Task 4 BMP Life-cycle Assessment Report for
Optimal Design of Stormwater Basins with Bio-Sorption Activated Media (BAM) in Karst Environments – Phase II: Field Testing of BMPs

BDV24-977-20

Principal Investigator: Dr. Kelly Kibler
University of Central Florida
4000 Central Florida Blvd.
Orlando, FL 32816-2993
Email Address: kelly.kibler@ucf.edu
Phone Number: (407) 823-4150

Project Manager: Catherine Earp
Florida Department of Transportation
Office: Roadway Design
Address: 605 Suwannee Street, MS 32, Tallahassee, FL 32399
Email Address: Catherine.Earp@dot.state.fl.us
Phone Number: (850) 414-4171

Report prepared by: Dr. Kelly M. Kibler, Dr. Ni-Bin Chang, Dr. Dan Wen, Mr. Mohammad Shokri, and Mr. Eranildo Lustoso-Alves

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Task 4 BMP Life-cycle Assessment Report
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TO: Katey Earp, FDOT

Name: Optimal Design of Stormwater Basins with Bio-Sorption Activated Media (BAM) in Karst Environments – Phase II: Field Testing of BMPs

Deliverable for Task 4: January 2019 – October 2019

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Agency number: BDV24 977-20

This project focuses on the design, development and implementation of stormwater Best Management Practices (BMPs) based on use of activated media for both stormwater treatment and groundwater protection. This is the second report on the third project deliverable, which details results of the operation, testing, and water quality sampling of the constructed BAM-based treatment alternatives for testing BMPs within two stormwater basins under different hydrogeological conditions.

Statement of Deliverable for Task 4

Upon completion of Task 4, the principal investigator will submit a written report detailing the LCA of the BAM-based treatment systems at the two stormwater basins. The principal investigator will submit this report to research.center@dot.state.fl.us.

Work Performed During This Deliverable Time Period

1. Field data quality assurance and final analysis: Roadway runoff and infiltrated stormwater sampling data were subject to quality assurance/quality control (QA/QC) procedures to ensure
that conclusions regarding BMP performance and cost effectiveness are drawn from high-quality data.

2. **Long-term nutrient removal assessment**: A life-cycle cost assessment of blanket filters and vertical reactors was undertaken to compare BMP costs and benefits over a 20- to 30-year time frame.
1. **Executive summary**

- In this Task, Life-Cycle Cost Analyses (LCCA) were completed for two stormwater BMPs: 1) blanket filters of BAM (as implemented in Basin 9b) and 2) vertical reactors of BAM and other media (as implemented in Basin 2).
- Modeling and field data were used to estimate total nitrogen (TN) and nitrate-nitrite (NO$_x$) removal through a 20-30 year BMP design life (through target years 2038 and 2048). LCCA was undertaken to compare BMP lifetime TN and NO$_x$ removal benefits to construction/operational costs.
- Due to its close proximity to the groundwater table, the West Blanket Filter (WBF) in Basin 9b experienced salient groundwater intrusion impacts during the field-testing period of 2018, while groundwater intrusion in the East Blanket Filter (EBF) was minimal. System dynamics models were formulated to simulate nitrogen removal performance of blanket filters without significant groundwater intrusion. However, we cannot draw conclusions regarding nitrogen removal efficiency of the WBF, and therefore cannot assess the lifetime nitrogen removal benefits of blanket filters persistently inundated by groundwater.
- It is estimated that through a 20- or 30-year design life, the cost of each pound of TN removed by blanket filters (a 3 ft layer of BAM placed in the vadose zone with 1 ft soil coverage) is $611-$715. It is estimated that each pound of NO$_x$ removed will cost $1,360-$1,590.
- The VR4 reactor, containing a 4 ft layer of BAM, was the optimal configuration for vertical reactors. Cost assessment of vertical reactors is based on the V4 configuration.
- It is estimated that through a 20- or 30-year design life, the cost of each pound of TN removed by vertical reactors placed in the vadose zone is $453-$498. It is estimated that each pound of NO$_x$ removed will cost $701-$732.
2. **Background**

This report presents a life-cycle cost analysis (LCCA) regarding nutrient removal efficiencies and costs of blanket filters, such as those located at Basin 9b, and vertical reactors, such as those located at Basin 2, in Ocala, FL (Figure 1). As detailed in previous reports, two biosorption activated media (BAM) blanket filters were constructed in Basin 9b, one at a depth of 0-6 ft below ground surface (West Blanket Filter, WBF) and the other 0-4 ft below ground surface (East Blanket Filter, EBF) (Figure ). The 3 ft BAM layer in the WBF was overlain by a 3 ft aerobic soil layer, while the EBF included a 1 ft soil layer. In Basin 2, six vertical reactors (VR1 to VR6) were constructed, containing different volumes of BAM (Table 1, O'Reilly et al., 2012) or Iron filings-based green environmental media (IFGEM-2) (Figure 3, Table 2, Chang et al., 2018b).

![Figure 1. Plan view and location of the Basin 9b and Basin 2 at Ocala, FL (Google, n.d. Retrieved April 21, 2019, from https://goo.gl/maps/D4epy3cLzxdk10vU6 and https://goo.gl/maps/XX1Web6FaBuVR2iTA).](https://example.com/figure1.png)
Figure 2. (a) Basin 9b WBF and EBF cross-section, (b) blanket filter plan view.
Figure 3. (c) Basin 2 reactors cross-section, (d) vertical reactor plan view.

Table 1. BAM Composition.

<table>
<thead>
<tr>
<th>BAM</th>
<th>Composition (by volume)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>59%</td>
</tr>
<tr>
<td>Silt and Clay</td>
<td>27%</td>
</tr>
<tr>
<td>Tire Crumb</td>
<td>14%</td>
</tr>
</tbody>
</table>

Source: (O'Reilly et al., 2012)
Table 2. IFGEM-2 Composition.

<table>
<thead>
<tr>
<th>IFGEM-2</th>
<th>Composition (by volume)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>80%</td>
</tr>
<tr>
<td>Tire Crumb</td>
<td>10%</td>
</tr>
<tr>
<td>Pure Clay</td>
<td>5%</td>
</tr>
<tr>
<td>Iron Filings</td>
<td>5%</td>
</tr>
</tbody>
</table>

Source: (Chang et al., 2018b)

Table 3. Volume of material used per nutrient removal technology.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Material</th>
<th>Volume (ft³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EBF</td>
<td>BAM</td>
<td>3,300</td>
</tr>
<tr>
<td>WBF</td>
<td>BAM</td>
<td>3,300</td>
</tr>
<tr>
<td>VR1</td>
<td>BAM</td>
<td>12.34</td>
</tr>
<tr>
<td>VR2</td>
<td>IFGEM - 2</td>
<td>12.34</td>
</tr>
<tr>
<td>VR3</td>
<td>IFGEM-2 / BAM</td>
<td>6.17 / 12.34</td>
</tr>
<tr>
<td>VR4</td>
<td>BAM</td>
<td>24.68</td>
</tr>
<tr>
<td>VR5</td>
<td>IFGEM - 2</td>
<td>24.68</td>
</tr>
<tr>
<td>VR6</td>
<td>IFGEM-2 / BAM</td>
<td>6.17 / 18.51</td>
</tr>
</tbody>
</table>

2.1. Data Quality Assurance/Quality Control procedures

Roadway runoff and infiltrated stormwater from multiple locations within blanket filters were sampled over 11 storm events (Events 1-11), as detailed in the Task 3b report. Data were subject to quality assurance/quality control (QA/QC) procedures to ensure that conclusions regarding blanket filter performance are drawn from high-quality data. Spurious data were identified and removed from analysis as follows.

Roadway runoff concentrations from Events 1 and 2 were found to be poorly characterized. As a result, the storm sampling methodology was amended for Events 3-11, providing a more thorough inlet concentration. Data from Events 1 and 2 should not contribute to the analysis and were removed.
During the sampling period, groundwater levels below the basin rose considerably, such that portions of the blanket filters were persistently saturated with groundwater (Figure 4). Samples collected from inundated lysimeters do not necessarily reflect stormwater that infiltrated through the blanket filters. When the groundwater table was above sampling devices, the sampling devices could fill with groundwater, rather than infiltrated stormwater. It is important to isolate and remove data that are representative of groundwater, as these samples are not indicative of blanket filter performance.

Figure 4. (a) EBF and (b) WBF relative lysimeter and potential groundwater table positions
Samples taken from lysimeters within the dark blue area of Figure 4 were likely affected by groundwater. Sample data from lysimeters within the light blue area were potentially affected by groundwater. Since there is uncertainty, additional methods of data QA/QC were applied to identify samples that contain groundwater. Considering mean trends in TN across the events, in WBF from the stormwater inlet to the bottom of the 3 ft soil layer (TOP lysimeter), TN concentration decreases by 78% (Table 4). However, TN then increases by 8% within the first 1.5 ft of BAM and by 148% in the deeper 1.5 ft of BAM. There are two possible mechanisms by which this can occur: 1) BAM is acting as a source of TN to infiltrated stormwater, or 2) there is a second source of water (groundwater) with greater TN concentration that has entered the sampling devices. The first explanation is highly unlikely. Extensive laboratory study of BAM has not indicated that BAM is a source of TN. Additionally, this trend is not observed in the EBF BAM layer. Rather, the increase in TN concentration through the WBF BAM layer indicates the growing influence of groundwater from the middle to bottom of the WBF. Event by event analysis indicates that this pattern is consistent in time, and analysis of spatial patterns confirm that all three lysimeters at each level of the WBF behaved similarly in each event. We conclude that the middle and bottom lysimeters of the WBF were persistently below the groundwater table throughout the sampling period and very likely contained groundwater. For this reason, these data should not be utilized to indicate performance of the WBF.

Similar analyses in the EBF reveal that TN concentrations drop consistently through the blanket filter for all events, with the exception of Event 9, when the groundwater table was at its highest position of the sampling period (Figure 4a). During Event 9, the sequence of TN concentration through the blanket filter is similar to what is observed in all events in the WBF (Table 4). TN concentrations drop from the inlet through the top soil layer, but then increases through the BAM layers. Again, the only plausible explanation for such occurrence is the presence of a second water source in the lower samples. We conclude that the middle and bottom lysimeters of the EBF were below the groundwater table during Event 9 and very likely contained
groundwater. For this reason, these data should not be utilized to indicate performance of the EBF and were removed from analysis accordingly.

Table 4. Mean trends in TN concentration through WBF and EBF. Positive values indicate TN removal, negative values indicate TN generation.

<table>
<thead>
<tr>
<th></th>
<th>Mean INLET TN (μg/L)</th>
<th>Mean TOP TN (μg/L)</th>
<th>Removal INLET to TOP (%)</th>
<th>Mean MIDDLE TN (μg/L)</th>
<th>Removal TOP to MIDDLE (%)</th>
<th>Mean BOTTOM TN (μg/L)</th>
<th>Removal MIDDLE to BOTTOM (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WBF mean across all Events</td>
<td>1299 μg/L</td>
<td>281 μg/L</td>
<td>78 %</td>
<td>304 μg/L</td>
<td>-8 %</td>
<td>756 μg/L</td>
<td>-148 %</td>
</tr>
<tr>
<td>EBF Event 9</td>
<td>440 μg/L</td>
<td>106 μg/L</td>
<td>76 %</td>
<td>138 μg/L</td>
<td>-30 %</td>
<td>282 μg/L</td>
<td>-104 %</td>
</tr>
<tr>
<td>EBF mean across all Events, Event 9 and Event 4 outlier removed</td>
<td>879 μg/L</td>
<td>564 μg/L</td>
<td>36 %</td>
<td>453 μg/L</td>
<td>26 %</td>
<td>301 μg/L</td>
<td>51 %</td>
</tr>
</tbody>
</table>

One sample from the EBF (Event 4, position 1, bottom lysimeter) produced an unrealistic nutrient concentration (Figure 5) well outside of the expected range. The value is a statistical outlier. It is possible that the sample was contaminated at the time of collection, or that there was an error in sample analysis. This sample should not be utilized to indicate performance of the EBF and data were removed from analysis. The other two lysimeter samples from this event and depth were used to characterize nutrient concentrations.
Figure 5: Mean TN concentration of bottom lysimeter samples in EBF through all events, plus two standard deviations. The Event 4 sample is a statistical outlier.

2.2. Nitrogen removal performance of blanket filters in the vadose zone

Following data QA/QC procedures detailed above, blanket filter performance in removing nitrogen was assessed according to the following research questions:

1. What is the nitrogen removal effectiveness of a blanket filter in the vadose zone?
2. What is the nitrogen removal effectiveness of a 1.5 ft vs. 3.0 ft BAM layer?
3. What is the nitrogen removal effectiveness of a 1.0 ft vs. 3.0 ft top soil layer?
4. How does blanket filter performance vary during small vs. moderate to large events?

2.2.1. Nitrogen removal through EBF

This section details the following research question:

1. What is the nitrogen removal effectiveness of a blanket filter in the vadose zone?
To evaluate this question, we compare nitrogen concentrations of stormwater runoff from the basin inlet to that of infiltrated stormwater that has been treated through the blanket filter (top soil layer and BAM layer, Figure 6). This question is assessed in the EBF only, since data from bottom and middle lysimeters in WBF are not available. Mean removals of TN, NO$_x$ and NH$_3$ within the EBF are above 60%.

![Figure 6](image)

Figure 6. Mean nitrogen removal after blanket filter treatment in the EBF, relative to stormwater inlet concentrations.

### 2.2.2. Nitrogen removal through a 1.5 ft vs. 3.0 ft BAM layer

This section details the following research question:

2. What is the nitrogen removal effectiveness of a 1.5 ft vs. 3.0 ft BAM layer?

To evaluate this question, we compare nitrogen concentrations of stormwater that has been treated by 1.5 ft of BAM (data from MIDDLE lysimeters) to stormwater that has been treated by 3.0 ft of BAM (data from BOTTOM lysimeters), relative to stormwater runoff entering the BAM layer (data from TOP lysimeters, Figure 7). This question is assessed in EBF only, since data from bottom and middle lysimeters in WBF are not available. This analysis indicates that a 3 ft BAM layer removes considerably more nitrogen, and particularly NO$_x$, as compared to 1.5 ft layer of BAM.
2.2.3. Nitrogen removal through 1 ft vs. 3 ft of aerobic media

This section details the following research question:

3. What is the nitrogen removal effectiveness of a 1.0 ft vs. 3.0 ft top soil layer?

To evaluate this question, we compare nitrogen concentrations of stormwater runoff from the basin inlet to infiltrated stormwater that has been treated through the top blanket filter layer of aerobic media (data from TOP lysimeters, Figure 8). In this case, the aerobic media is the sandy soil layer overlying the BAM. This question may be assessed using data from both EBF and WBF, since the top lysimeters in both BMPs were not affected by groundwater. This analysis indicates that a 3 ft soil layer may remove considerably more nitrogen as compared to a 1 ft soil layer.
Figure 8. Nitrogen removal of stormwater after treatment through 1.0 ft and 3.0 ft of aerobic media (sandy soil), relative to stormwater entering the basin. Positive values indicate removal, negative values indicate generation.

The comparison of inlet runoff to TOP lysimeter samples takes into account the entire infiltration process through top soil layers as of the time that stormwater enters the basin, which may include variable periods of surface ponding, depending on hydraulics of the event. Therefore, this analysis may not reflect only effectiveness of the soil layer, but effectiveness of surface detention plus infiltration through the soil layer. One study hypothesis was that nitrogen species may transform through aerobic media from NH$_3$ to NO$_x$. We do not see evidence of such transformation, which would likely manifest as unbalanced NH$_3$ reduction and NO$_x$ generation in this analysis. In the 1 ft soil layer we see the opposite (NH$_3$ generation and NO$_x$ reduction). In the 3 ft soil layer, removal of all species of nitrogen is so strong that transformations between inorganic nitrogen forms are difficult to detect.

2.2.4. Blanket filter performance as a function of event size

This section details the following research question:

4. How does blanket filter performance vary during small vs. moderate to large events?
To evaluate this question, we compare nitrogen removals through the entire blanket filter (comparing inlet stormwater concentrations to BOTTOM lysimeters) during small (cumulative precipitation depth < 0.1 in, cumulative runoff < 400 ft³) versus larger (cumulative precipitation depth 0.2 - 1 in, cumulative runoff 910 - 2870 ft³) runoff events. This question is assessed in EBF only, since data from bottom and middle lysimeters in WBF are not available. Though sample sizes are low, there is detectable variation in blanket filter performance related to event size (Figure 9). Removal of NOx and TN is greater in small events, while removal of NH₃ is much greater during large events.

![Figure 9](image_url)

Figure 9. Mean nitrogen removal after blanket filter treatment in the EBF, relative to stormwater inlet concentrations, for small and large events.

### 2.3. Life Cycle Cost Analysis Framework

In order to perform the Life Cycle Cost Analysis (LCCA) for 20 and 30-year time frames, conditions and assumptions must be established. Firstly, costs of BMP materials and construction were estimated (Table 4). We assume a compound interest rate of 2% per year, and cost of operation and maintenance equal to 10% of the initial construction cost. All future values were brought to present value.
Precipitation is an influential environmental factor to be considered during the prediction of nutrient removal based on the given fate and transport processes. Annual precipitation records from the past decade indicates that precipitation varies, with wet years occurring every 2 - 3 years (Figure 10). During years of high precipitation in the last 10 years (2010, 2014, 2017, and 2018) the mean annual rainfall was 63 inches per year. Mean annual precipitation was 44.2 inches during other years (2008, 2009, 2011, 2012, 2013, 2015, and 2016). Future annual precipitation predicted for Florida (Obeysekera et al. 2017) may change by ±5% and ±10% until 2040 and 2070, respectively. Assuming a 5% increase in annual precipitation before 2040 and 10% increase between 2040 and 2048, we projected future annual precipitation based on observed precipitation during the years from 2008 to 2018 (Figure11).
Figure 10. Annual precipitation observed in study area over the past 10 years. Data were obtained from stations USC00086414 and KFLPCALA105 of the National Centers for Environmental Information (NOAA) and Weather Underground PWS Data websites, respectively.

Figure 11. Projected future annual precipitation through study period.
2.4. Blanket filter LCCA

2.4.1. Model development

Dynamic models containing the interaction of variables (stocks and flows) over time (Figure 12) were utilized to assess annual nutrient removal of a blanket filter over a 20- and 30-year period. The stocks represent the amount of nutrients that exist at different depths of the blanket filter, while the flows indicate the nutrient transport at various depths (vertical flows) and the nutrient transformation from one form to another (horizontal flows). The system dynamics model used in this study was developed with Systems Thinking, Experimental Learning Laboratory with Animation (STELLA®). The proposed fate and transport processes simulate the transport and transformation of different forms of nitrogen species, including dissolved organic nitrogen (DON), ammonia (NH\textsubscript{3}), and nitrogen oxides (NO\textsubscript{x}). Concentrations of TN, NO\textsubscript{x} and NH\textsubscript{3} in samples collected from the BMPs were analyzed by a certified laboratory, Environmental Research & Design Inc. (ERD), as detailed in Task 3. DON concentration is equivalent to the TN concentration minus the sum of NO\textsubscript{x} and NH\textsubscript{3} concentrations.

As discussed above, groundwater continuously submerged the WBF. But groundwater had less impact on the EBF due to the difference in installation depths. The groundwater intrusion increased the amount of TN brought into the blanket filter. It also altered the filter environment for microbes and potentially changed the microbial community structure and ecology. We therefore are unable to model stormwater processes within the submerged WBF, and the model presented is to be applied to blanket filters located within the vadose zone (EBF). The nutrient flux from stormwater infiltration within a blanket filter is calculated via Equation 1.

\[ Q_{SW} = f \cdot C_{SW} \]  

(1)

where \( f \) is the estimated infiltration rate based on the record of stormwater level in the stilling well, \( C_{SW} \) the stormwater concentration analyzed from the lysimeter samples.
Three main nitrogen transformations were considered in this study, including ammonification, nitrification, and denitrification. The ammonification consists of the conversion of organic nitrogen to ammonium by microbes (Equations 2 and 3). The ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB) transform the ammonium to nitrate nitrogen in an aerobic environment. This transformation is called nitrification, as shown in Equations 4 and 5. The denitrifiers consume the oxygen from nitrate nitrogen to produce gaseous nitrogen through the denitrification process in an anaerobic environment, as shown in Equations 6, 7, 8, and 9.

\[
\text{NH}_2\text{CONH}_2 + \text{H}_2\text{O} \rightarrow 2\text{NH}_3 + \text{CO}_2
\]  

(1)
NH₃ + H₂O → NH₄⁺ + OH⁻  \hspace{1cm} (2)
2NH₄⁺ + 3O₂ → 2NO₂⁻ + 2H₂O + 4H⁺  \hspace{1cm} (3)
2NO₂⁻ + H₂O → 2NO₃⁻ + 2H⁺  \hspace{1cm} (4)
NO₃⁻ + 2H⁺ + 2e⁻ → NO₂⁻ + H₂O  \hspace{1cm} (5)
NO₂⁻ + 2H⁺ + e⁻ → NO + H₂O  \hspace{1cm} (6)
2NO + 2H⁺ + 2e⁻ → N₂O + H₂O  \hspace{1cm} (7)
N₂O + 2H⁺ + 2e⁻ → N₂ + H₂O  \hspace{1cm} (8)

Water and nutrient mass balances via the given infiltration process and fate and transport processes are the physical and biogeochemical bases of the proposed system dynamics model, as they are the fundamental elements for calculating the nutrient concentrations at different depths with respect to the flux of mass transfer and conversion. Differential equations in the system dynamics model describe mass flow and nitrogen transformations over the blanket filter depths. The final concentration at each depth was obtained based on the average nutrient concentrations from the three lysimeters at the corresponding depth. In relation to the biochemical transformation of nitrogen species, three main transformations were considered in this study: ammonification, nitrification, and denitrification. A previous column study using BAM media indicated a strong relation between first-order kinetics for the transformation (Chang et al., 2018a). In addition, a system dynamics model for an infiltration basin using BAM media successfully identified the first order reaction kinetics to represent nitrogen transformations (Xuan et al., 2013). Therefore, the biochemical reactions causing nitrogen transformation in the blanket filter were assumed to be first-order reaction kinetics. \[
\frac{d\text{DON}}{dt} = \frac{M_{\text{in}}}{v_{\text{in}}} \text{DON}_{\text{in}} + \frac{M_{\text{inz}}}{v_{\text{in}}} \text{DON}_{\text{inz}} - \frac{M_{\text{out}}}{v_{\text{out}}} \text{DON}_{\text{out}} - r_a
\]

(90, 11, and 12 were used to estimate DON, NH₃, and NOₓ mass fluxes in the top layer of the EBF (soil):

\[
\frac{d\text{DON}}{dt} = \frac{M_{\text{in}}}{v_{\text{in}}} \text{DON}_{\text{in}} + \frac{M_{\text{inz}}}{v_{\text{in}}} \text{DON}_{\text{inz}} - \frac{M_{\text{out}}}{v_{\text{out}}} \text{DON}_{\text{out}} - r_a
\]
\[
\frac{dNH_3}{dt} = \frac{M_{in}}{V_{in}} NH_3_{in} + \frac{M_{inz}}{V_{in}} NH_3_{inz} - \frac{M_{out}}{V_{out}} NH_3_{out} + r_a - r_n \quad (11)
\]

\[
\frac{dNO_x}{dt} = \frac{M_{in}}{V_{in}} NO_x_{in} + \frac{M_{inz}}{V_{in}} NO_x_{inz} - \frac{M_{out}}{V_{out}} NO_x_{out} + r_n - r_d \quad (12)
\]

where \( M_{in}, M_{out}, \) and \( M_{inz} \) represent the inflow, outflow, and downstream inflow mass, respectively; the \( V_{in} \) and \( V_{out} \) represent the effective inflow water volume and effective outflow water volume, respectively; \( DON_{in} \) represents the DON concentration input, and \( r_a, r_n, \) and \( r_d \) represent ammonification, nitrification, and denitrification rates, respectively. Equations 13, 14, and 15 were applied to estimate DON, NH₃, and NOₓ mass fluxes in the BAM layer of the EBF:

\[
\frac{dDON}{dt} = \frac{M_{in}}{V_{in}} DON_{in} + \frac{M_{inz}}{V_{in}} DON_{inz} - \frac{M_{out}}{V_{out}} DON_{out} - \frac{M_{outz}}{V_{out}} DON_{out} - r_a \quad (13)
\]

\[
\frac{dNH_3}{dt} = \frac{M_{in}}{V_{in}} NH_3_{in} + \frac{M_{inz}}{V_{in}} NH_3_{inz} - \frac{M_{out}}{V_{out}} NH_3_{out} - \frac{M_{outz}}{V_{out}} NH_3_{out} + r_a - r_n \quad (14)
\]

\[
\frac{dNO_x}{dt} = \frac{M_{in}}{V_{in}} NO_x_{in} + \frac{M_{inz}}{V_{in}} NO_x_{inz} - \frac{M_{out}}{V_{out}} NO_x_{out} - \frac{M_{outz}}{V_{out}} NO_x_{out} + r_n - r_d \quad (15)
\]

wherein \( M_{outz} \) refers to the upstream mass outflow from groundwater intrusion.

After the evaluation of the sampling dataset, 7 out of the 11 sampled events met the practical demands of the modeling analysis (Table 6). The events were divided into calibration and validation events (Error! Reference source not found.).

Table 6. Selected events for system dynamics modeling

<table>
<thead>
<tr>
<th>Event Date</th>
<th>Lysimeter Date</th>
<th>Antecedent Dry Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/15/2018</td>
<td>04/19/2018</td>
<td>5</td>
</tr>
<tr>
<td>05/14/2018</td>
<td>05/23/2018</td>
<td>21</td>
</tr>
<tr>
<td>07/08/2018</td>
<td>07/12/2018</td>
<td>1</td>
</tr>
<tr>
<td>07/18/2018</td>
<td>07/24/2018</td>
<td>1.5</td>
</tr>
<tr>
<td>09/03/2018</td>
<td>07/05/2018</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 7. Storm event utilized for model calibration and validation

<table>
<thead>
<tr>
<th>Calibration Events</th>
<th>Validation Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/15/2018</td>
<td>05/14/2018</td>
</tr>
<tr>
<td>09/03/2018</td>
<td>07/18/2018</td>
</tr>
<tr>
<td>09/26/2018</td>
<td>09/16/2018</td>
</tr>
</tbody>
</table>

The infiltration rate estimation is based on a semi-empirical approach through field measurements (see Appendix I) using the double ring method and pressure transducer information. The field measurements were conducted with an IN2-W Turf-Tec Infiltrometer. It provides the in-situ infiltration data for the dry and saturated blanket filter, which can be difficult to retrieve from the pressure transducer as the initial storm runoff normally happens in a short period of time. However, the pressure transducer measures the changes of the groundwater level in the stilling well, which is assumed to be the indicator of the water level within the whole blanket filter. The data from the pressure transducer can then be applied to estimate the infiltration rate after the water reaches the level below the surface of the ground using the below ground infiltration (below surface).

The infiltration simulation was divided into three stages: initial stage, where the storm runoff just starts to enter the dry blanket filter until the water level reaches the maximum; saturation stage, when the water level reaches the maximum in the blanket filter until it drops below the ground surface; and the below ground infiltration stage, which is the phase after the water level decreases below the ground level (Table 8). An example of this approach is shown in Figure 14, where the below ground infiltration rate tends to exhibit a linear relationship with the water depth. The volume of infiltrated stormwater was calculated by multiplying the water level change by the area of the blanket filter and the BAM media porosity. According to the volumetric water
content sensor installed in each layer in the blanket filters, the volumetric water content shows a 15-minute interval between soil saturation of the top, middle and bottom of the BAM layer (Figure ). This 15-minute interval was applied as the time lag of the infiltration rate from the top to bottom layers in the system dynamics model.

Figure 13. Infiltration rate over changing depths.

Table 8. Infiltration rates formulae.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Infiltration rate formula (m³/15 min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial infiltration (above surface)</td>
<td>( Q(t) = 0.025 \times A )</td>
</tr>
<tr>
<td>Saturated infiltration (above surface)</td>
<td>( Q(t) = 0.006 \times A )</td>
</tr>
<tr>
<td>Below ground infiltration (below surface)</td>
<td>( Q(x, t) = \Delta h(x(t)) \times A \times \theta )</td>
</tr>
</tbody>
</table>
The model calibration process consisted of adjustment to reaction rate values for ammonification, nitrification, and denitrification (final parameter values given in Table 11), while the validation consisted of the confirmation of calibrated parameters (Figure 15).

Table 5. Calibrated reaction rates for ammonification, nitrification, and denitrification in the EBF as compared to literature values using first order kinetics.

<table>
<thead>
<tr>
<th>Unit</th>
<th>$k_a$ (ammonification)</th>
<th>$k_n$ (nitrification)</th>
<th>$k_d$ (denitrification)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top of BAM</td>
<td>day$^{-1}$</td>
<td>0.096</td>
<td>0.096</td>
</tr>
<tr>
<td>Middle of BAM</td>
<td>day$^{-1}$</td>
<td>11.040</td>
<td>37.728</td>
</tr>
<tr>
<td>Bottom of BAM</td>
<td>day$^{-1}$</td>
<td>0.960</td>
<td>2.112</td>
</tr>
<tr>
<td>Literature values$^\dagger$</td>
<td>day$^{-1}$</td>
<td>0.05 to 2</td>
<td>0.2 to 2</td>
</tr>
</tbody>
</table>

$^\dagger$(Xuan et al., 2013)
Figure 15. Correlation between simulated and measured concentrations of nitrogen species in a) model calibration and b) model validation.

2.4.2. LCCA for Nitrogen removal

After model calibration and validation, the dynamic model was simulated using 2018 field data collected from the selected storm events with on-site measurements using pressure transducers and lysimeters. The 2018 scenario was projected to estimate and compare the amount of monthly input and output of nitrogen in EBF (Figure 3 and 17). The cost per pound TN and NO\textsubscript{x} removed for the 20- and 30-year scenarios were calculated (Table 12), assuming that nitrogen loading is similar to 2018, with the exception of precipitation which, as described above, is scaled for potential nonstationarity of climate.
Figure 3. Monthly estimated TN pollutant load in 2018 (a) coming into and leaving EBF and (b) estimated TN removal.

Figure 4. Monthly estimated pollutant load per nitrogen species in 2018 coming into and leaving EBF.
Table 6. Lifetime cost per pound TN and NOx removal from EBF after 20- and 30-year design life

<table>
<thead>
<tr>
<th></th>
<th>2038</th>
<th>2048</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost per pound TN</td>
<td>$715 ± $27</td>
<td>$611 ± $23</td>
</tr>
<tr>
<td>removal ($/lb)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost per pound NOx</td>
<td>$1,590 ± $61</td>
<td>$1,360 ± $52</td>
</tr>
<tr>
<td>removal ($/lb)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.5. Vertical reactor LCCA

The LCCA for vertical reactors in Basin 2 was completed based on the nitrogen removal performance documented by field sampling (see Task 3 report), followed by the calculation of the expected nutrient removal over 20- and 30-year periods. Monthly stormwater runoff to Basin 2 in the year 2018 was estimated by multiplying the total directly connected impervious areas (DCIA) draining to Basin 2 (220×10³ ft² (20×10³ m²) or 5.02 ac (2.03 ha)) by the 2018 precipitation. However, the vertical reactors in this study were not sized to treat all runoff to Basin 2. Capture efficiency of the vertical reactors was found to be approximately 0.2% of the stormwater runoff from the DCIA (see Task 3 report). Therefore, the volume of stormwater entering the vertical reactor for treatment was adjusted accordingly. It was assumed that runoff was partitioned equally into the 6 reactors. The most promising reactor configuration (VR4, consisting of 4 ft of BAM, Figure 5, based on highest and most consistent nitrogen removal performance, was selected for further cost analysis. Similar to the blanket filters analysis, a compound interest rate of 2% per year was assumed, and 10% of the initial construction cost was assumed as annual operation and maintenance cost. All costs to be incurred in the future were converted to present values. The cost per pound TN and NOx removed for the 20- and 30-year scenarios were calculated (Table 13), assuming that nitrogen loading is similar to 2018, with the exception of precipitation which, as described above, is scaled for potential nonstationarity of climate.
Figure 58. Estimated total nitrogen pollutant load coming into and out of VR4 in 2018.
Figure 6. Estimated pollutant load per nitrogen species coming into and out of VR4 in 2018.

Table 7. Lifetime cost per pound TN and NOx removal from vertical reactor after 20- and 30-year design life

<table>
<thead>
<tr>
<th></th>
<th>2038</th>
<th>2048</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost per pound TN removal ($/lb)</td>
<td>498 ± $25</td>
<td>453 ± $23</td>
</tr>
<tr>
<td>Cost per pound NOx removal ($/lb)</td>
<td>$732 ± $37</td>
<td>$701 ± $35</td>
</tr>
</tbody>
</table>
References


Appendix I

Table A. On-site infiltration measurements using IN2-W Turf-Tec Infiltrometer.

<table>
<thead>
<tr>
<th>Non-saturated infiltration (above surface) in mm per 15 min</th>
<th>Saturated infiltration EBF (above surface) in mm per 15 min</th>
<th>Saturated infiltration WBF (above surface) in mm per 15 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.0</td>
<td>6.0</td>
<td>12</td>
</tr>
<tr>
<td>6.5</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>6.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>25.0</td>
<td>6.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.5</td>
</tr>
</tbody>
</table>
Work To Be Performed in the Next Deliverable Time Period (before January 2019)

1. Draft final report.

Requested Modifications

None.

Research Impediments

None.

Respectfully Submitted,

Kelly M. Kibler, Ph.D.