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Evaluation of green sorption media blanket filters for nitrogen removal in a stormwater retention basin at varying groundwater conditions in a karst environment

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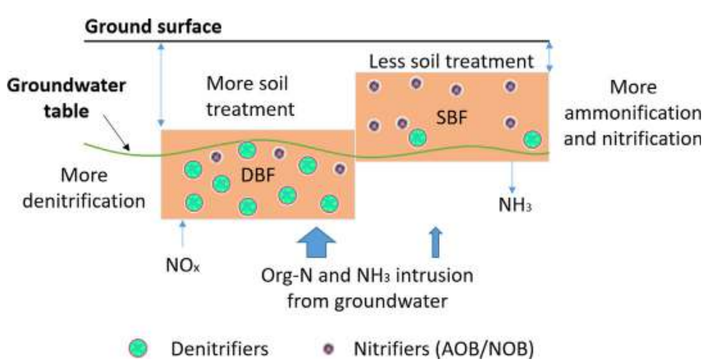
HIGHLIGHTS

- Blanket filters are a new biotechnology for improving nitrogen removal in stormwater dry basins.
- Nitrogen removal efficiency is tied to both groundwater fluctuations and storm types.
- Nitrogen removal efficiencies are also influenced by the population of nitrifiers and denitrifiers in blanket filters.

GRAPHICAL ABSTRACT



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ABSTRACT

Removing excess nutrient from stormwater runoffs is necessary to protect the water quality of receiving water bodies such as rivers, lakes, springs, and groundwater aquifers. Silver Springs Springshed, located in the vicinity of Ocala, Florida, has received widespread attention from the local government and residents due to its long-term nutrient impact, which has resulted in eutrophication. Blanket filters containing Bio-sorption Activated Media (BAM) were implemented with different depths of the vadose zone in a stormwater retention basin. The design combined the interaction with groundwater as an innovative Best Management Practice can potentially boost the performance of nutrient removal. Selected storm runoffs were collected at multiple points that cover the runoff timeframe to determine the pollutant load. Infiltrating water samples were collected at various depths within BAM using lysimeters to validate the treatment effectiveness. Significant pollutant load reduction of nutrients was confirmed with highest 99% and 91% removal of nitrate and nitrite (NO_x) and total nitrogen (TN) at the deep blanket filter (with more groundwater intrusion impacts) due to more effective denitrification and longer contact time. Yet the highest pollutant load reduction of 93% and 84% removal of NO_x and TN was also observed at the shallow blanket filter (with less groundwater intrusion impacts). On the other hand, better pollutant load reduction of ammonia in the BAM layer was found at the shallow blanket filter presumably due to more available oxygen for nitrification.

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1. Introduction

The world is now facing the largest wave of urban growth. An increase of 3 billion people before 2050 has been projected worldwide which will cause global urbanization to continue at high rates in the next few decades (Buhaug and Urdal, 2013; Seto et al., 2013). More urbanized regions imply more impervious land with high-intensity land uses, resulting in more stormwater runoff with possibly higher concentrations of contaminants, such as nutrients (Carle et al., 2005; Valtanen et al., 2014). Potential outcomes of fast urbanization include more severe water quality degradation, impacts related to eutrophication of the ecosystem, and harmful algal blooms (Anderson et al., 2008; Witte et al., 2005). In the State of Florida, where karst featured areas commonly exist at the landscape, springs and groundwater aquifers may be vulnerable to stormwater runoff that flows into karst aquifers with little or no natural attenuation (Anyona, 2009; Stephenson et al., 1999). Various best management practices (BMPs) for stormwater runoff treatment were conceived decades ago, for instance, to remove nutrients and store excess water for aquifer recharge. The most commonly used BMP is a stormwater infiltration basin (Anyona, 2009; Urbonas and Stahre, 1993). However, due to rapid urbanization and complex geophysical conditions, the treatability of stormwater infiltration basins can no longer satisfy the promulgated regulation standards for sustainable development (Birch et al., 2005; EPA, 2009; Pitt et al., 1999).

One of the best solutions is to improve nutrient removal capacity of stormwater infiltration basins by supplementing natural soil in the vadose zone with more effective green sorption media that included recycled materials for nutrient absorption and adsorption. These green sorption media are required to be able to fit into different landscapes flexibly and may provide better BMP service under a limited budget (O'Reilly et al., 2012). Bio-sorption activated media (BAM) is one of the promising green sorption media, with the media mix containing sand, clay, and tire crumb with various percentage depending on the need in applications. Many studies have highlighted its excellent treatment potential for inorganic nitrogen removal (Chang et al., 2010, 2011; Hossain et al., 2010; O'Reilly et al., 2012; Xuan et al., 2010), phosphorus (Hood et al., 2013), heavy metals such as copper (Chang et al., 2016; Wen et al., 2018), dissolved organic nitrogen (Chang et al., 2018), and pathogens (Chang et al., 2010). The technologies have been proven in many different applications, including constructed wetlands (Chang et al., 2013; Xuan et al., 2009), septic tank effluent treatment (Chang et al., 2010), and co-treatment of stormwater runoff and groundwater flows at varying temperature conditions (Chang et al., 2018).

Although BAM has been applied in multiple types of BMPs as stated in the previous section, many of them were designed to protect the groundwater quality. However, the shallower groundwater table in the central Florida area could be another critical factor in the consideration of designing a BMP. Since the seasonal fluctuations of groundwater may interact with the blanket filters and result in unknown influences in the treatment processes, the inclusion of the change of hydraulic patterns and the moisture content is essential. These changes may have an impact on the microbial communities in BAM that are directly related to ammonification, nitrification, and denitrification processes (Malhi and McGill, 1982; Nielsen et al., 1990; Ryzhakov et al., 2010; Zeng et al., 2014). In this study, two blanket filters have been installed in a stormwater dry basin near the Silver Springs state park where shallow groundwater table exists. The installation depth is different over the two blanket filters so that their performance can be compared to show the impacts from groundwater fluctuations. These types of BMPs have not yet been tested elsewhere and is an option for stormwater management. The innovation of this study rests upon deepening the understanding of the interaction between the BAM layers and the groundwater table reflecting the seasonal variability. It is particularly the case when considering the groundwater may have been highly contaminated before the BAM can be applied to the site, which is true for most treatment areas.

The objectives of this study are thus to: 1) evaluate the nitrogen removal effectiveness in both blanket filters that may have different nitrification and denitrification patterns, and 2) assess the groundwater intrusion impacts on nitrogen removal. Based on the objectives, the science questions to be answered include: 1) How would different depths of blanket filters in a vadose zone affect the nitrogen removal when facing varying levels of groundwater fluctuations? 2) How would the changing pollutant loads associated with different storm events impact the effectiveness of nitrogen removal at each of the two blanket filters?

2. Materials and methods

2.1. Study Site

2.1.1. Location and condition

Located at the intersection of SR-40 and SR-35 in Ocala, Florida, basin 9b was chosen as the study site. As shown in Fig. 1, the distance between basin 9b and Silver Springs is less than 0.5 km. This basin is a dry retention basin with a size of 0.29 ha (0.73 acres) and the urban watershed is about 2.15 ha (5.31 acres). The basin is connected to moderate business and residential areas, and also close to the Silver Springs state park (i.e., about 50 m from the edge of the park). The groundwater table is shallow with approximate 1.2–1.8 m, and the groundwater total nitrogen concentration in basin 9b ranged from 1.0 to 1.5 mg/L during our preliminary survey (Chang et al., 2015). Two blanket filters were constructed with different over-burden depths in design for a comparative study in the same basin. One was called the shallow blanket filter (SBF), with a depth of 1.2 m at the east side having almost no interaction with the local groundwater tables, and the other was called the deep blanket filter (DBF), with a depth of 1.8 m at the west side having been frequently affected by the groundwater fluctuations (Fig. 3 a). Both blanket filters (BFs) were designed to catch the inflow from an individual stormwater inlet pipe that is connected to the surrounding urban catchment area. After the construction of BFs, 4 wells were built in basin 9b, as shown in Fig. 1. Wells 1 and 4 are stilling wells with installed pressure transducers for the estimation of stormwater runoff, whereas wells 2 and 3 are groundwater sampling wells for monitoring the nutrient concentration. One additional pressure transducer was installed in well 2 for recording the groundwater level changes over time.

2.1.2. Design and operation of blanket filters

BAM was applied in this study to supplement the natural soil in both blanket filters. The mix of BAM contains sand, clay, and tire crumb, which are all environmentally-friendly or recyclable materials. In our study, BAM mixture is composed of 85% poorly graded sand, 10% tire crumb, and 5% clay (by volume) for both DBF and SBF (Table 1, Fig. 2). BAM mixture is potentially more capable of maintaining a faster infiltration rate for effective flood control and better performance for recharging the groundwater. Additionally, the clay content in BAM is able to keep moisture within the media longer, which is essential for the survival of the microbial community for denitrification (Hood et al., 2013; O'Reilly et al., 2014; Salamah, 2014).

Both blanket filters were designed to capture the stormwater runoff from one inlet pipe within basin 9b (Fig. 3b). In DBF there are two layers, which include depth of 0.9 m top natural soil layer

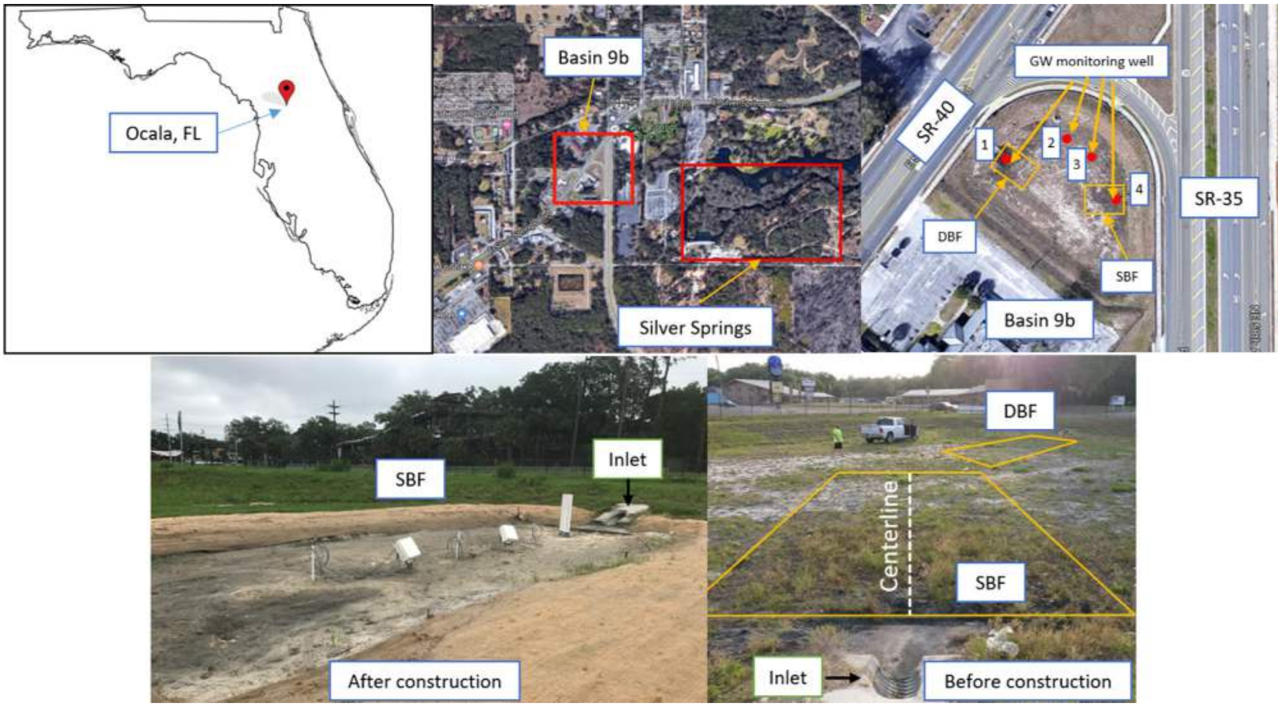

Fig. 1. Location, plan view, and land view of the study site before and after the construction of the deep blanket filter (DBF) and shallow blanket filter (SBF).

Table 1
Material characteristics for BAM and natural soil.

	BAM	Natural Soil
Density (g/cm^3)	1.39	2.36
BET Surface Area (m^2/g)	0.7059	9.3712
Porosity (%)	40.10	40.43
Hydraulic conductivity (cm/s)	0.026	0.003

and a 0.9 m depth bottom BAM layer within the same treatment area of 102 m^2. The major difference between DBF and SBF is the soil layer thickness in the vadose zone, which is 0.3 m for SBF and 0.9 m for DBF, and the potential to be invaded by the groundwater table. The excavated soil was compacted and made into a surrounding berm (not shown in the figure) to hold the runoff from the pipes and make sure the captured runoff could infiltrate through the BMP area slowly. Also, an impervious liner (ITL™ LINERS: 45 m $\times$ 0.9 m and 45 m $\times$ 1.8 m, not shown in the figure) was implemented around the vertical sides of the blanket filters to contain the water within the blanket filters to ensure treatment effectiveness for all captured runoff. Therefore, treated runoff exited through the bottom of blanket filters, at the marked BAM/soil interface (Fig. 3a). The location of lysimeters (Soilmoisture: PAN LYSIMETER, BUCKET TYPE, 19 L) for sampling vertically is shown in Fig. 3(b). Lysimeters are buckets with filter lid to collect infiltrating water through BAM, with one airline and water line that protrudes above the ground for the convenience of taking water samples. Three lysimeters were installed at the top, middle and bottom BAM layer, respectively to capture the water samples at desired depths. In each layer, three lysimeters were positioned in equal space along the blanket filters' centerline (Fig. 1). A stilling well was installed at the inlet area of each BF with a pressure transducer (TE Connectivity, TruBlue 555 Vented Level Data Logger, pressure range from 0 to 300 psi, accuracy of 0.05%, recording at 15 min intervals) to monitor the changing water level during storm events. Pressure transducers are located at the bottom of the BAM layer in the SBF and at the soil/BAM interface in the DBF. Note that the downstream groundwater monitoring well (well 2) may record the groundwater level changes outside the blanket filters that echo the water level fluctuations in the stilling well at the DBF to some extent.

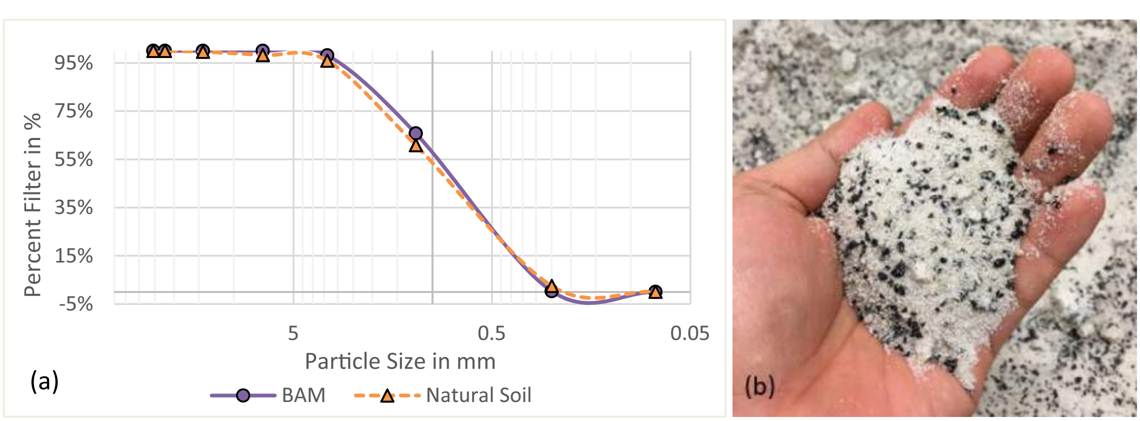

Fig. 2. (a) Particle size distribution of natural soil and BAM and (b) a picture of BAM.

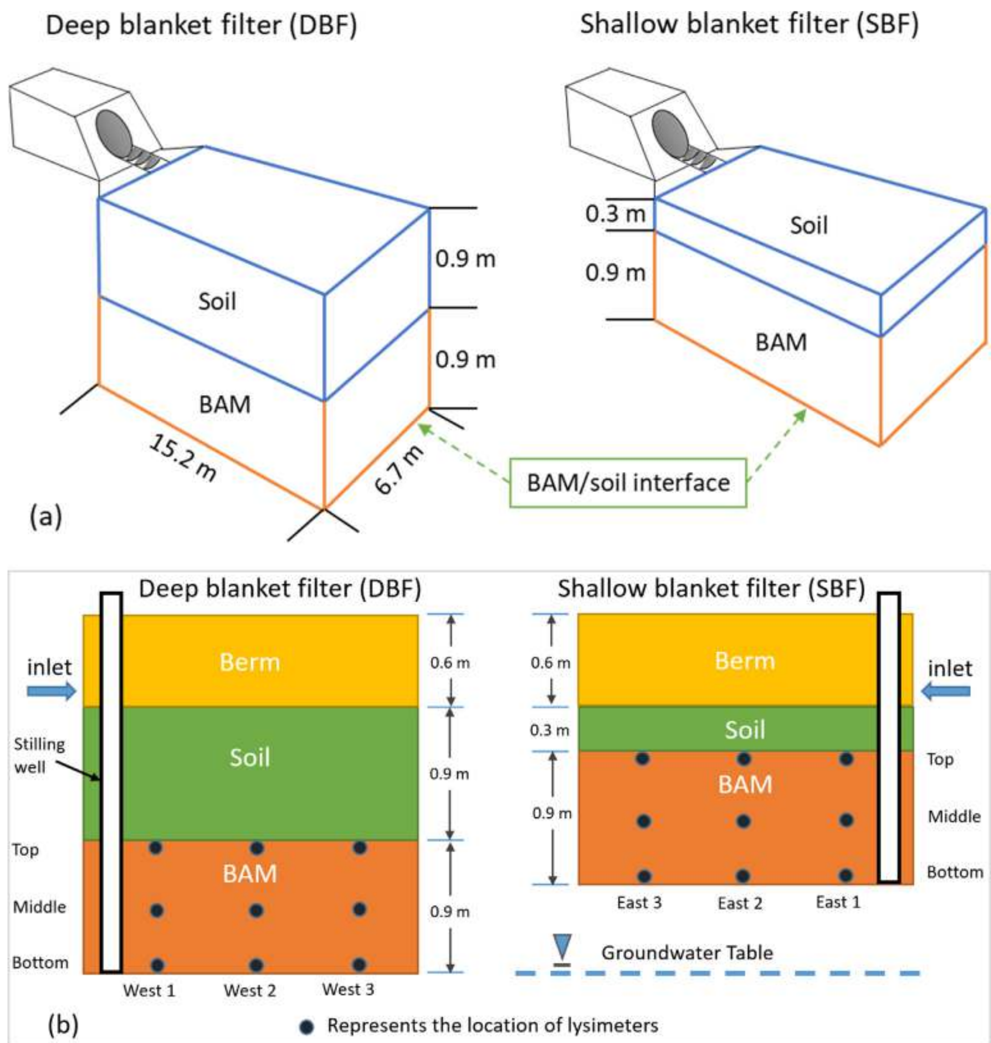

Fig. 3. (a) the design concepts and general dimensions of blanket filters in basin 9b and (b) the locations of lysimeters and the groundwater table.

2.2. Sampling and water quality measurements

2.2.1. Stormwater runoff sampling

In order to determine the pollutant load of each storm event, there is a need to take inlet water samples in regular time intervals from the start of the runoff until the end of the storm event. With such "chasing storm" efforts, the change of nutrient concentrations over the runoff time span can be realized for final assessment. In each storm event, 5 sampling time points were chosen based on the runoff condition over the entire storm duration. All water samples were taken in triplicates and preserved immediately after collection. Note that all lysimeters were evacuated before the storm events and were ready to capture the latest water samples of filtered runoff in each storm event, whether a convective storm or a frontal storm. The daily precipitation volume and temperature change over the operation time are shown in Fig. 4 with inlet

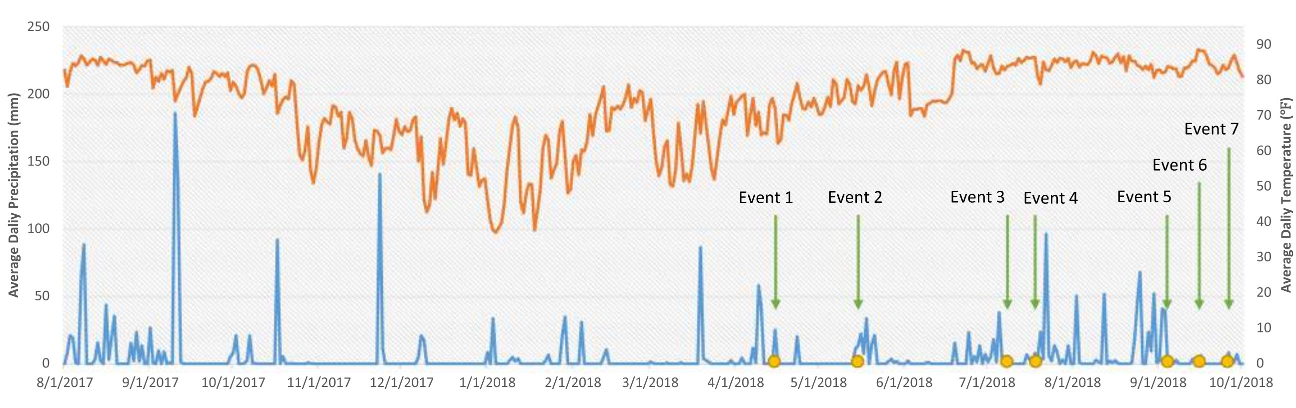

Fig. 4. Field daily precipitation volume and average temperature record over the period of operation with inlet sampling for stormwater runoff (Source: Weather Underground, Station ID: KFLOCALA105).

sampling between April and November 2018 marked as yellow dots along the timeline. However, the field campaign experienced a dry period from Oct 2018 to Apr 2019.

2.2.2. Lysimeter sampling

Water samples from lysimeters were collected 2 to 3 days after each selected storm event when all runoff could be filtered through the natural soil layer and treated within the BAM layer at each BF. All water samples were taken in triplicates and preserved for laboratory analyses. Note that both inlet samples and lysimeter samples were delivered to a certified laboratory, Environmental Research & Design, Inc., within 24 h of collection. The analyzed parameters and corresponding methods are summarized in Table 2.

2.3. Pollutant load reduction and treatability analysis

Two main factors are required in pollutant load estimation. One is the nutrient concentrations of stormwater runoff at the inlet of a stormwater dry basin in the storm event and the other is the nutrients delivered into those 3 lysimeters at each BAM layer of a blanket filter within the stormwater dry basin over the storm event. The former was obtained from the inlet manual sampling of the stormwater runoff at 5 data points as the base for calculating geometric mean concentratioin (GEC) of a storm event. The latter was collected right after a storm event from the lysimeters installed at each BAM layer of a blanket filter. The reasons for adopting the GEC are due to the heterogeneity of the field conditions, different sampling methods between the inlets and the lysimeters in the blanket filters, and the advantage of diminishing the outliers' impact in both data sets associated with the inlets and the lysimeters. Water volume information flowing into each blanket filter was retrieved from the water level changes over the storm time span in the stilling well of each blanket filter based on the pressure transducer records. As shown in Fig. 5 with an example of a recession curve that was used for calculating the hydraulic conductivity, which is applied in the combination of runoff from precipitation and the vertical flux caused by infiltration. Then the pollutant load of each storm event can be estimated based on the geometric mean concentration (GMC) and the water volume information flowing into each blanket filter. Note that the treatment systems are not in large scale, and direct precipitation and evapotranspiration are assumed negligible. It is assumed that the change of water level in the stilling well during the course of infiltration represents the water level change in the corresponding blanket filters when the surrounding media are saturated up to the water level in the stilling well. The vertical flux was calculated using Darcy's Law, based on the hydraulic gradient concept at each recorded data point with respect to the groundwater table. The media hydraulic conductivity was calculated with the recession curves recorded by the pressure transducer after each event. The cumulative

Table 2
Water quality analysis methods.

Parameters	Analysis Methods
Total Nitrogen	SM-21, Sec. 4500 N C
Nitrate + Nitrite (NO_x)	SM-21, Sec. 4500-NO3 F
Ammonia	SM-21, Sec. 4500-NH3 G
Alkalinity (lysimeter samples only)	SM-21, Sec. 2320B

†SM = Standard Methods for the Examination of Water and Wastewater, 21st Edition, 2005

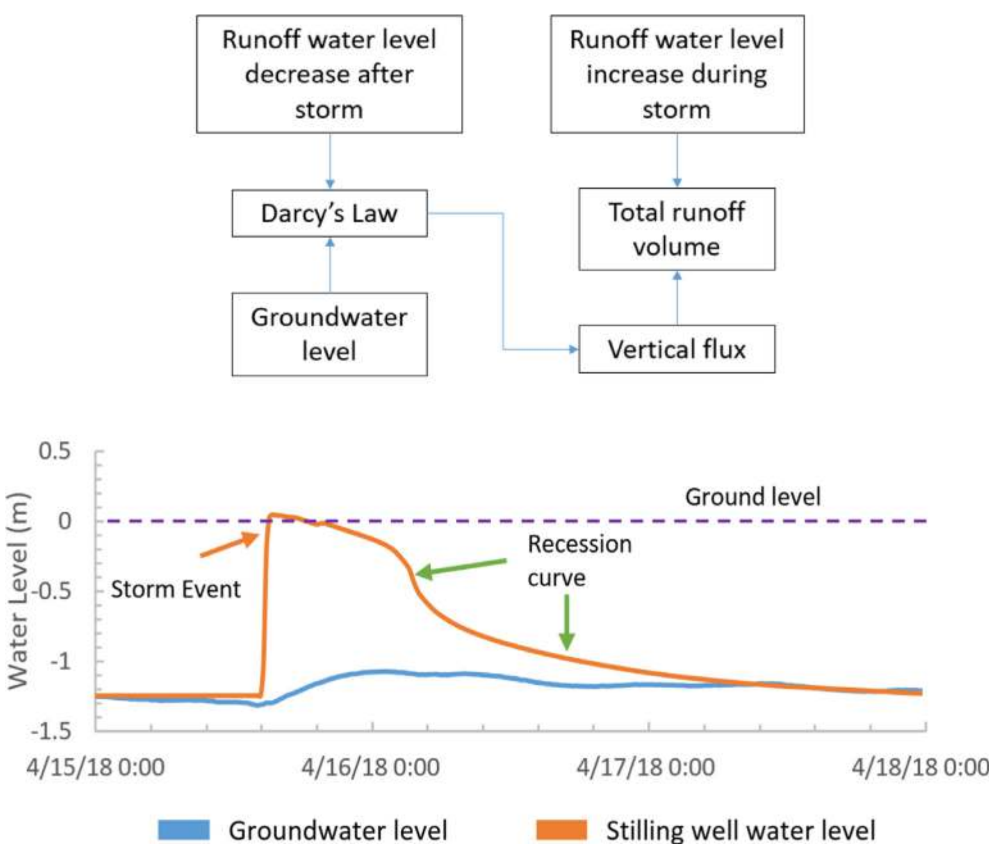

Fig. 5. The calculation flowchart for illustrating the storm runoff process and an example of the recession curve in the storm events.

nutrient removal efficiencies of the entire blanket filter treatment process can be estimated based on the GMC difference between the inlet and the bottom lysimeters.

2.4. Microbial population analysis in soil layer

Determining the gene copy number of ammonia oxidizing bacteria (AOB), nitrite oxidizing bacteria (NOB), anaerobic ammonium oxidation bacteria (annamox), and denitrifiers helps provide additional perspectives. These include the understanding of how different soil layer depths impact nutrient removal effectiveness and how the nitrification/denitrification process affects BAM performance with the aid of population dynamics of relevant microbial species. Real-Time PCR, also known as quantitative polymerase chain reaction (qPCR), is applied to analyze the microbial species within different depths of the soil layers in SBF and DBF at the Bioenvironmental Research Laboratory at University of Central Florida (UCF). The collected samples of soil were stored at −80 °C until gene extraction by using Qiagen DNeasy PowerSoil Kit, the extraction process followed the kit protocol provided by the vendor. All extracted DNA elutes were stored in *Tris-EDTA* buffer under −20 °C. The real-time PCR was performed with PowerUp™ SYBR® Green Master Mix and analyzed with StepOne software from Applied Biosystems. The primer sets and running methods utilized are described in Table 3.

2.5. Groundwater monitoring

In order to compare the groundwater quality between pre- and post-construction, multiple samples were taken from monitoring well 3 (Fig. 1) in basin 9b for the analysis of TN and NO_x. These parameters were analyzed with HACH kit (Product #: 2672245 and TNT835). The comparison of groundwater quality before and after construction is necessary for validation of the blanket filters' performance.

2.6. Analysis of variance (ANOVA)

The statistical analysis of varience (ANOVA) helps determine if there are any significant differences between the removal efficiencies for DBF and SBF due to groundwater intrusion and fluctuation. ANOVA was performed to determine statistical differences between the nutrient removals (NO_x, ammonia, and Org-N) for the DBF and SBF at each layer of BAM corresponding to lysimeter locations. The null hypothesis (H_0) states that there is no significant difference between the mean nutrient removals of each layer (top, middle and bottom) of DBF and SBF. It can be rejected when p-value < α (0.05) at a confidence level of 95%. The alternative hypothesis (H_1) states that there is a significant difference between the mean nutrient removals of each layer (top, middle and bottom) of DBF and SBF which can be accepted with the rejection of the null hypothesis.

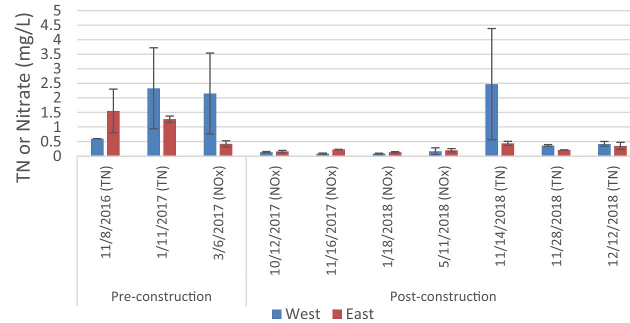

Fig. 6. Nitrogen concentration in groundwater from the West and East monitoring well *(well 2)* after one and a half years of BMP construction versus the total nitrogen concentration in groundwater before construction.

Table 4
One-way ANOVA analysis results.

Source of Variation	F	F-crit	p-value
NO_x			
Top	15.52	3.55	$1.21(10)^{-4}$
Middle	17.10	3.55	$6.88(10)^{-5}$
Bottom	7.75	3.55	$3.74(10)^{-3}$
NH_3			
Top	16.29	3.55	$9.17(10)^{-5}$
Middle	16.18	3.55	$9.51(10)^{-5}$
Bottom	8.36	3.55	$2.70(10)^{-3}$
Org-N			
Top	13.08	3.55	$3.11(10)^{-4}$
Middle	13.97	3.55	$2.58(10)^{-4}$
Bottom	14.16	3.55	$2.02(10)^{-4}$

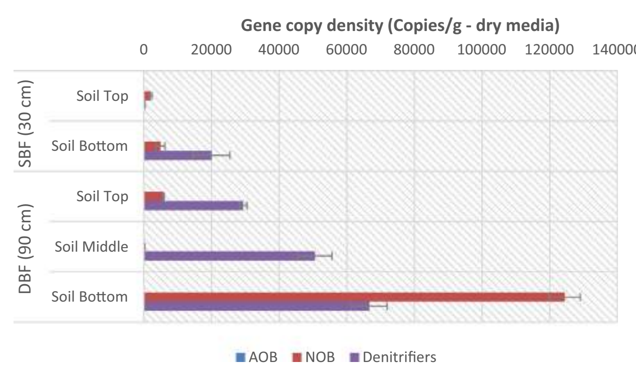

Fig. 7. The gene copy density of each bacteria at different soil layer depths in SBF and DBF.

Table 3
Primers set information and running methods in qPCR analyses.

Target bacteria	Primer name	Oligonucleotide Sequence	Running method	References
Ammonia-Oxidizing Bacteria (AOB)	amoA1F amoA-2R	GGGGTTTCTACTGGTGGT CCCCTKGSAAAGCCTTCTTC	2 min 50 °C and 95 °C; 45 cycles [15 s at 95 °C and 1 min at 62 °C]	Rotthauwe et al. (1997)
Nitrite-Oxidizing Bacteria (NOB)	NSR1113F NSR1264R	CCTGCTTTCAGTTGCTACCG GTTTGCAGCGCTTTGTACCG	2 min 50 °C and 95 °C; 45 cycles [15 s at 95 °C and 1 min at 62 °C]	Dionisi et al. (2002)
Anaerobic ammonium oxidation (Anammox)	809-F 1066-R	GCCGTAAACGATGGGCACT AACGTCTCACGACACGAGCTG	2 min 50 °C and 95 °C; 45 cycles [15 s at 95 °C and 1 min at 62 °C]	Tsushima et al. (2007)
Denitrifying bacteria	1960m2f 2050 m2	TAYGTSGGGCAGGARAAACTG CGTAGAAGAAGCTGGTGCTGTT	2 min 50 °C and 10 min for 95 °C; 40 cycles [15 s at 95 °C; 60 s at 60 °C; and 45 s at 60 °C]	López-Gutiérrez et al. (2004)

3. Results and discussion

3.1. Groundwater impact

3.1.1. Nitrogen removal under groundwater impact

The results of groundwater nitrogen concentrations in basin 9b are shown in Fig. 6 for the groundwater quality comparison of pre- and post- construction and operation of the BF. The total nitrogen and nitrate were chosen as the parameters for this comparison. The groundwater from DBF showed a 26% average TN reduction when excluding the outlier, while SBF showed a 76% average TN reduction in groundwater. The average nitrate reductions are 95% and 57% for DBF and SBF, respectively. Both blanket filters showed significant nutrient removal and improved the groundwater quality in terms of total nitrogen concentration due to the enhanced denitrification and nitrification in the BAM layer. However, the organic nitrogen might be more resistant than inorganic nitrogen and may become the main contaminant in groundwater after

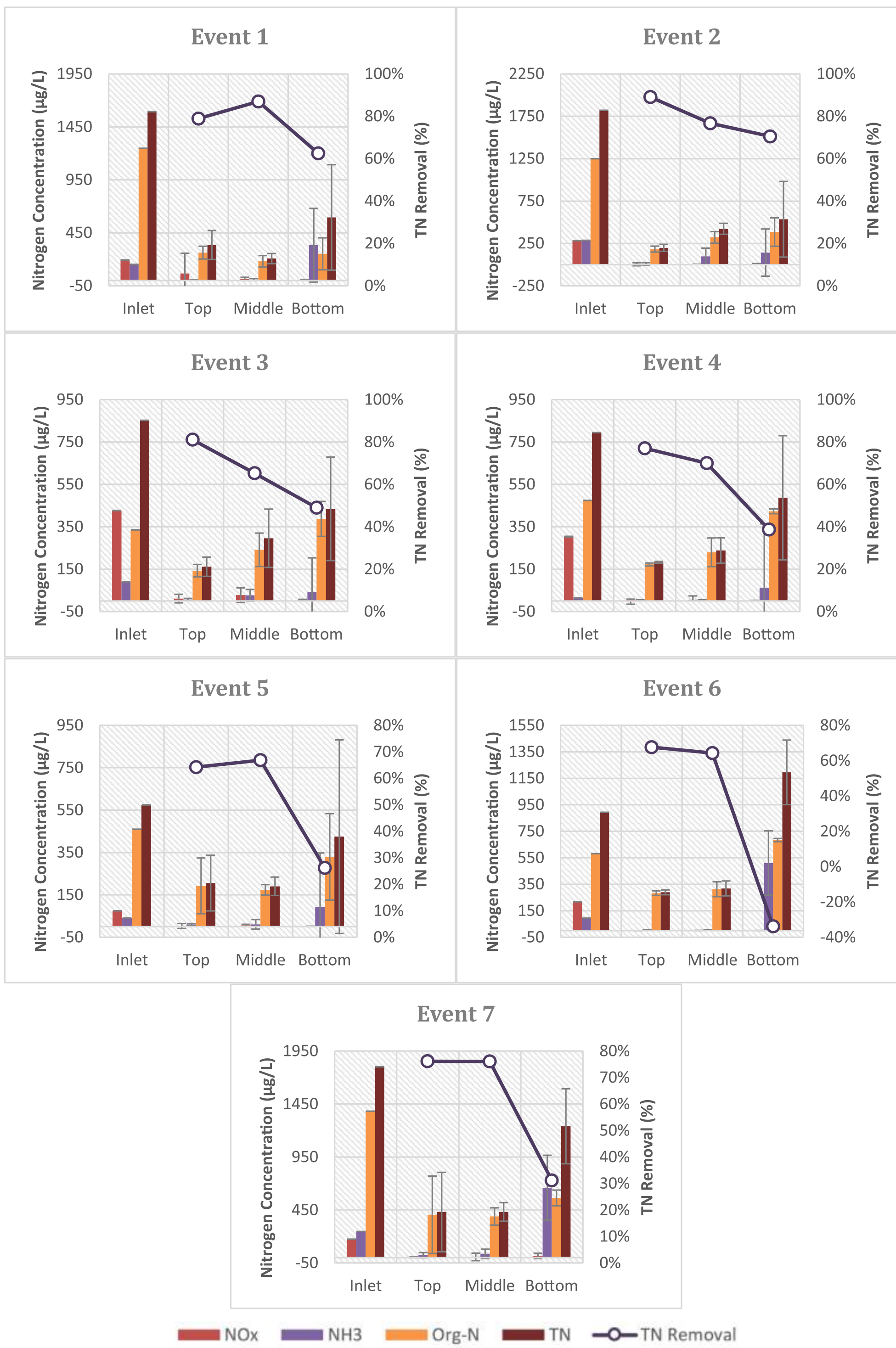

Fig. 8. NO_x, ammonia, organic nitrogen, TN event mean concentration of inlets versus lysimeter samples at different depths in the deep blanket filter (DBF) for each event with respective TN removal (Note: the inlet concentration was calculated as event mean concentration and no error bar can be applied to it.)

treatment through blanket filters, which is explained in details in the following section.

3.1.2. Statistical analysis of groundwater impact

The results from the statistical analysis (Table 4) from the *p*, *F* and *F-critical* values (Table 4) suggest the rejection of the null hyphothesis in favor of the alternative hypothesis indicating a significant difference between NO_x, ammonia and Org-N removals at each layer of BAM in the DBF and SBF. In general, all the *p-values* were less than 0.05, and the *F-value* was less *than F-critical* both indicating rejection of the null hypothesis. These results support the differences observed in the treatment efficiency and pollutant load reduction of DBF and SBF designs. Groundwater intrusion resultant from the groundwater table intruding into the lysimeters was predominant in the SBF. Inherently the DBF nutrient removal and nutrient load capacity was improved due to anaerobic conditions in comparison to the SBF.

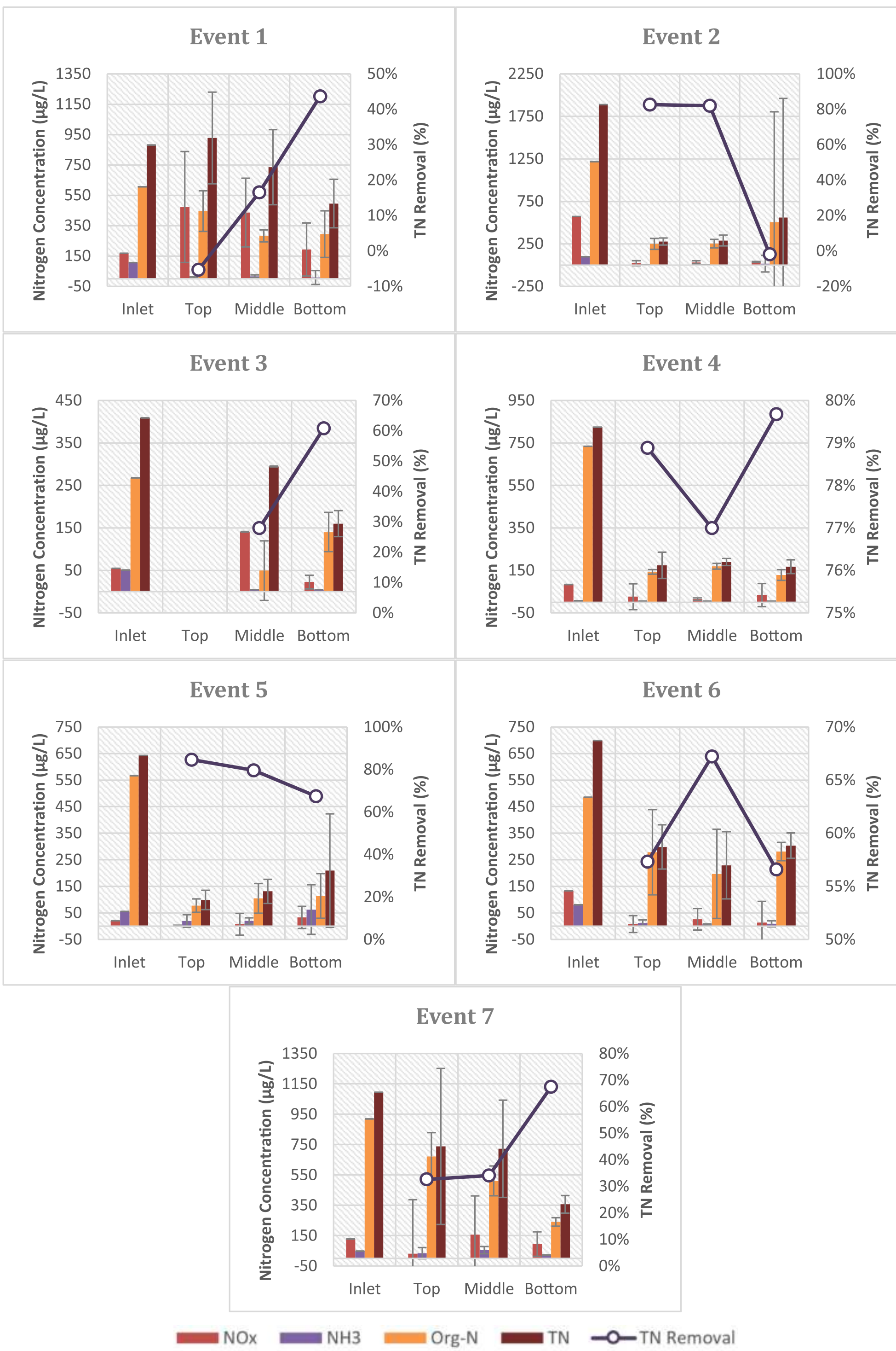

Fig. 9. NO_x, ammonia, organic nitrogen, TN event mean concentration of inlets versus lysimeter samples at different depths in the shallow blanket filter (SBF) for each event with respective TN removal (Note: the inlet concentration was calculated as event mean concentration and no error bar can be applied to it.)

3.2. Nutrient removal and pollutant load reduction

3.2.1. Nutrient removal over blanket filter layers

The inlet GMC of NO_x, ammonia, and Org-N of the 7 storm events were calculated based on the geometric mean through testing their corresponding concentraions. The GMC of organic nitrogen (Org-N) was obtained by the subtraction of the TN by the sum of NO_x and Ammonia. The results of inlet GMC, the lysimeter samples' nutrient concentration, and the TN removals are shown in Fig. 8 and Fig. 9 for DBF and SBF, respectively (inlet GMC values can be found in Appendix A). Note that the lysimeter sample values were calculated as the average value of all lysimeter data at each depth over the top, middle, and bottom BAM layer for each storm event, respectively. Significant NO_x removals at the bottom BAM layer were observed in DBF, mainly due to the fact that DBF was impacted more by the groundwater than SBF across all events (Fig. 11); the capillary effect kept the above media saturated which enhanced the anaerobic condition that benefited the denitrification as more denitrifiers could then be cultivated. For the opposite reason, the SBF showed less NO_x removal at the bottom BAM layer as more oxygen was available in the media matrix. It is noticeable that the natural soil layer also provided significant TN removal potential when comparing the GMC between the inlet and lysimeter samples, because a significant amount of bacteria, especially denitrifiers and NOB, were found at the soil layers (Fig. 7). Even the deeper depth soil layer in DBF triggers more denitrifiers, as mentioned before since the groundwater intrusion formed a better environment for them. The ammonia and Org-N concentrations increased gradually from the top to the bottom lysimeters in DBF as the downside of groundwater intrusion, which are also the main contributors to the increased TN concentration. Because no enough oxygen were available for nitrification and organic degradation. This lead to the accumulation of ammonia and organic nitrogen and eventually result in excess nutrients in the lysimeter without effective treatment (Fig. 11). The impact of these factors is also reflected by the level of TN removal from Fig. 8, which has decreased as the groundwater intrusion became more severe in the wet season (Fig. 11). Notice that even the lysimeters were emptied before the storm event for more accurate analysis, it is possible that the groundwater intrusion is a continuous process since it is normal that groundwater was observed above the lysimeter depth. However, in this study, this cumulative effect of groundwater table intruding the lysimeter was counted as part of the final concentration in the specific layer of the lysimeter.

The performance of SBF is different from that of DBF in two aspects. One is that the removal of NO_x in SBF is not as significant as that in DBF. Sometimes NO_x even increased in lysimeters when compared to the inlet GMC. This is because in some cases the groundwater table (Fig. 11) was below or close to the bottom BAM layer of SBF, which allowed more oxygen to be available for nitrification and the convertion of ammonia into NO_x in the BAM layer (Ye et al., 2012). The other difference is also caused by the mild groundwater intrusion in SBF when compared to that in DBF, as the increase of TN at the bottom lysimeter of SBF is also not as significant as that in DBF. However, the shallower depth of the natural soil layer in SBF limited the nutrient removal effectiveness in the natural soil section when compared to DBF, which is an inevitable trade-off for less groundwater intrusion; this can also be supported by the qPCR results (Fig. 7).

The pollutant load reduction can be derived from the inlet GMC and lysimeter sample results, as shown in Appendix B, for the summary of the cumulative nutrient load reduction of each water quality constituent at the top, middle, or bottom layer relative to each event's initial pollutant load. Using this reference base, the cumulative nutrient removal efficiencies of the top, middle, and bottom BAM layer are shown in Appendix C by comparing the inlet GMC with the nutrient concentrations of the top, middle, and bottom lysimeters. DBF showed much higher overall TN removal in storm events 1 and 2 with significant pollutant load reduction, but the removal efficiency decreased from storm events 3 to 7. This can be explained by looking at the groundwater fluctuation in Fig. 11. Because the groundwater intrusion at DBF was severe throughout the wet season; as a result, more nutrients from groundwater can be detected at the bottom lysimeter while less treated runoff can reach there. Hence, the deeper media depth of DBF gives it more chance of nutrient intrusion when compared to its counterpart in SBF. The variations of removal efficiencies can be further realized by taking both data presented in Appendixes B and C into account simultaneously. It is noticeable that the ammonia and Org-N are the main nitrogen species that increased in concentration at the bottom lysimeters as a result of groundwater intrusion. By analyzing the pollutant reduction among all the events, the DBF showed positive removal of 43.47 g TN, 17.68 g NO_x, 26.75 g Org-N, except NH_3 increased by 0.96 g, whereas the SBF removed 40.33 g TN, including 11.36 g NO_x and 4.49 g NH_3, and 24.30 g of Org-N. The groundwater intrusion and the soil layer difference are the main reasons for the performance differences. Even though the higher groundwater table

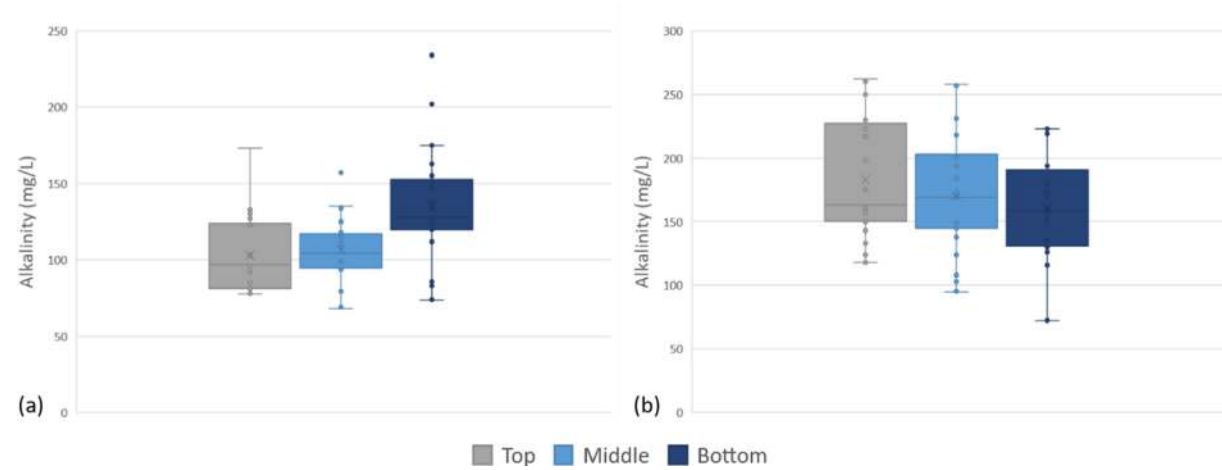

Fig. 10. The boxplot of alkalinity concentration at the top, middle, and bottom lysimeters of (a) SBF and (b) DBF (The bottom of the box means the first quartile, and the middle line and the upper boundary of the box are the second and third quartile. The "x" is the mean value. The points beyond whiskers are outliers.)

brings more Org-N and ammonia into the lysimeter, it also enhances the NO_x removal in DBF. In addition to the groundwater intrusion, the deeper depth of soil layer also provides more opportunities for the bacteria to grow and potentially enhance the ammonification and nitrification processes that produce ammonia and NO_x as the food for enhanced denitrification. SBF seems to have a more appropriate soil layer depth that keeps the groundwater intrusion away but it also has limited nutrient removal capacity due to shorter contact time for the microbial community to consume the nutrients. The cumulative nutient removal efficiencies within the two blanket filters are summarized layer by layer in Appendix C.

3.2.2. Microbial community interactions in nutrient removal

In addition to changes in nitrogen concentration, the alkalinity concentration difference between SBF and DBF also signifies their different nitrogen removal patterns (Fig. 10). One of the major differences between nitrification and denitrification is the consumption/production of hydrogen ions; nitrification produces hydrogen ions but denitrification requires hydrogen ions as one of the reactants. Water alkalinity can be impacted under the two reverse steps in the nitrogen cycle. In Fig. 10, the average alkalinity concentration in DBF is 46% higher than that in SBF, and this difference means that nitrification is more active in SBF while there is an opposite trend in DBF. As stated in previous sections, more severe groundwater intrusion in DBF triggers this phenomenon, as oxygen availability is different from the top layer to the bottom layer in the DBF and SBF for the microbes, whichhelps develop two different microbial communities.

$$NH_3 + O_2 \rightarrow NO_2^- + 3H^+ + 2e^- \quad (1)$$

$$NO_2^- + H_2O \rightarrow NO_3^- + 2H^+ + 2e^- \quad (2)$$

$$2NO_3^- + 10e^- + 12H^+ \rightarrow N_2 + 6H_2O \quad (3)$$

$$NH_3 + NO_2^- \rightarrow NO_2^- + 3H^+ + 2e^- \quad (4)$$

The coexistence of nitrification (AOB, NOB) and denitrification microbial communities in soil above the BAM layers provided initial nitrogen removal and load reduction. The microbial ecology in soil layer above the DBF and SBF differs from BAM layers due to the difference in depth, BF characteristics and groundwater intrusion as previously described. The interactions between the microorganisms in the aerobic (e.g., top layer of the DBF and SBF) and anaerobic section (e.g., the rest layers in the DBF and SBF) deliniate relationship between different types of microbial species in the transformation of nitrogen species (Fig. 12). In the nitrification pathway completed by AOB and NOB in aerobic environments ammonia is transformed into nitrite and then nitrate in a two-step process (Equations (1) and (2)). In denitrification, nitrate is utilized as an electron acceptor under anaerobic conditions and is transformed into nitrogen gas (Equation (3)). As a result denitrifiers and NOB complement each other specially in the bottom layer near the groundwater table where ammonia and Org-N are more available due to groundwater interference and limited oxygen availability. Although insufficient nitrite production by NOB may suppress denitrifier population, nitrogen can also be eliminated in a separate process achieved by anammox through the utilization of ammonia/ammonium and nitrate as an electron acceptor (Equation (4)). Competition between NOB and anammox for the utilization of nitrite occurs, although one species is aerobic and the other is anaerobic. This competion is the possible reason for anammox to be quantified as under detection limit.

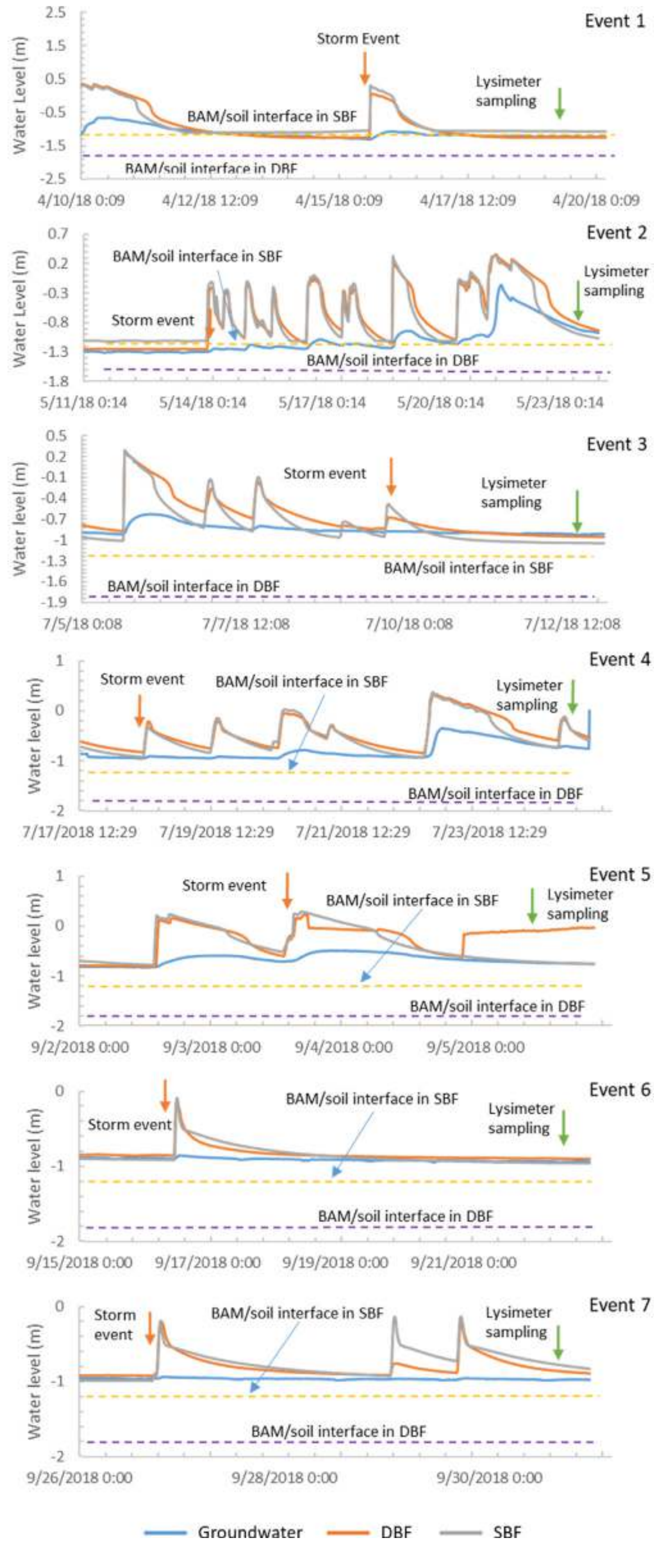

Fig. 11. Changes of groundwater depth over each storm event and lysimeter sampling time relative to the BAM/soil interface depth, as defined in Fig. 3.

3.3. Hydraulic retention time vs. nutrient removal

The hydraulic retention time (HRT) of each event with its TN removal is shown in Fig. 13. Note that the storm events 2, 4, and 7 were impacted by the next storm events before the water level in stilling well could get close to the groundwater table. The HRT

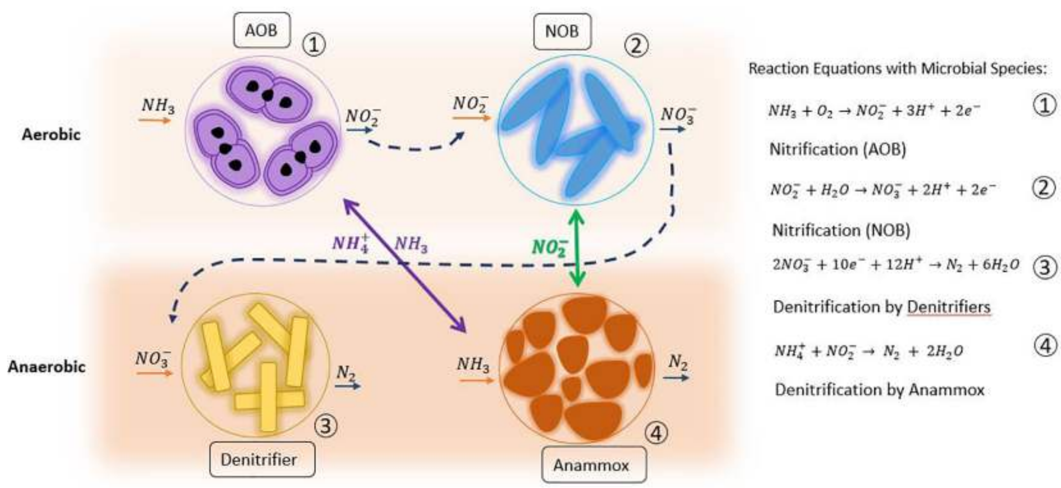

Fig. 12. Microbial community interactions in soil layers.

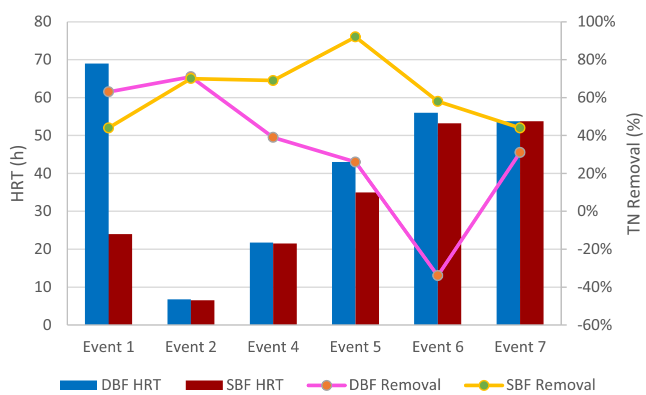

Fig. 13. The HRT and related overall TN removal for each event (HRT in event 2, 3 and 6 were shorter than it should be since another storm happened after them).

of those events was therefore calculated from the storm sampling time to the beginning of the next storm event. It is noticeable that the HRT in events 2, 4, and 7 were shorter than they would be and seem equivalent in both Blanket filters. Also, event 3 was too small to generate adequate stilling well water level fluctuation for calculating the HRT, as a result it was dropped from Fig. 13. Overall, DBF tends to show larger HRT than SBF due to its deeper depth of soil layer, as the high clay contained soil could slow down the infiltration process. For SBF the groundwater has less influence (Fig. 11), hence the TN removal of SBF is more HRT dependent because larger HRT means longer contact time for the microorganisms to remove nutrients (Fig. 13). However, the DBF performs differently when the groundwater impacts are more severe. Depending on the impact degree, nutrient removal performance is different. When the groundwater intrusion was not intensive for a longer period of time (such as events 1 and 2), the nutrient removal from the

Table 5
Comparison with previous studies regarding TN removal in field applications.

Infiltration Media	Recipe	Total Nitrogen removal	With groundwater intrusion?	Source
BAM	• 14.0% tire crumb (volume) • 26.0% clay (volume) • 59.0% sand (volume)	42.8%	No	Xuan et al. (2013)
BAM	• 10.0% tire crumb (volume) • 5.0% clay (volume) • 85.0% sand (volume)	78%	No (Linear Ditch)	Chang et al. (2019)
BAM	• 10.0% tire crumb (volume) • 5.0% clay (volume) • 85.0% sand (volume)	85%	Yes (Groundwater treatment in Linear ditch)	Chang et al. (2019)
BAM	• 10.0% tire crumb (volume) • 5.0% clay (volume) • 85.0% sand (volume)	42-51%	No (Roadside swale)	Hood et al. (2013)
BAM	• 14.0% tire crumb (volume) • 27.0% clay (volume) • 59.0% sand (volume) (1:1.9:4.1 mixture)	69%	No (Stormwater dry ponds)	O'Reilly et al. (2012)
BAM	• 10.0% sawdust (volume) • 45.0% tire crumb (volume) • 45.0% expanded clay (volume)	17-47%	No (Stormwater wet ponds)	Ryan et al. (2010)
BAM (SBF)	• 10.0% tire crumb (volume) • 5.0% clay (volume) • 85.0% sand (volume)	44% (Average at the bottom layer)	Yes	This study
BAM (DBF)	• 10.0% tire crumb (volume) • 5.0% clay (volume) • 85.0% sand (volume)	32% (Average at the bottom layer)	Yes	This study
Fine Sand	• 16.66% zeolite • 83.33% quartzitic sand (1:6 mixture)	38%	No (Infiltration basin)	Birch et al., 2005

BAM bottom layer remained consistently 47–67% TN removal no matter how the HRT changed, as the groundwater intrusion was not a major influence in that case and the microbial community had already adapted to the current environment. During the groundwater table increasing time (from event 4 to event 6), the effluent TN concentration increased at DBF; this might be caused by the additional nutrients brought by the groundwater intrusion and the disturbed microbial community as the result of a suddenly changed environment. In event 7, when the groundwater table was stable above the BAM layer in DBF for a while, even the infiltration rate was much faster and the contact time was not as sufficient as the previous case, the microbial community adapted to the new micro-environment with severe groundwater intrusion and the TN removal began to recover. Table 5 is presented to provide a comparison of nitrogen removals from previous studies and the current study in filed applications. In summary, the average TN removal in SBF reached percentages close to other similar studies utilizing BAM for roadside sawle and infiltration basin. Yet the DBF TN removal percentage was below the removals from other studies due to additional nutrient loading from groundwater intrusion.

4. Conclusion

Two BAM-based BMPs through the use of DBF and SBF were implemented in Ocala, Florida for the evaluation of nitrogen removal capacity from stormwater runoffs under the impacts of the groundwater fluctuations that affect the nitrification and denitrification patterns. Investigation of the seven selected storm events in 2018 highlighted the effectiveness of the use of blanket filters in a vadose zone at a stormwater dry retention basin in a subtropical region. The DBF nutrient removal performance is affected more by the groundwater fluctuations; fluctuations altered the oxygen availability and more denitrification was triggered in DBF to assimilate NO_x and produce nitrogen gas. In addition, the groundwater table can also affect the micro-environment and HRT for the stormwater runoff, which is also critical to the microorganisms as they control the bioactivity and contact time for microorganisms to consume nutrients. On the contrary, higher rates of nitrification are present in SBF to convert ammonia to NO_x as more oxygen is available when groundwater intrusion is less severe. With the deeper depth of the natural soil layer, significant nutrient removal, especially NO_x, was found in DBF while less removal of all nutrients except NH_3 was found in SBF. In addition, the groundwater intrusion was more severe in DBF than SBF which may potentially introduce excess nutrients into the BAM layer from the groundwater aquifer, which may be deemed as a groundwater remediation tool from a long-term perspective.

Overall, this study provides genuine engineering perspectives to understand the effectiveness of BAM applications with the involvement of groundwater. We suggest using DBF under most scenarios since it provides the best nitrate removals when compared to SBF, especially for its high efficiency in denitrification. However, SBF can also be applied in these places where ammonia might be the primary contaminant in the runoff, and stronger nitrification in SBF would be helpful to reduce the ammonia concentration before it reaches the receiving water bodies. Life cycle cost-benefit analysis for SBF and DBF may be worthwhile for future work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. The calculated inlet GMC for both blanket filters over the selected events

	DBF			SBF		
	NO_x (μg/L)	NH_3 (μg/L)	TN (μg/L)	NO_x (μg/L)	NH_3 (μg/L)	TN (μg/L)
Event 1	194	152	1594	168	107	881
Event 2	283	287	1821	572	99	1888
Event 3	426	90	852	55	51	409
Event 4	305	15	794	84	6	824
Event 5	75	40	575	21	55	642
Event 6	218	94	893	133	80	699
Event 7	173	246	1801	128	48	1094

Appendix B. The cumulative pollutant load reduction at differente depths of BAM in DBF and SBF associated with each storm and the mean removed nutrients for all selected events (unit: grams)

	Location	DBF				SBF			
		NO_x (g)	NH_3 (g)	Org-N (g)	TN (g)	NO_x (g)	NH_3 (g)	Org-N (g)	TN (g)
Event 1	Top	−12.25	−14.92	−71.15	−98.31	23.67	−12.78	−8.90	1.99
	Middle	−17.12	−14.41	−77.07	−108.60	20.84	−11.79	−17.97	−8.92
	Bottom	−17.69	18.41	−71.95	−71.22	1.94	−12.84	−17.31	−28.21
Event 2	Top	−73.79	−42.62	−127.52	−243.93	−74.13	−15.37	−138.19	−227.69
	Middle	−74.26	−28.99	−111.02	−214.27	−72.94	−15.37	−137.77	−226.08
	Bottom	−72.91	−22.12	−103.51	−198.55	−72.08	−13.40	−101.65	−187.13
Event 3	Top	−0.30	−0.05	−0.12	−0.47	N/A	N/A	N/A	N/A
	Middle	−0.28	−0.04	−0.06	−0.38	0.67	−0.54	−0.66	−1.85
	Bottom	−0.30	−0.03	0.03	−0.28	−0.17	−0.54	−0.23	−2.14

Appendix B (*continued*)

	Location	DBF				SBF			
		NO_x (g)	NH_3 (g)	Org-N (g)	TN (g)	NO_x (g)	NH_3 (g)	Org-N (g)	TN (g)
Event 4	Top	−13.18	−0.52	−8.32	−22.01	−2.69	−0.06	−8.36	−11.11
	Middle	−13.24	−0.52	−6.74	−20.50	−3.21	−0.04	−7.99	−11.24
	Bottom	−13.31	2.49	−1.41	−12.23	−2.31	−0.04	−8.58	−10.93
Event 5	Top	−2.02	−0.80	−8.64	−11.47	−0.25	−0.38	−5.71	−6.35
	Middle	−1.94	−0.78	−9.26	−11.97	−0.18	−0.39	−5.40	−5.97
	Bottom	−2.07	1.42	−4.21	−4.86	0.16	0.08	−5.29	−5.05
Event 6	Top	−9.97	−1.02	−7.63	−18.61	−6.04	−3.35	−12.00	−21.39
	Middle	−9.96	−1.02	−6.88	−17.85	−5.17	−3.63	−16.72	−25.53
	Bottom	−9.96	4.75	2.63	−2.58	−5.78	−3.49	−11.86	−21.12
Event 7	Top	−8.20	−0.97	−10.52	−19.69	−3.80	−0.62	−9.17	−13.58
	Middle	−8.00	−0.92	−10.69	−19.60	1.14	0.31	−15.16	−13.70
	Bottom	−7.53	1.80	−8.81	−14.54	−1.31	−1.21	−25.21	−27.73
Mean overall removed	Top	−17.10	−8.70	−33.41	−59.21	−10.54	−5.43	−30.39	−46.36
	Middle	−17.83	−6.67	−31.67	−56.17	−8.41	−4.49	−28.81	−41.90
	Bottom	−17.68	0.96	−26.75	−43.47	−11.36	−4.49	−24.30	−40.33

†Positive value = the pollutant load gained; negative value = the pollutant load reduced

Appendix C. The cumulative nutrient removal efficiencies at different depths of BAM in DBF and SBF associated with each storm and the mean removal for all seven storms (unit: %)

	Location	DBF				SBF			
		NO_x	NH3	Org-N	TN	NO_x	NH3	Org-N	TN
Event 1	Top	66%	97%	79%	79%	−181%	91%	26%	−5%
	Middle	92%	93%	85%	87%	−160%	84%	53%	17%
	Bottom	95%	−119%	80%	63%	−15%	92%	51%	44%
Event 2	Top	98%	97%	85%	89%	96%	95%	79%	85%
	Middle	99%	66%	74%	77%	94%	95%	79%	85%
	Bottom	97%	50%	69%	71%	93%	83%	58%	70%
Event 3	Top	97%	92%	57%	81%	N/A	N/A	N/A	N/A
	Middle	94%	70%	28%	65%	−196%	90%	82%	47%
	Bottom	98%	55%	−15%	49%	51%	90%	48%	54%
Event 4	Top	98%	66%	64%	77%	69%	69%	69%	69%
	Middle	99%	66%	52%	70%	69%	69%	69%	69%
	Bottom	99%	−318%	11%	39%	69%	69%	69%	69%
Event 5	Top	96%	75%	58%	64%	92%	92%	92%	92%
	Middle	92%	73%	62%	67%	92%	92%	92%	92%
	Bottom	98%	−132%	28%	26%	92%	92%	92%	92%
Event 6	Top	100%	95%	51%	68%	77%	79%	61%	67%
	Middle	99%	95%	46%	64%	70%	87%	70%	72%
	Bottom	99%	−443%	−18%	−34%	83%	83%	46%	58%
Event 7	Top	98%	91%	71%	76%	−136%	1%	10%	−12%
	Middle	96%	85%	72%	76%	−138%	−8%	28%	1%
	Bottom	90%	−168%	59%	31%	−55%	42%	62%	44%
Mean overall removed	Top	93%	87%	66%	76%	3%	71%	56%	49%
	Middle	96%	78%	60%	72%	−24%	73%	68%	54%
	Bottom	97%	−154%	31%	35%	45%	79%	61%	61%

†Positive value = positive removal efficiency; negative value = negative removal efficiency

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