-2}$)	2.9
	HRT (min)	60
Sorption media	Porosity	0.27
	% Fine sand	50%
	% Fine expanded clay	20%
	% Recycled tire crumb	20%
	% Limestone	10%
Electrical	Battery type	Deep cycle
	Battery amp-hours (A h)	90
	Photovoltaic module wattage (W)	30
Pump	Pump type	Submersible brushless
	Vertical lift (m)	3.0
	Current (mA)	220
Study	Duration (months)	6
	Location	Palatka

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