Floating Treatment Wetland Testing and Optimization

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Abstract

Stormwater basins are widely used in the United States for management of urban runoff; however, poor design and/or lack of maintenance can cause performance to be inconsistent. Further, due to the increase in impervious surfaces, urban runoff contains higher levels of chronic pollutants, including phosphorus, nitrogen, and sediment. A floating treatment wetland (FTW) is an increasingly popular bioremediation practice that can be retrofitted into a stormwater basin to reduce pollutants by sustainable and inexpensive means. However, due to the number of confounding variables that exist in nature, it is difficult to assess the effectiveness of FTW applications at the field scale and across the range of environmental conditions. Most studies have been performed in controlled experimental systems called mesocosms so that the environmental conditions can be controlled as much as possible. While this method may save more time and money than full-scale testing, these studies rarely account for the typical hydraulic design of a stormwater basin, which can involve a permanent pool of water and a dynamic pool dependent on inflow and outflow characteristics. This project aimed to develop a system of small-scale, hydraulically accurate representations of stormwater basins within a controlled setting so that FTWs could be tested and optimized for stormwater basin applications. A target flow rate of 740 mL min⁻¹ and an outflow rate of 372 mL min⁻¹ at each mesocosm was selected to mimic a designed storm of 6 hours and a drawdown of 12 hours. Measurements taken during test runs showed an average inflow rate of 830 mL min⁻¹ (standard error +/- 230 mL min⁻¹) across all mesocosms. Outflow collection deviated less than 3% from targets. The project objective was achieved as demonstrated by a fully operational system of 12 mesocosms that can be used to test two critical FTW design parameters (surface area coverage and recirculation impacts) under hydraulically-accurate flow conditions for stormwater basin applications.

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1. Introduction

As a result of an increase in impervious surfaces, large volumes of water that cannot infiltrate must flow across the surface, collecting sediment, nutrients, and other pollutants. This runoff is commonly referred to as urban stormwater. Managing this stormwater is critical in preventing flooding, minimizing sanitary sewer overflows, and limiting erosion in local streams or rivers. A common method for controlling the flow of stormwater is the use of basins, which are best management practices that capture water and then release it at a desired rate (McAndrew, Ahn, & Spooner, 2016). For the purposes of this project, the general term “stormwater basin” will be used to represent the target design condition, which is a wet pond application. Wet ponds are designed for stormwater retention and treatment, and involve an inflow, an outflow, and a permanent pool (Leber, 2015). Stormwater basins are often lined with macrophytes that aid in pollution reduction, but the water level may change rapidly, leaving the plants without sufficient access to water. Further, if sediment and debris are not regularly removed to prevent the outflow orifice from becoming clogged, the basins will not function properly and can be very expensive to repair. Because of these reasons, pollutants may rise to dangerous levels. Nitrogen, phosphorus, and sediment have been identified by the Environmental Protection Agency as chronic pollutants seen in stormwater basins (EPA, 1983). High concentrations of the nutrients nitrogen and phosphorus can cause what are collectively known as harmful algae blooms, or HABs. Sediment is also a pollutant of concern, as large particles can clog pipes and contribute to flooding, while finer particles that remain suspended carry pathogens and nutrients. These fine, suspended particles are measured as total suspended solids (TSS).

A floating treatment wetland (FTW) is a stormwater control measure that employs bioremediation, through the natural processes of plant root uptake and microbial degradation of pollutants, to provide a sustainable and cost-effective solution to contaminated urban runoff, as seen in figure 1. Main components of a FTW include a buoyant support structure, native wetland plants, and an anchor system. The various treatment processes of FTWs are complex; therefore, monitoring the effect of a full-scale FTW is difficult to do in situ, and can be expensive should the design fail or it is not properly maintained. Mesocosms are constructed model ecosystems used to monitor the natural environment under controlled conditions (Kangas & Adey, 2008). Most studies only incorporate batch-loading of contaminated water (Spangler et al., 2019, Colares et al., 2020) and do not account for the typical hydraulic design of a stormwater basin, which involves a dynamic pool elevation, inflow, and outflow.
Figure 1. Components of a stormwater basin and the role of a FTW.

In this project, we aimed to develop an experimental infrastructure with the capacity to conduct hydraulically-accurate simulated events within a controlled setting so that FTW design parameters could be more readily tested and optimized. Examples of specific FTW design questions this system could answer are how surface area coverage of the FTW and the incorporation of a recirculation pump impact water treatment. The decision to pilot a test of optimal surface area coverage percentage, which is defined as the ratio of FTW area to the surface area of the body of water, stems from an already existing coverage recommendation from the Chesapeake Storm Water district (Lane, 2016). This study recommends at least 10% of the pond surface must be covered by the FTW to improve nutrient and sediment removal functions, and at most 50% of the surface area should be covered in order to not detract from the pond performance. Such a large range in size can have significant impacts on costs. This is the type of problem where full scale testing of this parameter would be difficult that this system aims to address. Specific objectives of this project include the following: 1) design and test a scaled mesocosm system that will mimic movement in a stormwater basin by transporting contaminants at controlled inflow and outflow rates; 2) develop a pilot system that could be used to research optimal surface area coverage for reduction of pollutants, as well as the treatment impact of a recirculation pump; and 3) consider full-scale deployment parameters in the design of the scaled model.

2. Materials and Methods

2.1. System Overview

The mesocosms were located in a greenhouse at the East Tennessee AgResearch and Education Center Plant Science Unit in Knoxville, Tennessee. The overall system, as seen in figure 2, was conceptualized with three main components: first, the basins which consisted of variable floating wetland size with a native plant palate; second, an inflow manifold that would deliver a simulated stormwater
solution; and third, an outflow system. When designing the small-scale stormwater basin system, the main design components of a FTW were considered so that the designed system could ultimately be used to test treatment success of a FTW and other practices.

Figure 2. Twelve mesocosms, the inflow manifold, and outflow sample collection containers.

The inflow and outflow components of the design in conjunction create what is defined as “storm events” in order to mimic a stormwater basin more accurately than batch mesocosm studies. Testing utilized an inflow of 284 gallons over 6 hours, which results in a rate of 790 mL min⁻¹. Similarly, outflow of 284 gallons occurred over 12 hours, resulting in a 395 mL min⁻¹ rate. These events will occur once per week, while the remaining 6 days consist of static time. A hydrograph of this event can be seen in figure 3. The controls of the system are structured so that these flow rates can easily be altered to result in a different hydrograph.

Figure 3. Event Hydrograph of Simulated Storm Event
2.2. Basin Selection

A 568-liter Rubbermaid® stock tank was selected to create the mesocosm basin, as it provides a representation of a stormwater basin with regards to sizing design standards. Knox County Stormwater Management Manual designates a minimum length to width ratio for a stormwater pond to be 1.5:1 (Stormwater Ponds, 2008). In accordance with this standard, the dimensions of the selected stock tank for length and width are 147.3 and 99.0 centimeters, respectively. The recommended water depth is 1.2 to 1.5 meters so that the plants cannot root into sediment and cause the FTW to be submerged when the water level rises (Sample, et. al., 2013). While the basin is only 0.6 meters deep, this problem is beyond the scope of this project’s parameters, as there is no sediment within the basin. Knox County Stormwater Management Manual also recommends a permanent pool volume for a standard wet pond to be 100% of the volume of water treated. Therefore, within the 568-liter tank, the water treatment volume and permanent pool volume are 264 L each. In order to determine the depth of the permanent pool, a stage-storage curve was created using measurements of depths taken at increments of 19 L. This curve was used to extract an equation representative of the volume of water within the basin at any depth. Each mesocosm had a platform support system that was made from 2x4-inch nominal lumber, a sheet of \(\frac{1}{2}\)-inch plywood, and concrete blocks. These platforms needed to be able to support up to approximately 544 kg, the total mass of the basin when completely filled.

2.3. Inflow Manifold System

A 6-h inflow period was selected to represent a 24-h scaled down storm event. Each mesocosm was filled simultaneously at a continuous inflow rate, which raised the mesocosm water level from permanent pool to the top of the basin. A flow rate of 790 mL min\(^{-1}\) was required per mesocosm to fill each tank with the needed 284 L storm volume. The manifold was aligned along two rows of six mesocosms in the greenhouse, as shown in figure 1. Materials included \(\frac{1}{2}\)-inch and \(\frac{3}{4}\)-inch PVC pipes with flow controlled by orifices above each mesocosm, as displayed in figure 2.

Friction components were calculated using equation one, and were completed using \(\frac{1}{2}\)-inch nominal diameter PVC pipe to verify that there would be enough pressure to deliver the correct volume of water to each mesocosm (Uni-Bell PVC Pipe Association, 2012). The minor frictional losses were calculated using

\[
\text{minor loss} = K \times (v^2 / 2g)
\]

where,

\[
\begin{align*}
K &= \text{loss coefficient (unitless)} \\
v &= \text{velocity (ft s}^{-1}\text{)} \\
g &= \text{gravity (ft s}^{-2}\text{)}.
\end{align*}
\]
The frictional losses were determined to be 0.53 ft, which was added to the static head of this system. The static head was calculated using the height above the ground, 3.25 ft, and dividing it by 2.31 ft of head per 1.0 psi to get 1.4 ft of head loss. Combining the frictional losses and the static head results in a total of 1.93. Once the frictional losses were determined, they were used to calculate the size of the orifice required to reach the desired outflow of 0.79 L min⁻¹ per mesocosm. Using the orifice equation,

\[ Q = C_d \times A \sqrt{2gh} \]  

(2)

where,
- \( Q \) = flow rate (ft³ s⁻¹)
- \( C_d \) = coefficient of discharge (unitless)
- \( A \) = cross-section area (ft²)
- \( g \) = gravitational acceleration (ft s⁻²)
- \( h \) = head (ft)

it was determined that an orifice of 1.5 mm is required for the proper function of the system. Furthermore, calculations were completed using the frictional losses, pipe sizes, and orifice size to determine what pressure this water source needed to provide to achieve the desired outflow rate. A pressure of 8 psi was determined from the total loss of 1.93 psi that the system must overcome. This pressure was sufficient in producing the target flow rate from each orifice. To control the flow rate, a gate valve and pressure gage were installed to allow adjustments to the inflow from the water source. These components are shown in figure 4 portions a and b.

![Figure 4. Flow rate control set-up with (a) gate valve, (b) pressure gage, and (c) injection location.](image)

In addition to the inflow rate of water, an injection system for synthetic stormwater was incorporated into the design of the inflow manifold. For the injection to achieve its purpose of evenly distributing nutrients among all mesocosms simultaneously, the solution must be well-mixed within the manifold. The calculated flow characteristics, Reynold’s number of greater than 20,000, showed the flow to be turbulent, indicating that flow in the manifold was well-mixed resulting in an even distribution to the mesocosms. The pump used, shown in figure 4 part c, was a Flojet Model 2100-12 Type IV that operated on 12 VDC. It was controlled by a timer and set to inject the concentrated solution directly into the inflow stream, depicted in part c of figure 3. The pump was cycled on for 6 seconds and off for 60
seconds over the course of 6 hours. This timing was calculated using the flow rate of the pump, 2.3 gpm, and the volume of concentrated solution, 50 gallons, to deliver the correct amount of nutrients during the 6-hour time period. It was controlled by the timers found in the electrical box in part b of figure 5. A 120V source was converted to 12V to power the timer and relay, when the relay was closed the pump would turn on and when the relay was open, the pump would go off.

![Image of injection system setup](image)

**Figure 5. Injector system set-up including (a) tank for synthetic stormwater concentrate solution, (b) electrical control box, (c) pump for injection.**

A stage storage curve was made for the injection tank so that delivery of simulated stormwater could be readily monitored. This provided a depth to fill the tank with the appropriate volume of concentrate needed for the simulated stormwater.

### 2.4. Outflow System

An outflow system simulated a 12-h drawdown period immediately following inflow and created the capacity for composite sampling. The water level was drawn down from full volume (568 L) to the permanent pool volume (284 L) at a desired outflow rate of 394 mL min⁻¹. The system implemented had three unique components as seen in figure 6: a peristaltic pump, a three way valve, and a collection bucket. The Joyoya peristaltic pump runs on a 12VDC power source, at a true setting value of 10.76 V-DC. This allows the water to be removed at a rate of 372 mL min⁻¹. This value was determined adequate in comparison to the desired and results in a true outflow period of 12 hours and 45 minutes approximately.

The pumps drew water from within the mesocosm 2.50 cm below the permanent pool level, which occurred at 30 cm, and directed it to a three-way 24 VAC mechanical valve which acts as an
automatic sampler for the system. The valve was controlled by an electronic timer which dictated when power was supplied, thus controlling the sample collection rate. When power was not supplied to the valve, water was discharged to the ground as waste. When the valve was powered, water was collected in a 19-L sample bucket for analyses. Electrical control boxes housed and protected the controls as seen in figure 7. These boxes consist of I) the 12 VDC source, II) the 24 VAC transformer, and III) the timer controlling the 3 way valve. In order to supply sufficient power, each side in the greenhouse has its own control box. A challenge with this project ensuring that the outflow sample represented the change in concentration of the outflow in the 12 hour period. The timer allows for the rate of sampling to be uniform over time, thus if the sample is well mixed, it is assumed it is a representative sample.

Figure 6. Components of the outflow system including a) peristaltic pump, b) timer, c) captured volume. Figure 7. Inside of the outflow electrical control box.

2.5. Raft Structure and Materials

The two FTW design parameters selected to pilot were basin surface area coverage and the implementation of a recirculation pump. Surface area coverages of 10%, 30% and 50% were chosen for testing because they fell into the 10-50% coverage range recommended by the Chesapeake Storm Water district (Chesapeake Stormwater Network, 2018). These percentages included both extremes as well as the middle of that range. Three replications were used to account for variability. The raft is made from a nonwoven polyester fiber material, called *Americo FM JCII Cream* (Americo Manufacturing Company, Inc., 6224 N. Main St. Acworth, GA), that is light in weight, durable, and permeable enough for plant roots to penetrate. Each raft was composed of three layers of 2-inch thick sheets of the fiber material that were secured together with zip ties, as seen in figure 8.
Figure 8. FTW raft structure with penetrating root system and secured flotation material. In figure 9, the smallest sized raft is 23.5x46.9 cm and covers 10% of the surface area of water within the mesocosm. The medium raft is 40.6x54.9 cm and covers 30%, and the large raft is 52.1x104.1 cm and covers 50% of the surface area.

Figure 9. From left to right, the 10%, 30%, and 50% coverage rafts within the basins. Photographs taken on 30 March, 2020, 32 days after plants were incorporated.

To keep the rafts buoyant, flotation was added to each of the rafts based on their respective mass of water displaced. The plants were placed in each raft and weighed with a hanging scale. The weight of each raft was used to determine the amount of floatation needed. From smallest to largest the rafts weigh 1.27, 2.27, 3.81 kg. Polystyrene with a density of 45 kg m$^{-3}$ was then attached to the sides and bottom of each raft using plastic cable ties. The polystyrene strips were chosen over more traditional methods
because they provide a cost effective alternative and allow each raft to maintain the surface area coverage within the tank without added bulk.

2.6. **Plant Selection**

The National Resource Conservation Service (NRCS) provides an extensive list of wetland plants according to native range in the United States (NRCS, 2019). From this list, the following plants were selected due to their availability and their documented performance in the literature: softstem bulrush (*Schoenoplectus tabernaemontani*), marsh hibiscus (*Hibiscus moscheutos*), and hop sedge (*Carex lupuliformis*). This selection provides the project with a variety of plants that would commonly be found in a naturally occurring wetland and have shown a significant decrease in nutrient pollution in literature. The ratio of plants was kept consistent between rafts where the marsh hibiscus occupies 20% and the hop sedge and soft stem bulrush each occupy 40% of the raft. The plant layout for each size raft can be seen below in figure 10.

![Plant Layout](image)

**Figure 10. An overview of the plant layout on a 10%, 30%, and 50% surface area coverage raft depicting plant species layout.**

2.7. **Recirculation Pump**

An Aquascape 70 GPH Statuary Pump was used to relocate water from within the mesocosm to the top of the FTW. The pump was attached to ¼-inch nominal inner diameter PVC tubing that drew the water from inside the mesocosm and distributed it over the top of the FTW for additional filtration provided by the porous rooting media shown in figure 11. Each pump moves 5% of the treatment volume in a one-hour period, which is equivalent to treating the entire basin within one day. This amount was chosen to keep the treatment volume consistent between mesocosms. The plastic tubing was placed on top
of the raft and woven between the rows of plants. A 1.5-mm biopsy punch was used to create consistent orifices for water to escape along the length of the tubing. The smallest raft had a total of 72 cm of plastic tubing and the holes were placed 10 cm apart. The tubing along the medium raft was 146 cm long and contained holes that were 20 cm apart, and the largest was 356 cm with holes 30 cm apart. Each recirculation pump is powered through an analog timer that allows the pump to be signalled on and off. The pumps are on for 30 minutes for every 90 minutes off. Although the loading rates are inconsistent for each raft size, the timer combined with the ratio of orifices to the length of tubing created a consistent treatment rate.

![Image of raft with tubing and pump](image.png)

**Figure 11. Recirculation pump with tubing woven between rows of plants.**

2.8. **FTW Anchoring System**

The FTW will rise and fall with the stormwater inflow and outflow. These mesocosms needed a mechanism that allowed for rise and fall while keeping the FTW centered within the basin. For the purposes of our project, the FTWs were centered within the basin for two purposes: first, to reduce interference with the pump systems; and second, to ensure all system parameters were kept constant excluding those of interest. In order to keep the rafts generally centered while maintaining accessibility to the entire system, a removable guiding system was designed using wooden dowels and large screw eyes. An example of a FTW secured with the anchor system is shown in figure 12.
Figure 12. 30% coverage FTW secured in the tank center with the anchoring system.

The vertical wooden dowels are secured within the raft using ½-in. nominal diameter PVC bushing, which serves to reduce friction as the FTW moves with the water level. These vertical dowels are 36 inches in length, which is sufficient to allow for the expected vertical movement of the raft within the 24-in. deep basin and the additional height needed to reach the overhanging dowel apparatus. The placement of the PVC bushing was selected so that the dowels were as close to the center of the edge of the raft without interfering with the plants or raft flotation. The horizontally extended dowels were spaced accordingly in order to line up with the PVC pipe. The purpose of this design within our system is to reduce pump interference by keeping the FTW relatively centered. This design element is not intended to be translatable to full-scale systems, which most commonly utilize deadweight anchor systems. A standard cinder block anchor was considered for the mesocosm study, but was decided against due to the relatively large volume displacement it would cause within the basin.

2.9. Selection of Constituents in Simulated Stormwater

Due to their status as chronic urban pollutants, the contaminants of focus were total nitrogen (TN), total phosphorus (TP), and total suspended sediment (TSS). The target concentration for each pollutant was sourced from the Nationwide Urban Runoff Program conducted by the EPA in 1983. Within our stormwater, phosphorus will only be expressed as soluble phosphorus compounds. Nitrogen will be monitored in the forms of nitrate-nitrite and ammonium. Shown in appendix 1, our target concentration for soluble phosphorus, or orthophosphates, is 56 μg L⁻¹, while the target concentration of nitrate-nitrite Nitrogen, or N-N, is 558 μg L⁻¹. Per our advisor’s instruction, we estimated the value of nitrogen expressed as ammonium, NH₄-N, to equal approximately 20% of the Total Kjeldahl Nitrogen, giving us a target ammonium concentration of 258 μg L⁻¹. Monoammonium phosphate, ammonium
sulfate, and potassium nitrate salts were dissolved in tap water to meet these concentrations according to their respective dissolution formulas below:

\[ \text{NH}_4\text{H}_2\text{PO}_4(s) \rightarrow \text{NH}_4^+(aq) + \text{H}_2\text{PO}_4^-(aq) \]  
\[ (\text{NH}_4)\text{SO}_4(s) \rightarrow 2\text{NH}_4^+(aq) + \text{SO}_4^{2-}(aq) \]  
\[ \text{KNO}_3(s) \rightarrow \text{K}^+(aq) + \text{NO}_3^-(aq). \]  

(3) \hspace{1cm} (4) \hspace{1cm} (5)

The molecular ratio between the pollutant compound of interest and the corresponding salt can be applied to determine the mass of each salt needed per 284-L inflow treatment per basin using the following conceptual equation format:

\[ A \times \frac{\text{1 g}}{\text{1 \mu g}} \times \frac{\text{1 mol pollutant}}{\text{mol pollutant}} \times \frac{\text{1 mol salt}}{\text{mol salt}} \times \frac{\text{Sw}}{\text{g}} \times \text{75 gal} \times \frac{\text{3.785 L}}{\text{1 gal}} \]  

(6)

where,

- \( A \) = target pollutant concentration (\( \mu g/L \))
- \( \text{Aw} \) = molecular weight of compound (g)
- \( \text{Sw} \) = molecular weight of salt (g).

Using the sequence described above, it was determined that 0.019 g of monoammonium phosphate, 0.514 g of ammonium sulfate, and 0.258 g of potassium nitrate are needed per inflow event per mesocosm to meet the target stormwater concentrations. Total suspended solids, or TSS, represents particles suspended in a moving body of water. While this could consist of soils, metals, organic materials, and debris, this value was represented using only finely ground soil. The target concentration of 67 mg L\(^{-1}\) was met by adding 19.02 g per 284-L inflow treatment per basin.

2.10. Consideration of Alternatives

Another consideration made for the outflow was an implementation of an orifice to drain the water over the period into a 24-slot flow divider. A problem with this approach was the size of the orifice needed to execute this, less than 1 mm in diameter. In addition to the inability for machinery to create this, this size would be prone to clogging from the organic material in the basin. This idea was also ruled out from challenges associated with the flow divider. The flow divider requires a minimum flow rate of 1 GPM to ensure even water division across the slots, which is critical to get the representative sample of the outflow required. Due to surface tension effects at the low flow rate, one slot could be favored over others. These reasons are ultimately why this method was ruled out.

3. Results and Conclusions

3.1. System Testing Overview
The system was tested to determine how well it performed based on the chosen design criteria: mimic movement in a stormwater basin with controlled inflow and outflow rates. Design success was described in terms of achieving target inflow and outflow rates as well as ability to be semi-autonomous. Both of these objectives were achieved.

3.2. Inflow Testing

Protocols for inflow testing were developed specifically to accomodate for the established project parameters. Sampling consisted of taking 1-L measurements from each mesocosm inflow orifice while monitoring time so that flow rates of each orifice could be compared. Two tests were taken producing results shown in appendix 2. Appendix 2 shows the standard error from each test. Although it is difficult to achieve an equal flow rate from each orifice, the flow rate likely varied from desired flow rate due to multiple sources of error. With varying water pressure from the water source, it could have alternated above the 8 psi desired, resulting in higher flow rates. Error may also be caused by inaccurate machining of the orifices. Each PVC cap was created using a handheld drill to bore orifices, which created room for error in angle and location. Due to the orifice size being small, any movement of the arm during drilling could have affected the orifice negatively. This may have resulted in varied paths for the flow rates to occur out of each orifice.

The injection system was tested during a run of the inflow manifold system. A flow meter reading was taken before and after the manifold system ran to determine the volume from the injection pump in addition to the water source. Additionally, an initial depth of the blue injection tank was taken to be 0.79 meters, with a final depth of 0.23 meters. The injector system ran for 254 minutes, injecting a volume of 134 liters. The volume of concentrated solution that entered the manifold was 31.7 L h\(^{-1}\), compared to the desired 31.5L h\(^{-1}\).

3.3. Outflow Testing

The data shown in table 3 represents the water volume captured in the sample bucket during a drawdown event. Each bucket was weighed with a hanging scale. The weight of the water collected was then converted to a volume. Since each side has its own electrical controls, there is a possibility that each side could collect different volumes of water, as seen in table 3 at the differing projected collection values. This can be corrected via additional adjusting of the timer settings. Test 1 represents tubs A through F where the timer cycle was 922 seconds, 22 seconds of which went to the collection bucket. Test 2 represents tubs G through K with a timer cycle of 924 seconds with a sampling interval of 11 seconds. These were then used to determine how much water would be projected to be in the collection bucket during the 12-h period using the peristaltic pump flow of 372 mL min\(^{-1}\).

3.4. Achievement of Objectives
Objectives of this project include the following: 1) design and test a scaled mesocosm system that will mimic movement in a stormwater basin by transporting contaminants at controlled inflow and outflow rates; 2) develop a pilot system that could be used to research optimal surface area coverage for reduction of pollutants, as well as the treatment impact of a recirculation pump; and 3) consider full-scale deployment parameters in the design of the scaled model. All of these objectives were adequately accomplished for the purposes of this project. Regarding the second and third objectives, the system currently houses FTWs that were designed to be translatable to full-scale. Materials, plant species, plant spacing, and the anchoring system are consistent between the FTWs, and are able to be translated to full-scale excluding the anchoring system. Further, each FTW incorporates a recirculation pump to improve movement of water within the basin. Not only is the system prepared so that the second objective is satisfied, the implementation of a recirculation pump is an aspect that can potentially be translated to a full-scale FTW, thus satisfying the third objective as well.

3.5. Future Testing and Considerations

Immediate improvements that could increase accuracy of the system include better machining of the inflow orifices, leveling of the tanks, and more durable securement of the outflow tubing. Once modifications are complete, this system could be used for a variety of research topics, including but not limited to estimation of pollutant reduction by the FTW through quantifying biomass accumulation, plant assimilation, root development and effects on nutrient assimilation, and suspended sediment removal efficiency. The system is currently prepared to assess the impact of surface area coverage and the incorporation of a recirculation pump on nutrient removal. Results from testing could ultimately be used to inform full-scale design, deployment, and maintenance recommendations for hydraulically-dynamic application conditions.
References


## Appendix

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<tr>
<td>Total Lead</td>
<td>µg/l</td>
<td>144</td>
<td>0.75</td>
<td>114</td>
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<td>104</td>
<td>0.68</td>
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<tr>
<td>Total Copper</td>
<td>µg/l</td>
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<td>27</td>
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<tr>
<td>Total Zinc</td>
<td>µg/l</td>
<td>135</td>
<td>0.84</td>
<td>154</td>
<td>0.78</td>
<td>226</td>
<td>1.07</td>
<td>195</td>
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<tr>
<td>Total Kjeldahl Nitrogen</td>
<td>µg/l</td>
<td>1900</td>
<td>0.73</td>
<td>1288</td>
<td>0.50</td>
<td>1179</td>
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<td>965</td>
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</tr>
<tr>
<td>Nitrate + Nitrite</td>
<td>µg/l</td>
<td>736</td>
<td>0.83</td>
<td>558</td>
<td>0.67</td>
<td>572</td>
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<td>543</td>
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</tr>
<tr>
<td>Total Phosphorus</td>
<td>µg/l</td>
<td>383</td>
<td>0.69</td>
<td>263</td>
<td>0.75</td>
<td>201</td>
<td>0.67</td>
<td>121</td>
<td>1.66</td>
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<tr>
<td>Soluble Phosphorus</td>
<td>µg/l</td>
<td>143</td>
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<td>56</td>
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<td>80</td>
<td>0.71</td>
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</table>

**Appendix 1. Median Event Mean Concentrations for Urban Land Uses, Nationwide Urban Runoff Program conducted by US EPA, 1983.** Red boxes indicate compounds of interest and their respective target concentrations.
### Appendix 2. Results of 2 tests of inflow for each mesocosm.

<table>
<thead>
<tr>
<th>Mesocosm</th>
<th>Test 1 (L min⁻¹)</th>
<th>Test 2 (L min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.91</td>
<td>0.76</td>
</tr>
<tr>
<td>B</td>
<td>0.67</td>
<td>0.63</td>
</tr>
<tr>
<td>C</td>
<td>0.77</td>
<td>0.74</td>
</tr>
<tr>
<td>D</td>
<td>0.84</td>
<td>0.81</td>
</tr>
<tr>
<td>E</td>
<td>0.98</td>
<td>0.92</td>
</tr>
<tr>
<td>F</td>
<td>0.74</td>
<td>0.72</td>
</tr>
<tr>
<td>G</td>
<td>0.73</td>
<td>1.09</td>
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<tr>
<td>H</td>
<td>0.84</td>
<td>0.82</td>
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<tr>
<td>I</td>
<td>0.83</td>
<td>0.95</td>
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<tr>
<td>J</td>
<td>0.94</td>
<td>0.89</td>
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<tr>
<td>K</td>
<td>0.85</td>
<td>0.83</td>
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<tr>
<td>L</td>
<td>0.85</td>
<td>0.79</td>
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</table>

**Average Flow Rate**
- **Test 1**: 0.83
- **Test 2**: 0.83

**Max Flow Rate**
- **Test 1**: 0.98
- **Test 2**: 1.09

**Min Flow Rate**
- **Test 1**: 0.64
- **Test 2**: 0.61

**Standard Error**
- **Test 1**: 0.027
- **Test 2**: 0.035
### Appendix 3. Results of two outflow collection tests.

<table>
<thead>
<tr>
<th>Tub Letter</th>
<th>Water (L)</th>
<th>Tub</th>
<th>Water (L)</th>
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<tbody>
<tr>
<td>A</td>
<td>6.07</td>
<td>G</td>
<td>3.08</td>
</tr>
<tr>
<td>B</td>
<td>5.44</td>
<td>H</td>
<td>3.08</td>
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<tr>
<td>C</td>
<td>5.80</td>
<td>I</td>
<td>2.90</td>
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<tr>
<td>D</td>
<td>5.89</td>
<td>J</td>
<td>2.90</td>
</tr>
<tr>
<td>E</td>
<td>6.07</td>
<td>K</td>
<td>3.08</td>
</tr>
<tr>
<td>F</td>
<td>5.08</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Test 1</th>
<th></th>
<th>Test 2</th>
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</thead>
<tbody>
<tr>
<td>Average:</td>
<td>5.73</td>
<td></td>
<td>3.01</td>
</tr>
<tr>
<td>Maximum:</td>
<td>6.07</td>
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<td>3.08</td>
</tr>
<tr>
<td>Minimum:</td>
<td>5.44</td>
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<td>2.90</td>
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<tr>
<td>Standard Error:</td>
<td>0.16</td>
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