Development of a bio-retention system for urban storm water management

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Abstract: Urban stormwater that flows through all the manmade structures contains high levels of BOD, TSS, orthophosphate, surfactants etc. It raises concerns of water quality in the receiving natural water courses. Bio-retention is one of the prominent methods of stormwater management for the removal of contaminants from stormwater. In this experimental study, a column containing mulch, blast furnace slag, sand, silt etc. was used to assess the removal of suspended solids and nutrients (nitrate and phosphate) from stormwater. The tests were conducted with a flow through period of 3, 7 and 15 days. Removal efficiency of 80% total suspended solids for 15 day, 60% nitrate for 7 days and 70% phosphorous for 3 and 7 days was observed through the column. pH variation was found to be insignificant in the range of 6-7.5.

Key words: bio-retention, nutrients, suspended solids, stormwater management

1. Introduction

Water that originates from rainfall and snowmelt is called stormwater and it results in a runoff that flows over the surface and ultimately enters into the rivers or the lakes or ponds. It carries all the particles and contaminants that came in the way and causes sanitation and quality issues to its destination. The issue is more prominent in urban areas as compared to rural areas as urban stormwater contains high BOD, TSS, orthophosphate [1–3], surfactants while rural stormwater contains mostly the total organic carbon. The issue raises a concern to take adequate measures for stormwater management. There are different types of
stormwater control measures taken around the world some of them are low impact development (LID), Water sensitive urban design (WSUD), Integrated Urban Water Management (IUWM), Sustainable urban drainage system (SUDS), or Sustainable drainage system (SuDS), Best management practices (BMPs), Stormwater control measures (SCMs), Source Control (American Public Work Association), Green infrastructure, Stormwater quality improvement devices (SQIDs). Low impact development is one of the most effective tools used for stormwater management. Low impact development (LID) has been used in many countries as a new strategy for urban water environmental protection and sustainable stormwater management. It takes land planning and stormwater management as green infrastructure and utilization of onsite natural materials and methods to protect and enhance the water quality [4–7].

Bio-retention is a primary component of a new form of stormwater management termed low impact development (LID) (Dietz 2007). The overall goal of this approach is to “mimic the predevelopment site hydrology by using site-design techniques that store, infiltrate, evaporate, and detain runoff” (Prince George’s County 1999). The Bio-retention system as one of the low impact development methods and is composed of a multi-layer system comprising porous media, mulch, and vegetation. Stormwater collects in the bio-retention system and infiltrates into the media, which is usually composed primarily of sand, soil fines and leaf compost can be added to the sand to manipulate the media infiltration rate and organic matter content. The media is covered with a layer of mulch, and the area is planted with pollution and water-tolerant trees, shrubs, and herbaceous species. The primary goals of bio-retention are to decrease surface runoff, increase groundwater recharge, and remove pollutants from stormwater entering the facility [8–10]. Previous studies demonstrate that bio-retention effectively removes sediment and nutrients from stormwater. Various studies reported the removal of phosphorus as total phosphorus (TP), the results reported 70 to 90% removal for laboratory column media studies, 94% removal of TP in two different columns and 84% removal reported in field results of TS. Other studies also reported 32% to 63% removal of TP.

This study represents the initial work in the stormwater management that utilizes bio-retention system to remove nutrients. The removal of nutrients and TSS from synthetic urban stormwater runoff using bio-retention systems were evaluated. The treatment capacities of bio-retention systems were estimated and effects of system design parameters were evaluated under controlled conditions [11–13].

2. Materials and Methods

2.1 Experimental set-up
A plexiglass column of dimension 1.3m x 0.15m x 0.15m was fabricated as shown in figure 1. The column contains 4 layers system, from top ponding depth of 20 cm, covering 5 cm mulch layer, 50 cm Powdered Blast Furnace Slag (BFA) + sand + silt + clay layer and sand layer 55 cm, and the outlet pipe was set at the bottom of the sand layer [14–17].

2.2 Hydrology parameters:

In this study, Chandigarh city rainfall data was used for simulation and analysis using method proposed. It is a non-uniformly designed rainfall storm pattern based on the relationships of intensity – duration – frequency (IDF). The selected rainfall patterns were 60 min rainfall duration under 5 years rainfall return period, see figure 1.

**IDF Relationship:**

Average intensity \( i = \frac{p}{t} \)

Where \( p \) = the rainfall depth and \( t \) = the duration of rainfall

the precipitation depth is calculated for a given return period as

\[
x_T = \bar{x} + K_T S
\]

Where \( \bar{x} \) = mean, \( S \) = standard deviation and \( K_T \) = frequency factor for return period \( T \).

\[
K_T = -\frac{\sqrt{6}}{\pi} \left\{ 0.5772 + \ln[\ln(\frac{T}{T - 1})] \right\}
\]
2.3 Hydraulic performance

In this study, the bio-retention systems take smooth stormwater runoff hydrographs by reducing peak flow, that reduces erosion, scour, and sediment transport to the receiving stream. In bio-retention, a buffer to runoff peak flow is by: forming ponding water on the surface and retaining water within the media and releasing it slowly via infiltration and evapotranspiration. Different peak flow reduction rates have been reported and range from 44% to 95%. In bio-retention systems, a delay in the peak flow of runoff is used
and this is often reported in different forms, such as lag time, lag coefficient, or peak delay ratio. Lag time, expressed in minutes, is the time from the beginning of inflow into the bio-retention cell to when outflow reaches the underdrain and has been observed to range from approximately 60 to 600 min shown in table 1.

Table 1: Experimental simulated influent water volumes

| p (min) | t (min) | q (L/s.ha) | Φ | F (ha) | V (L) |
|---------|---------|------------|---|--------|-------|
| 5       | 360     | 9.08       | 0.9| 0.0001 | 18.2  |

**Note:** p-Return period, t-Duration of rainfall, q-Rainfall intensity, φ-Runoff coefficient, F- Catchment area, V-Influent volume of bio-retention tank

2.4 Synthetic stormwater

Experiments were conducted using a synthetic rather than natural stormwater. Since the focus of these experiments was on the nutrients and suspended particles found in stormwater it was preferred not to use natural stormwater given its composition variability. Using a synthetic stormwater allows more consistency and repeatability of the composition of the stormwater. The synthetic stormwater is made by adding different type of stormwater pollutants and testing the efficiency of the bio-retention. In the Table 2, the characteristics of synthetic stormwater used in this study is given. The synthetic water characteristics was taken from different studies, Davis (2003) made a synthetic water by inducing pollutants like TSS 120 mg/L (CaCl$_2$), TN 2 mg/L (NaNO$_3$), TP 0.6 mg/L (Na$_2$HPO$_4$) and organic N 4 mg/L (Glycine) and Hong et al. (2006) also used nearly same type of pollutants in his study.

Table 2: characteristics of synthetic stormwater

| Parameters          | Value          | Source                               |
|---------------------|----------------|--------------------------------------|
| pH                  | 7.0            | HCl or NaOH                          |
| Total dissolved solids | 120 mg/L      | CaCl$_2$                             |
| Phosphorus          | 3 mg/L as p    | Na$_2$HPO$_4$                        |
| Nitrate             | 2 mg/L as N    | NaNO$_3$                             |
| Suspended solids    | 150 mg/L       | Local soil passed through a 0.59 mm sieve |
| Motor oil           | 20 mg/L        | Used oil from local garage           |

2.5 Bio-retention column experiment

A test run with tap water was done to optimize the inflow and outflow rate of the column.
The samples were taken at 1 hour interval after first instant of outflow from the column. Six samples were taken and analysed for the parameters. The parameters were analysed using standard protocol as described in APHA (2017).

3. Results and discussion

3.1 Properties of soil

The results of soil analysis used in the column as described in section 4.1, are shown in table 3. The grain size distribution curve is shown in figure 2.

![Grain Size Distribution Curve of Soil Sample](image)

| Properties      | Value  |
|-----------------|--------|
| Specific gravity| 2.71   |
| Sand (%)        | 3      |
| Silt (%)        | 67     |
| Clay (%)        | 30     |
| Liquid limit (%)| 41.5   |
| Plastic limit (%)| 24.5  |

As per USDA Textural triangular diagram, the soil sample is classified as silty clay loam as shown in figure 3 (USDA 1987).
3.2 Bio-retention column study

3.2.1 Total suspended solids

Figure 4 shows the percent TSS removal profile with duration. Influent concentrations had an average TSS concentration of 120 mg/L. The highest removal efficiency was observed in 15 days that had a removal rate ranging from 85-100%. This result suggests that the long-term dry period gives the best result in TSS removal.

Despite the high influent levels of TSS into the column the percent removal of solids in all dry period effluent is high, averaging 85%. Bio-retention is the most effective LID for TSS removal via filtration and sedimentation at generally over 80% total removal efficiency and 96% removal efficiency for particles larger than 50 mm. Although TSS is effectively removed via bio-retention, the continuous blockage of finer pore spaces makes TSS one of the leading factors causing reduction in hydraulic conductivity and a minimized lifetime of the media. This is especially an issue when the systems are subjected to large rainfall events causing massive runoff volumes transporting large quantities of sediment that generally are not picked up in smaller storms.
The filtration mechanism of bio-retention cells was investigated by Li and Davis (2008) through a series of bio-retention column tests and field observations. It was found that, as particulate matter is captured by bio-retention media, stratification tends to occur in the media. Finer soil particles were found in the upper media layer as suspended solids were trapped inside the media altering its characteristics and reducing its hydraulic conductivity.

3.2.2 Nitrate removal

In 7 dry days run, 75 to 78% nitrate removal was observed. Second best removal of nitrate results was observed in the 3 dry days: 60 to 69%. However, 15 days the removal rate was 58 to 67%. Nitrate removal in bio-retention cells is generally due to organic nitrogen mineralization, ammonium adsorption, microbial and plant uptake, and nitrification and de-nitrification. Dissolved nitrogen is primarily
removed through assimilation via biomass growth. Usually, ammonia is the only nitrogen species effectively removed by bio retention via adsorption and nitrification. Nitrate is a highly mobile ion that does not sorb to soil particles and requires long retention times and saturated conditions to be removed and is therefore not removed by conventional designs. Conventional systems in warm climate have achieved – 64% to 90% nitrate removal. Results from additional laboratory and pilot bio-retention studies showed moderate to poor ammonia and nitrate reductions.) the poor nitrate removal observed could be due to ammonification and nitrification processes occurring in the bio-retention unit between storm events. Since bio-retention systems are designed to drain rapidly, aerobic conditions should exist inside bio retention soils between storm events. Aerobic conditions are required for nitrification, while ammonification can be carried out by both aerobes and anaerobes. However, under low soil moisture conditions, de-nitrification rates are considered negligible as they are favored by anaerobic conditions. Nitrate can thus accumulate inside unsaturated bio-retention soils, to be released during subsequent storm events.

3.2.3 Phosphate removal

The 3 dry days period testing showed maximum removal of 89% as shown in figure 6. The next highest removal of total phosphorus is observed in 7 days dry period. The 7 days average removal was 83%. showed that a relationship existed between the amount of available phosphate in the treatment media and the TP removal efficiency of a bio-retention cell. The TP removal rate reported in the study was around 80 to 90%.

3.2.4 pH

Results from the laboratory tests on effluent pH showed that bio-retention soil media can significantly buffer the stormwater through the bio-retention column. Figure 7 shows no significant change in pH and it remained within the range of 7.0-8.0.

Table 4 summarizes the average removal efficiencies with respect to the dry days based on the bio-retention column studies.

| Parameter | Phosphate | Nitrate | TSS |
|-----------|-----------|---------|-----|
|           |           |         |     |

Table 4: Removal efficiency of phosphate, nitrate, TSS
| Duration | I mg/L | O mg/L | R (%) | I mg/L | O mg/L | R (%) | I mg/L | O mg/L | R (%) |
|----------|--------|--------|-------|--------|--------|-------|--------|--------|-------|
| 3 days   | 1 0.173 | 2 0.74 | 63    | 1 0.167 | 2 0.752 | 62.4 | 1 0.199 | 2 0.631 | 68.4 |
|          | 2 0.74  | 2 0.752 | 62.4  | 3 0.199 | 2 0.631 | 68.4 | 4 0.192 | 2 0.69  | 65.5 |
|          | 3 0.173 | 2 0.74  | 63    | 4 0.192 | 2 0.69  | 65.5 | 5 0.109 | 2 0.8   | 60   |
|          | 4 0.192 | 2 0.69  | 65.5  | 5 0.109 | 2 0.8   | 60   |        |        |      |
|          | Average | Average | Average | Average | Average | Average |
|          | 83.6    | 63.9   | 73.8   |        |        |      |
| 7 days   | 1 0.165 | 2 0.466 | 76.7  | 1 0.161 | 2 0.498 | 75.1 | 1 0.171 | 2 0.513 | 74.3 |
|          | 2 0.161 | 2 0.498 | 75.1  | 3 0.171 | 2 0.513 | 74.3 | 4 0.173 | 2 0.44  | 78   |
|          | 3 0.173 | 2 0.44  | 78    | 4 0.173 | 2 0.44  | 78   | 5 0.182 | 2 0.436 | 78.2 |
|          | 4 0.182 | 2 0.436 | 78.2  | 5 0.182 | 2 0.436 | 78.2 |        |        |      |
|          | Average | Average | Average | Average | Average | Average |
|          | 83      | 67.2   | 80.8   |        |        |      |
| 15 Days  | 1 0.25  | 2 0.65  | 67.2  | 1 0.254 | 2 0.824 | 58.8 | 1 0.232 | 2 0.787 | 60.6 |
|          | 2 0.254 | 2 0.824 | 58.8  | 3 0.232 | 2 0.787 | 60.6 | 4 0.257 | 2 0.684 | 65.8 |
|          | 3 0.232 | 2 0.684 | 65.8  | 4 0.257 | 2 0.684 | 65.8 | 5 0.259 | 2 0.644 | 67.7 |
|          | 4 0.259 | 2 0.644 | 67.7  | 5 0.259 | 2 0.644 | 67.7 |        |        |      |
|          | Average | Average | Average | Average | Average | Average |
|          | 75.2    | 64     | 90.2   |        |        |      |

Note: I- Inflow; O-Outflow; R- Removal

4. Conclusions

Bio-retention systems are efficient in removing nutrients and suspended solids from the stormwater. They could be an effective method of treatment in the urban stormwater management system. Maximum removal efficiency of 100 %, 78.2% and 89% was observed for TSS, nitrate and phosphate, respectively. pH change during the treatment was insignificant. The scale up these experimental results may be of practical value in urban stormwater management and pollution control.
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