SOIL HYDROLOGY AND NITROGEN FILTRATION IN RAIN GARDENS

by

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SOIL HYDROLOGY AND NITROGEN FILTRATION IN RAIN GARDENS

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ABSTRACT

Urbanization is causing increasing amounts of contaminated stormwater runoff to enter streams, rivers, and other aquatic ecosystems. In particular, nitrogen concentrations in stormwater can damage ecosystems by causing eutrophication and lowering available oxygen levels in water. Rain gardens are an efficient method of filtering stormwater before it enters ecosystems. In this study, we examined three types of soil to determine which would be the most viable for use in a rain garden in terms of nitrogen filtration efficiency, water volume output, and cost. By pouring “contaminated” water through columns of soil, we measured the flow rate and nitrogen concentrations of discharged water. Although there was no significant difference in the filtration capacity of the three soils, compost was determined to be a poor choice due to extremely low discharge flow rates. Both the sandy loam and the sand/peat mixture had comparable flow rates and filtration capacity, filtering nitrate at 65% and 79% average efficiency respectively. The sandy loam is significantly cheaper than the sand/peat mixture and is most likely the best option for use in rain gardens.
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INTRODUCTION

Contaminated stormwater runoff due to urbanization is causing major stress to streams, rivers, and other aquatic ecosystems (Burns et al. 2014). Impervious surfaces such as parking lots and sidewalks increase the volume of stormwater entering drains. A study by Burns et al showed that the area of impervious landscape and the distance from stormwater drains to streams had the most direct impact on stream health rather than flow regime by itself (Burns et al. 2014).

Streams have rich species diversity, which impacts services provided to both the ecosystem and to humans (Roy et al. 2003). A study by Roy et al. examined how urban runoff affected 30 streams by comparing and contrasting urban runoff, forest runoff, and agricultural runoff. Urban runoff had significantly more detrimental effects on the streams, impacting macroinvertebrate diversity, sediment size, suspended solids, turbidity, conductance, and stream chemistry. In particular, nitrogen and phosphorous concentrations were very high (Roy et al. 2003). A 2009 Water Quality Inventory by EPA reported that stormwater was increasingly becoming a contributor to rising nitrogen concentrations in aquatic ecosystems (National Water Quality Inventory: Report to Congress: 2004 Reporting Cycle).

Nitrogen in stormwater runoff causes eutrophication in streams and other aquatic ecosystems, leading to excess nutrients and growth of weeds and algal blooms. These blooms affect the structure of the communities in the ecosystem, and damage the entire habitat by depleting available oxygen (Liqing et al. 2014).
Numerous storm-water management tools have been studied and used in attempt to reduce pollutant concentration and volume of runoff entering streams. Bioretention is one of the most frequently used and effective practices (Davis et al. 2009). Bioretention techniques catch contaminated runoff and filter the water by a variety of means before discharging the water. These techniques reduce volume of runoff significantly, remove pollutants, and lower the volume of “suspended solids, nutrients, hydrocarbons, and heavy metals” (Davis et al. 2009).

A study by Lim et al in 2014 found that biofiltration columns removed over 90% of heavy metals in runoff. Another study used bioretention to treat untreated stormwater runoff from Seattle and exposed Coho Salmon (*Oncorhynchus kisutch*) and its daphniid prey to both treated and untreated water. All those exposed to untreated water were either killed or their reproduction was impaired. Water that was filtered through soil media in bioretention columns had no adverse effects on either mortality or reproduction in the salmon or their prey (McIntyre et al. 2015).

Bioretention is an inexpensive, highly effective method for improving water quality and reducing volume of stormwater runoff. In 2013, the city of Fort Worth, Texas expressed a need for best management practices. A graduate student from Texas Christian University, Jared Williams, tested bioretention techniques to improve water quality at O.D. Wyatt High School. His system was designed to reduce pollution and volume of runoff at the school, create a source of reusable (non-potable) water to be repurposed, and to
incorporate students from the school and other programs to provide education (Williams 2014).

Williams (2014) used both columns and test plots and analyzed the physical filtration capacity of three different kinds of soil. Filtration of E. coli, nitrate, and other common pollutants were examined, as well as runoff volume (Williams 2014). The results showed no significant difference in filtration capacity among the three soil types, but the volume of filtered water released varied substantially. All soils were highly effective at removing pollutants, and Williams concluded that the practice could be a viable option to improve water quality and provide reusable water to the school. Williams suggested that further studies focus on EMC (event mean concentration) efficiencies, and mechanisms that affect differences in filtration and efficiencies between the different soils (Williams 2014).

In this study, Williams’ work is continued and extended. The goal of this study is to quantify the hydrologic response of three columns of different soil types and to verify Williams’ nitrogen concentration results by using much higher concentrations of nitrogen. Higher concentrations create much less room for error when using an imprecise and limited nitrogen test to determine concentrations. These results will determine which soil type is the most viable for use in rain gardens in terms of filtration efficiency, water volume output, and cost.
METHODS

This work follows from the columns constructed in Jared Williams’ work (Williams 2014). A wooden frame holds six vertical columns, which are constructed from PVC pipe 10 inches in diameter and 37 inches high. Only three of the columns were used in this study. Each column was filled to a depth of 24 inches with a sand/peat mixture, compost, or sandy loam mixture on top of 8 inches of pea gravel (Figure 1 and Appendix A). Each of these soil materials is readily available for purchase to everyday rain garden users though their costs vary significantly per cubic foot (Table 1).

Figure 1: Column Design. Image not to scale. (Williams 2014)
<table>
<thead>
<tr>
<th>Filter Material</th>
<th>Cost per cubic yard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy Loam</td>
<td>$15.00</td>
</tr>
<tr>
<td>Compost</td>
<td>$40.00</td>
</tr>
<tr>
<td>Sand/Peat</td>
<td>$100.00</td>
</tr>
</tbody>
</table>

Table 1: Cost of Filter Material (Williams 2014).

Four trials were conducted on the three columns. For each trial, 3-6 liters of DI water were poured over each column through a rain filter to reduce rain splash detachment and to minimize disruption of the soil surface. Each experiment was run for 60 minutes. Water was collected in separate test bottles from the outlet at the bottom of each column at varying intervals depending on the timing of discharge. The first and third trials were flush runs with no nitrogen added. For the second and fourth trials 30 mg/L NaNO₃ was added to the DI water. The water samples were measured and tested for nitrogen concentrations using a LaMotte Nitrate Nitrogen Kit 3319. This kit records ppm Nitrate as Nitrate Nitrogen (NO₃-N) which was converted to ppm Nitrate (NO₃) by multiplying by 4.4 (See Appendix B).

Soil moisture was measured using Delta-T SM200 soil moisture probes, which were inserted vertically in the surface of each column to a depth of approximately 6 cm. The moisture probes measured volumetric moisture content (θᵥ) throughout the simulated “storm” event within +/- 3% over an optimal range of 0-55% soil water by volume.
Bulk density was measured using a split core. Samples were dried overnight at 105°C to remove moisture. Organic matter content was measured using Loss on Ignition and heated at 400°C for 3 hours.

RESULTS

Hydrologic Response of the Columns

Across the four runs, Column 1 contained sandy loam (SL), Column 2 contained compost (C), and Column 3 contained a peat/sand mixture (PS). The bulk density of Column 1 (SL) was 1.381 g/cm³, the bulk density of Column 2 (C) was 0.196 g/cm³, and the bulk density of Column 3 (PS) was 0.901 g/cm³. The organic matter contents were 0.694% for Column 1 (SL), 11.081% for Column 2 (C), and 3.161% for Column 3 (PS). Measured runoff from the three columns is shown in Figure 2. Hydrologic response was consistent for each column. Column 1 (SL) was the flashiest, with steep rising limbs, the steepest recession limbs, fastest average response time (7.2 minutes vs. 26.7 minutes and 11.1 minutes for Columns 2 (C) and 3 (PS) respectively), highest peak discharges, and largest overall runoff volumes (Tables 2 & 3; see Appendix C for definition of terms). Column 3 (PS) had a delayed response relative to Column 1 (SL) with peak flow occurring on average 10.65 minutes after the hydrograph peaks in Column 1 (SL). Discharge remained elevated in Column 3 (PS) with gradual recession limbs toward the end of each experiment. Column 2 (C) took progressively longer over each trial to generate discharge, and had significantly less total flow, volume output, and flow-rate than Columns 1 (SL) and 3 (PS). For Trial 4 runoff for Column 2 (C) was only measured after 63.5 minutes. Runoff coefficients (discharge expressed as a percentage of inflow) were 69.2% and
43.3% for Columns 1 (SL) and 3 (PS) respectively (Table 4). Column 2 (C) only generated on average 1.5% runoff.

The soil moisture probes failed during Trials 1 and 2 but high-resolution moisture data was collected for the second flush (Trial 3) and the final nitrate run (Trial 4) (Figure 3). Changes in near surface moisture were consistent across all three columns. Column 2 (C) reached saturation within 2 minutes of water application and remained at approximately 85% moisture by volume throughout both runs. The moisture response curves for Column 1 (SL) also rose rapidly to saturation or near saturation within 3 minutes of water application, but began to decline after approximately 8 minutes. For both Trial 3 and Trial 4 the near surface soil began to dry fairly rapidly, approaching 25% at 60 minutes in Trial 3 and 35% at 60 minutes in Trial 4. In Column 3 (PS), the near surface soil wet more slowly relative to Column 1 following water application, with saturation reached at approximately 8-10 minutes after the beginning of the experiment. The soil in Column 3 (PS) remained saturated for approximately 30 minutes following water application, approaching 55% at 60 minutes for Trial 4 (Figure 3).

**Nitrogen Filtration**

Although nitrogen filtration varied between the columns, there was no significant difference in the efficiency of the three columns (Figure 4). However there were differences between the columns in terms of how nitrogen responded during the runs. The nitrogen concentrations for Column 1 (SL) increased over time, while the nitrogen concentrations for Column 2 (C) decreased over time (Figure 5). In Column 3 the
nitrogen response was more complex. Trial 2 began with a steep decline in nitrate but then began to rise again toward the end of the event. Trial 4 showed a similar trend for Column 3 but overall the nitrogen concentrations were higher. Column 1 (SL) showed greater variance in its efficiency (Table 4), but on average, all three columns lowered nitrogen concentrations between 65-85% (Table 3). The flush run between Trials 2 and 4 contained some nitrogen in the initial flow of Columns 1 (SL) and 3 (PS), then quickly dropped off.

**Figure 2:** Volumetric Flow. Velocity of water released by the columns over one hour measured in ml/s. Data for Column 2 (red) is measured on a secondary axis.
Table 2: Volume Output and Flow Rate.
** Only one sample was able to be taken after one hour

<table>
<thead>
<tr>
<th>Trial</th>
<th>Total Q (ml)</th>
<th>Vol % Output</th>
<th>Response time (min)</th>
<th>Peak Q Avg Flow Rate (ml/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column 1</td>
<td>2162</td>
<td>72.1</td>
<td>9.4</td>
<td>13</td>
</tr>
<tr>
<td>Column 2</td>
<td>174</td>
<td>4.4</td>
<td>6.2</td>
<td>30</td>
</tr>
<tr>
<td>Column 3</td>
<td>1613</td>
<td>53.8</td>
<td>13</td>
<td>18</td>
</tr>
</tbody>
</table>

**Trial 2**

| Column 1 | 1991 | 66.4 | 7.8 | 9.5 | 0.9 |
| Column 2 | 23 | 0.6 | 27.7 | 55 | 0.01 |
| Column 3 | 1276 | 42.5 | 14 | 30.5 | 0.4 |

**Trial 3**

| Column 1 | 2659 | 88.6 | 4 | 5.8 | 1.1 |
| Column 2 | 36 | 0.6 | 9.5 | NA | 0.01 |
| Column 3 | 1277 | 42.6 | 7 | 13 | 0.5 |

**Trial 4**

| Column 1 | 1493 | 49.8 | 7.6 | 7.6 | 0.6 |
| Column 2** | 7 | 0.1 | 63.5 | NA | NA |
| Column 3 | 1033 | 34.4 | 10.2 | 17 | 0.4 |

Table 3: Average Values for Volume, Flow, and Filtration

<table>
<thead>
<tr>
<th>Total Q (ml)</th>
<th>Vol % Output</th>
<th>Response time (min)</th>
<th>Peak Q (min)</th>
<th>Avg Flow Rate (mL/sec)</th>
<th>Avg NO3 ppm</th>
<th>Avg % Efficiency (22.885 ppm NO3 start)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column 1</td>
<td>2076.25</td>
<td>69.225</td>
<td>7.2</td>
<td>8.975</td>
<td>0.925</td>
<td>8.1</td>
</tr>
<tr>
<td>Column 2</td>
<td>60</td>
<td>1.425</td>
<td>26.725</td>
<td>42.5</td>
<td>0.02</td>
<td>3.5</td>
</tr>
<tr>
<td>Column 3</td>
<td>1299.75</td>
<td>43.325</td>
<td>11.05</td>
<td>19.625</td>
<td>0.45</td>
<td>4.95</td>
</tr>
</tbody>
</table>
**Figure 3:** Soil Moisture. Volumetric soil moisture measured over one hour for each column over 2 trials (runs).

**Figure 4:** Nitrate Concentration. A box and whiskers chart of NO3 concentrations over all trials for all three columns. There was no significant difference.
**Figure 5:** Flow Rate and Nitrogen Concentration. Flow rate is shown by solid lines and nitrogen concentrations are shown by dashed lines. Data is shown for Trials 2-4. 30 mg/L NaNO₃ was added to Trials 2 and 4. Only one data point was recorded for part B Trial 4.
Table 4: Nitrate Filtration. Average concentration, efficiency, and range of efficiency for all three columns across all four runs. * Was 95% until last nitrogen test of 89%; **Only one sample was able to be taken after 1 hour.
DISCUSSION AND CONCLUSIONS

The results presented in this study confirmed those of Williams (2014) in that the volume of filtered water released for each column varied greatly and all three soil types were efficient in filtering nitrogen. The hydrologic response of the three soils was quite consistent for each column. One purpose of the rain gardens at OD Wyatt High School would be to provide a source of filtered water for non-potable uses. With this in mind, Column 2 (C) would be a poor choice of substrate. Column 2 (C) not only had significantly less total output than the other two soils, it held all contaminated water in a soupy mixture (consistent moisture levels of 85%) that could allow for significant runoff in a plot. Columns 1 (SL) and 3 (PS) both had a steady volume output of water. Because Column 1 (SL) had the highest volume output and average flow rate and is the cheaper option, it is most likely the best choice for a rain garden strictly in terms of output of useable water.

The use of a high initial concentration of nitrate in the water samples provided much more precise results and greater resolution to the response in the three columns. The purpose of this was to analyze the behavior and comparative abilities of the three soil types more exactly, and this was accomplished. Although there was no significant difference in overall nitrogen filtration between the three soil types, the behavior of each soil varied during the trials.

Column 2 (C) had extremely low volume output and therefore was not a reliable source to measure nitrate concentrations. However, the concentrations that were measured were
low and much more consistent than Column 1 (SL). Concentrations of nitrate decreased over the 60-minute period.

Nitrate concentrations in the output of Column 1 (SL) increased over time. This trend was contrary to Column 2 (C) and much more drastic than Column 3 (PS). The most likely explanation for this is that anion exchange sites in the soil were quickly filled with nitrate in the initial flush of water, and the soil was unable to continue bonding nitrates from the increased quantities of water as effectively once all the sites were filled. Efficiency of Column 1 (SL), although not significantly different from Columns 2 and 3 when averaged, dropped as low as 42% by the end of the 60-minute trials. If this percent efficiency remained constant or continued to increase beyond the 60-minute period, Column 1 (SL) would not be as effective as the other two columns at filtering nitrate. This cannot be determined however without a longer trial period.

Column 3 (PS) had the least variance in efficiency. In Trial 4, ppm NO3 remained within 2-3 ppm the entire 60 minutes. Unlike Column 1 (SL), the initial output of Column 3 (PS) significantly lowered the concentration of nitrate, but in both runs, there was a slight increase in concentrations toward the end of the event. It is probable that over a longer event time, the nitrate concentrations would have continued to steadily rise, just like in Column 1 (SL). The best explanation for this is once again that anion exchange sites initially bonded with nitrates from the water and then over time the soil’s ability to bond nitrates decreased as all sites were filled. The delayed response of Column 3 (PS) is most likely due to the higher organic matter concentration than Column 1 (SL) (Column 3 had
an organic matter content of 3.161% and Column 1 had an organic matter content of 0.694%.) Organic soil holds nitrates more strongly than non-organic soil, and so the peat/sand mixture was able to “hold” the nitrates for a longer period of time than the sandy loam before it became less effective.

When the total filtration efficiencies of the columns are averaged, there is ultimately no significant difference in the results. This means that for most rain and storm events, any one of the soil types would greatly decrease nitrate concentrations in collected and/or runoff water. Because of the hydrologic responses of these soils however, the compost used in Column 2 is most likely a poor choice of substrate. Column 1 (SL) had higher concentrations of nitrate than Column 3 (PS) towards the end of the event, but since it is likely that concentrations in Column 3 (PS) would have continued to rise beyond the 60 minutes and Column 1 (SL) may have leveled out, it cannot truly be said that one performs better than the other. Longer trials would provide a better view of the long-term efficiency of each Column.
## APPENDIX A: FILTER DESIGN

<table>
<thead>
<tr>
<th>Top of Filter</th>
<th>50% Peat/Sand Filter</th>
<th>Compost Filter</th>
<th>Sandy Loam Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Column</td>
<td>Test Plot</td>
<td>Column</td>
</tr>
<tr>
<td></td>
<td>0.46 m (18&quot;) compost</td>
<td>0.46 m (18&quot;) compost</td>
<td>0.61 m (24&quot;) sandy loam</td>
</tr>
<tr>
<td></td>
<td>0.15 m (6&quot;) Sand</td>
<td>0.15 m (6&quot;) Sand</td>
<td>0.15 m (6&quot;) Sand</td>
</tr>
<tr>
<td></td>
<td>0.093 m² (1 ft²) S-B* fabric</td>
<td>1.24 m² (13.4 ft²) S-B* fabric</td>
<td>0.093 m² (1 ft²) S-B* fabric</td>
</tr>
<tr>
<td></td>
<td>0.2 m (8&quot;) pea gravel</td>
<td>0.2 m (8&quot;) pea gravel</td>
<td>0.2 m (8&quot;) pea gravel</td>
</tr>
<tr>
<td>Bottom of Filter</td>
<td>0.093 m² (1 ft²) S-B* fabric</td>
<td>0.093 m² (1 ft²) S-B* fabric</td>
<td>0.093 m² (1 ft²) S-B* fabric</td>
</tr>
<tr>
<td>Total Filter Height</td>
<td>0.84 m (33&quot;)</td>
<td>0.84 m (33&quot;)</td>
<td>0.84 m (33&quot;)</td>
</tr>
</tbody>
</table>

*Source: Data adapted from Clayton and Schueler 1996.*

*Spun-Bond Fabric*

*Source: Williams 2014*
APPENDIX B: NITRATE-N TO NITRATE CONVERSION

Interconverting Nitrate as Nitrate (Nitrate-NO3) and Nitrate as Nitrogen (Nitrate-N)

The atomic weight of nitrogen is 14.0067 and the molar mass of nitrate anion (NO₃⁻) is 62.0049 g/mole

Therefore, to convert Nitrate-NO3 (mg/L) to Nitrate-N (mg/L):

Nitrate-N (mg/L) = 0.2259 x Nitrate-NO3 (mg/L)

And to convert Nitrate-N (mg/L) to Nitrate-NO3 (mg/L):

Nitrate-NO3 (mg/L) = 4.4268 x Nitrate-N (mg/L)

Source: State Water Resources Control Board
APPENDIX C: DEFINITION OF TERMS

Flashiest: To respond the quickest

Rising Limbs: The response of a hydrologic entity from pre-event conditions to peak runoff or flow

Recession Limbs: The decline in hydrologic response, from peak flow to antecedent conditions

Response Time: The time (in seconds or minutes) between the initial inflection in the runoff curve or hydrograph and the peak flow or discharge

Peak Discharges: The highest discharge or runoff rate achieved during a single hydrologic event
BIBLIOGRAPHY


