Environmental Influences on Pollutants Removal in Modular Bioretention Swale

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Abstract: **The change in land use due to industrialization and urbanization has resulted in an increase in percentage perviousness in urban landscape. Nutrients and suspended solids accumulated on surfaces of urban cities are often washed into stormwater runoff receiving waterbodies causing eutrophic and unattractive waterbodies. As such, there is a pressing need to mitigate the impact of urbanization and industrialization by shifting towards the use of bioretention systems as a sustainable urban stormwater management system. Despite the large numbers of studies conducted to understand the influences and optimize the performance of bioretention systems; many of these studies were conducted on laboratory or pilot scale, which may not be applicable in field-based studies. Furthermore, many of the researches were done in Australia where there is seasonal changes thus may not be applicable to a tropical country like Singapore. In this study, a modular bioretention swale was constructed and monitored for its performance to improve the quality of urban stormwater runoff. Effluent quality from the bioretention system was observed to meet stormwater treatment guideline set by local government agency, with average removal efficiency of 50.7, 52.6 and 83.8% for total nitrogen, total phosphorus and total suspended solids respectively. It was observed that removal efficiencies of pollutants were affected by influent concentrations and their dissolved (soluble) percentages. Environmental influences such as soil moisture and air temperature also played a part in the performance of the bioretention system. However, due to different nature and removal pathway of the pollutants, the extent in which performance was impacted varied among the pollutants monitored in the project.**

Keywords: Bioretention; Modular bioretention swale; Urban stormwater runoff; Macronutrients removal; Nonpoint source pollution

I. INTRODUCTION

Nitrogen and phosphorus are macronutrients essential for plant growth. However, high concentration of these nutrients in waterbodies can lead to eutrophication. Anthropogenic eutrophication can be detrimental to the health of natural waterbodies as the increase in nutrients encourages algal growth (algae bloom). When the algae dies or respire at night, dissolved oxygen (DO) is used causing a drop in DO concentration in the waterbodies. This could result in the death of aquatic organism due to the lack of oxygen content for respiration. Eutrophication can also cause a drop in biodiversity due to increased competition and change dominating biota in waterbodies. Furthermore, it affects the amenity value of the water, increases downstream water treatment cost and may cause water to be injurious to health.

Growing population, industrialization and urbanization has resulted in the replacement of green areas like forests and natural wetlands with impervious surfaces for various urban land uses. Such developments alter stormwater runoff hydrology as well as water quality and the use of traditional stormwater management systems to divert stormwater runoff bypasses treatment of runoff through the infiltration of soil and vegetation. Pollutants accumulated on urban surfaces are washed into receiving waterbodies by stormwater runoff as they are not retained by the natural treatment processes causing elevated nutrients concentration and eutrophication in receiving waterbodies [1].

In response, PUB, Singapore's national water agency, launched the Active, Beautiful, Clean Waters (ABC Waters) Programme in 2006 that aims to improve the quality of water and to integrate drains, canals and reservoirs into surrounding landscape , creating blue and green community spaces and aesthetically pleasing streams, rivers and lakes [2]. In the initiative, bioretention swale was identified as an environmental-friendly feature which can mitigate the impact of urbanization by provided in-situ stormwater treatment before it is discharged into receiving waterbodies.

Many studies had been conducted to demonstrate the effectiveness of bioretention systems to minimize adverse effect of urbanization. Davis et al. found that bioretention systems were able to reduce 70 to 80% and greater than 40% of overall TP and TN concentration respectively [3]. An "optimally" designed biofilter was observed to remove up to 70% TN, 85% TP and consistently over 95% for TSS in a study done by Bratieres et al. [4]. Vegetated biofiltration mesocosms achieved 63 to 77% TN removal and 85 to 94% TP removal in another study by Henderson et al. [5].

The performance of bioretention systems is greatly dependent on its design and soil mixture used. Thus, many researches had been done to optimize the performance of bioretention systems. Hsieh and Davis [6] varied the media mixtures and configurations of 16 columns. Both infiltration rate and treatment capacity changed when soil media of different properties were utilized. The addition of soil amendments such as mulch or water treatment residue (WTR)

5th Annual International Conference on
Sustainable Energy and Environmental Sciences (SEES 2016)

ISSN 2251-189X
doi: 10.5176/2251-189X_SEES16.42

was able to improve nutrients removal due to increased complexation processes or sorption capacity.

Environmental parameters such as influent flow rate and duration, air temperature, influent concentration of the pollutant and the number of antecedent dry days before a rain event also affected pollutant removal efficiency. Increased influent flow rate and duration resulted in poorer pollutant removal due to possible bypass (overflow) and an increase in ponding height and flow rate through the media, compromising contact time [7]. Temperature and soil moisture affected microbial activities [8] which influence nutrients immobilization by microorganisms. McNett et al. [9] noted that effluent tended towards a baseline concentration thus "dirtier" influent yielded higher removal efficiency by the bioretention facilities. Long dry periods can lead to nitrate production worsening nitrogen removal [10].

However, many of these researches were done on laboratory or pilot scale. There are a limited number of field studies done on bioretention systems. Furthermore, the researches were done mainly in Australia where seasonal changes in weather are observed. Differences in seasonal weather and meteorological conditions will affect plants and microbial health as well as microbial consortium present thus shaping the performance of bioretention systems. Thus, this project aims to monitor and determine possible environment influences of the performance a modular bioretention swale system in a tropical country, Singapore.

II. Materials and Methods

A. Modular Bioretention Swale

The bioretention swale constructed consists of 3 different soil layers – filtration layer, transition layer and drainage layer. Figure 1 shows the vertical profile of the swale constructed.

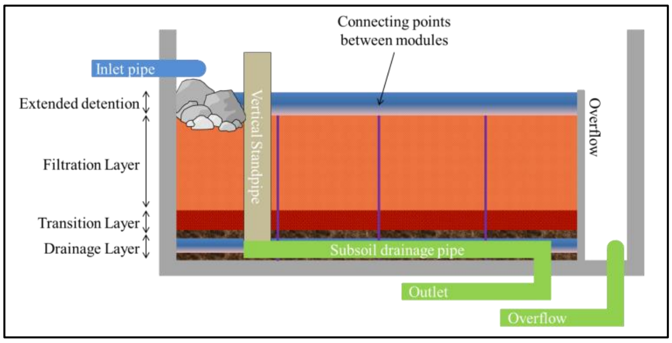

Figure 1. Vertical Profile of bioretention swale

The modular bioretention swale was constructed in fiberglass reinforce plastic (FRP) modules. Such design allowed for ex-situ construction which minimizes time required and disturbance to the general public during construction. The modular design also help to ensure a standard good design and consistent construction quality. The modular design could be customized according to the length of swales required. A total of 4 modules, which included 1 inlet module, 2 mid modules and 1 overflow module, were used in this case.

An engineered soil (patent pending) containing WTR and coconut fiber as soil amendments was used as filter media of the bioretention system. The use of these amendments had shown to achieve high removal efficiencies of pollutants in previous studies [11].

B. Site Location

Singapore is small country (with total land area of 719.1 km^2) located near the equator. Owing to its geographical location and maritime exposure, Singapore experiences uniform temperature and pressure, high humidity and abundant rainfall throughout the year. There are two major monsoons seasons – Northeast Monsoon from December to early March and Southwest from June to September [12]. The country receives an average of 2338.5 mm rainfall annually with higher rainfall occurring from November to January during the wetter period of the Northeast Monsoon.

The bioretention facility studied was constructed in NUS High School of Mathematics and Sciences (NUSH), an education institute in Singapore, in November 2014. The school is located in the southwest of Singapore. The school has a student population of approximately 1300 ranged from 13 to 18 years of age. The bioretention swale is located beside a small road that runs around the school. Stormwater runoff from a section of the road was diverted into the bioretention system. The facility was also located near the school canteen where the student population gathered during mealtimes throughout the day.

C. Sampling and Analysis

Influent samples were collected using an automatic water sampler (Hach, 900MAX Portable Sampler). The sampler was triggered when water level in the inlet chamber reached 1 cm measured by a flow and level sensor (Hach, Sigma Submerged AV Sensor). Sampling interval was set at 6 minutes interval. A single effluent sample was collected at the subsoil drainage pipe of the system for each rainfall event.

Apart from flow data, soil moisture information at different soil depth (100 mm, 200 mm and 400 mm) was also collected using soil moisture sensor (Decagon, EC-5) installed. Air temperature (Decagon, VP-3) and rainfall (Hach, Rain gauge) information at the site were also recorded.

Water quality tests performed were in accordance to the Standard Methods for the Examination of Water and Wastewater [13]. Water quality tests included tests for total and dissolved phosphorus (TP, DP), total and dissolved nitrogen (TN, DN), as well as total suspended solids (TSS). Filtration with 0.45 µm pore size membrane filter (Pall Corporation, GN-6 Metricel MCE membrane disc filters, S Pack) was done to obtain "dissolved" pollutants. TP concentration was measured using PhosVer 3 with Acid Persulfate Digestion Method (Hach method 8190) [14] (Hach, Phosphorus (Total) TNT reagent set). Total organic carbon (TOC) analyzer (Shimadzu, Total organic analyzer TOC-L series) was used to determine TOC and TN concentration. 0.7 µm pore size glass microfiber filters (Whatman, GF/F) was used to filter out TSS in the samples

D. Result Analysis

Event mean concentration (EMC) was calculated for influent sample. The calculation of EMC allowed for a more accurate representation of pollutant loading as flow variation was accounted for. Equation 1 as shown was used to calculate EMC.

$$EMC = \frac{\sum(C_t \times V_t)}{V_{total}} \quad (1)$$

III. Results and Discussion

A. Pollutants Removal

The performance of the bioretention swale to removal pollutants was evaluated with respect to the local guidelines on stormwater treatment objectives for TN, TP and TSS removal as shown in table 1.

TABLE 1 STORMWATER TREATMENT OBJECTIVES **[2]**

Pollutants	Stormwater Treatment Objectives
Total suspended solids	80% removal or less than 10 ppm
Total nitrogen	45% removal or less than 1.2 ppm
Total phosphorus	45% removal or less than 0.08 ppm

1) TN Removal

Effluent TN concentration from the bioretention facility ranged from 0.05 to 1.18 ppm (Figure 2). All effluent samples collected during the monitoring period met stormwater quality guideline of lower than 1.2 ppm. This could be due to low nitrogen loading in the influent (influent TN concentration ranged from 0.13 to 1.61 ppm). Thus, little or no treatment was required by the swale. Despite so, the system was able to achieve an average TN removal of 50.7% after stabilization period.

Leaching of nitrogen was observed for 8 months (until July 2014) since the monitoring of the system. The long leeching period could be due to a drought period from December 2013 to March 2014. Frequent rainfall events can help to wash out nutrients in the soil column thus shortening leaching period of the bioretention system. Furthermore, prolonged dry periods can lead to nitrate production in the soil column. The nitrate produced could be washed out in the following rainfall causing TN concentration to be higher in the effluent sample compared to the influent samples.

2) TP Removal

Effluent TP concentration ranged from 0.02 to 0.12 ppm with average removal efficiency of 52.6% (Figure 3). Unlike TN, no leeching was observed for TP. This could be because of the presence of WTR in the filter media. WTR contains alum (coagulant used in water treatment process) which had shown to have high sorption capacity of phosphate. Furthermore, a percentage of TP was noted to be associated with particles or particulates. This allowed for better removal of TP as the pollutant can be removed through filtration by the soil column.

Most effluent samples contained TP concentration lower than 0.08 ppm, stormwater treatment guideline, during the monitoring period. Effluent samples with TP concentration higher than 0.08 ppm could be due to high TP loading. For these events, removal efficiency of TP was observed to be higher than 45%, meeting stormwater treatment guideline.

3) TSS Removal

Excellent TSS removal was achieved by the bioretention swale. Effluent TSS concentration ranged from 0.1 to 20.0 ppm with average removal efficiency of 83.8% (Figure 4). Average pollutant removal efficiency met stormwater treatment guideline of 80% TSS removal. No leaching was observed for TSS.

B. Influent Concentration and Distribution

Pollutant removal efficiency, but not effluent pollutant concentration, was observed to be affected by the influent concentration. Influent samples with high pollutant loadings tend to produce high removal efficiency while low pollutant loading resulted in lower removal efficiency. This observation was similar to that of McNett et al. [9]. One possible explanation for this observation could be the increase in microbial activities when influent stormwater runoff contained higher nutrients loading. Increased bioavailability of nutrients can stimulate uptake by plants and soil microorganisms thus allowing for better removal efficiency. Increase pollutant loading would also allow for easier removal as large amount of pollutants were present in the stormwater runoff.

Apart from influent concentration, the distribution of nutrients between dissolved and particulate also affected removal efficiency of pollutants as shown in Figure 5.

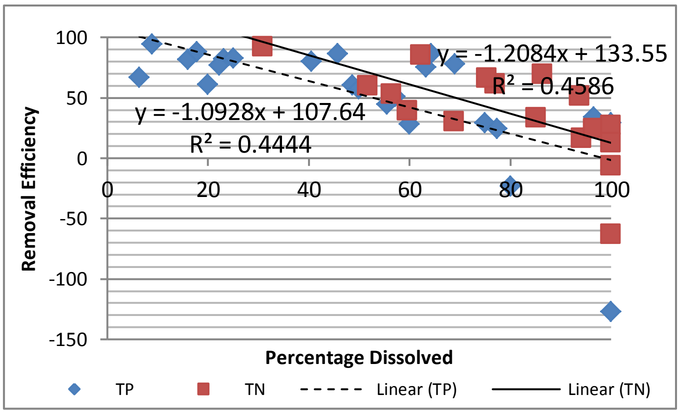

Figure 5. Influence of dissolved percentage on removal efficiency

Particulate pollutants were observed to be more effectively removed by the bioretention system. This could be due to the different removal mechanisms involved in pollutant removal. Suspended solids were removed via filtration process through the soil column. Such physical means were less affected by environmental factors. However, for dissolved pollutants, removal mechanisms include sorption and plants or microbial uptake. These mechanisms were influenced by environmental parameters such as soil moisture, temperature and number of antecedent dry days. Soil moisture affected the availability and mobility of pollutants for sorption and microbial uptake, while temperature and number antecedent dry days may affect the health of microbial community in the soil. Thus, the removal of dissolved pollutants may be more difficult thus resulting in a relatively lower and more variable removal efficiency.

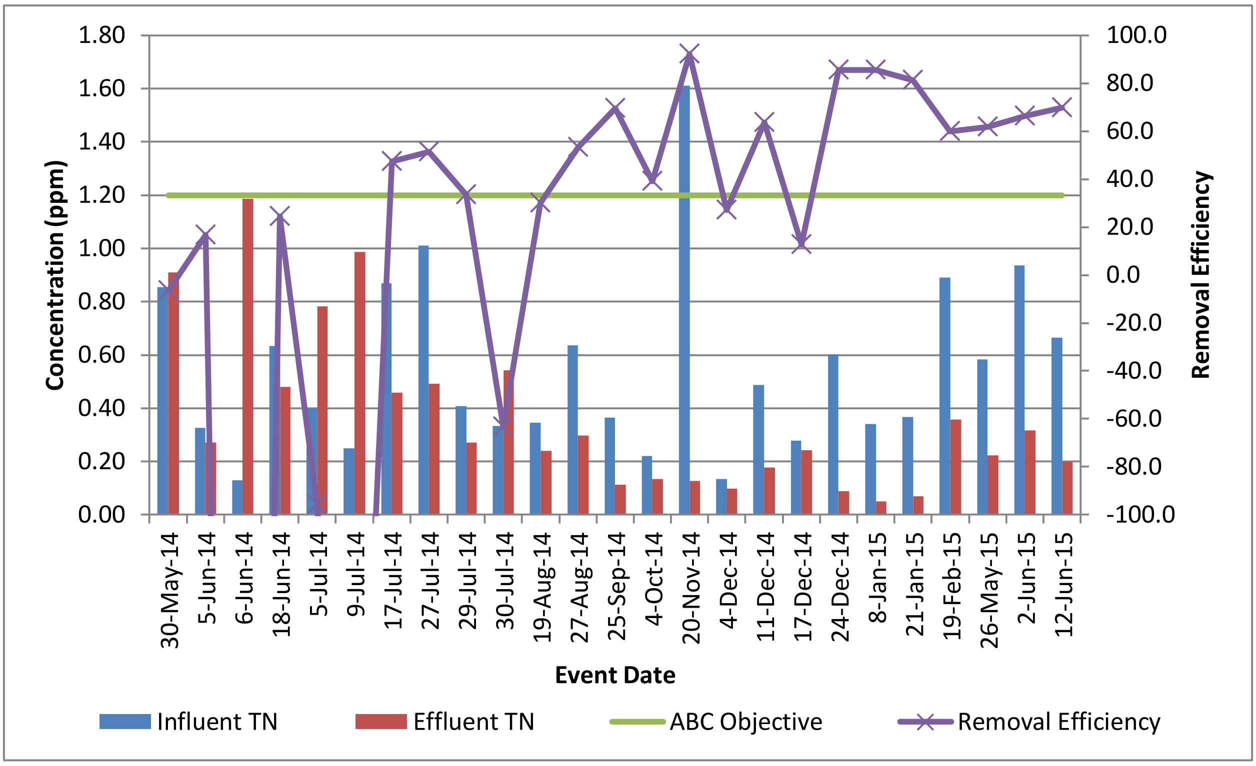

Figure 2. Influent and effluent TN concentration and removal efficiency

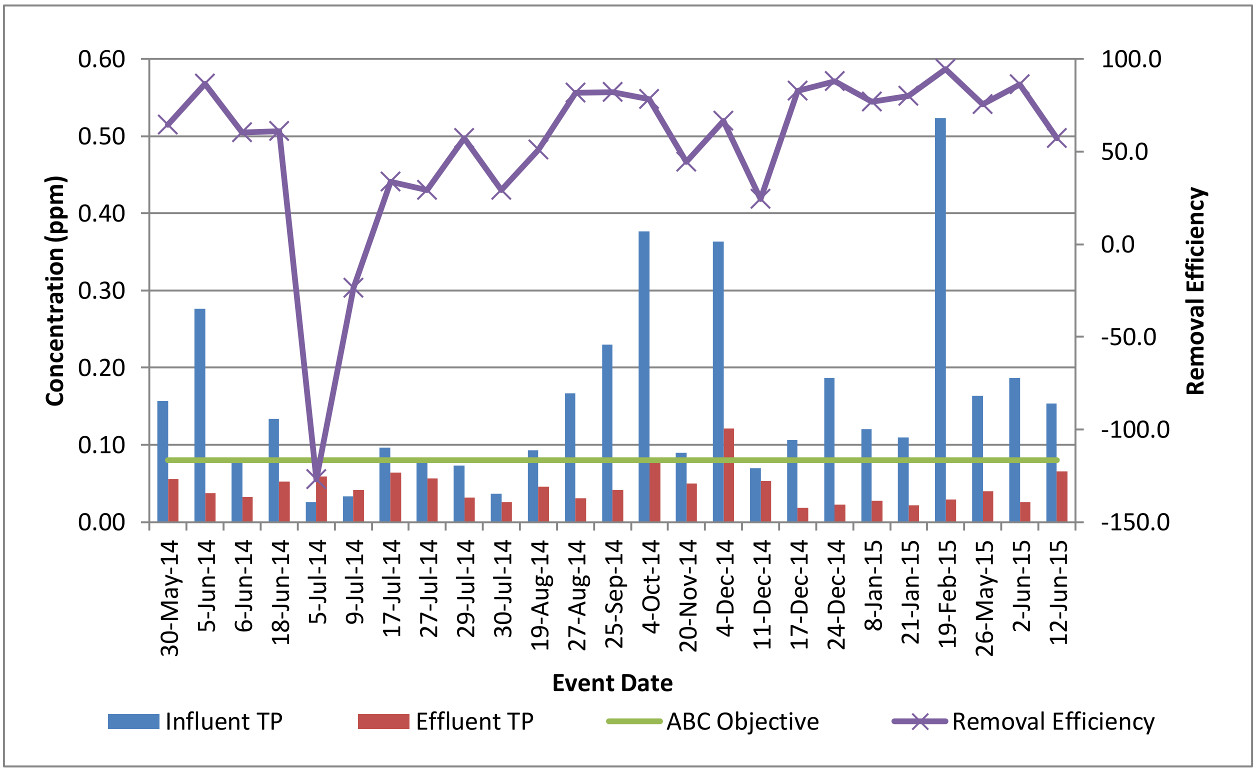

Figure 3. Influent and effluent TP concentration and removal efficiency

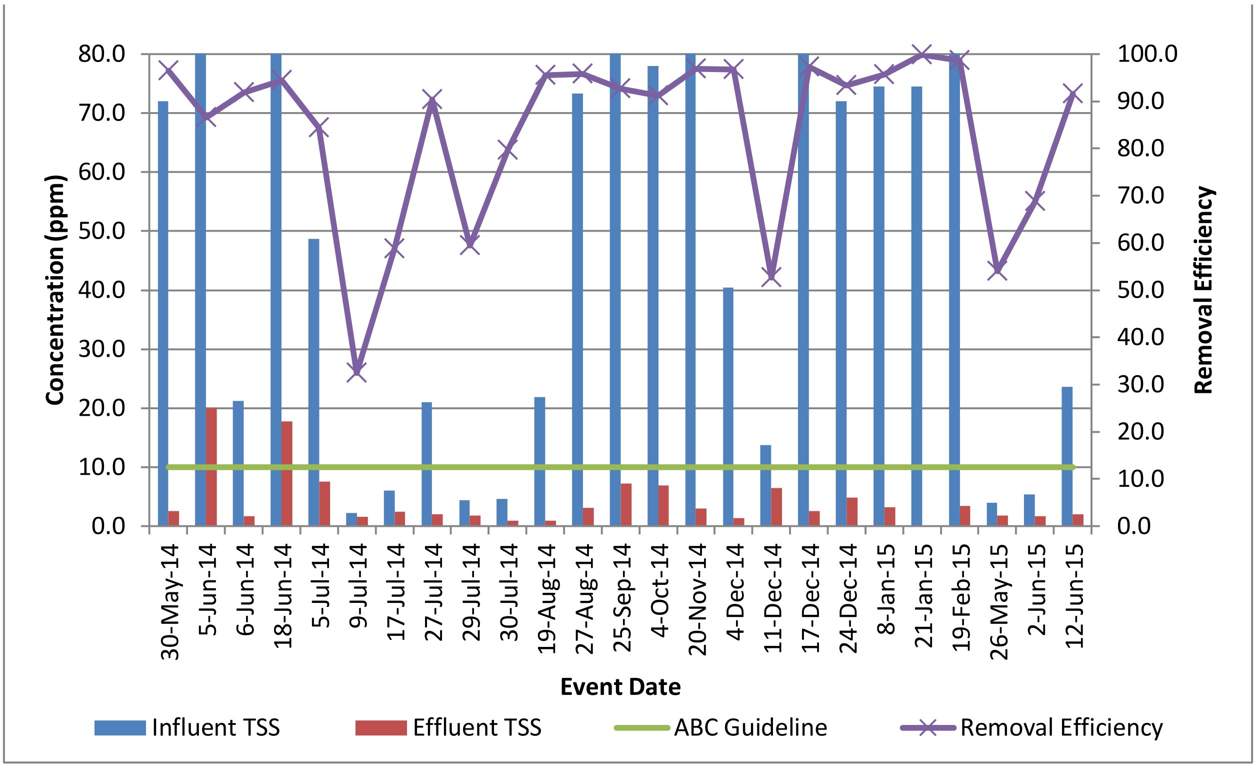

Figure 4. Influent and effluent TSS concentration and removal efficiency

C. *Soil Moisture*

Removal efficiency of TP and TSS was observed to have little relationship with soil moisture. However, TN removal efficiency displayed relatively stronger relationship with the maximum soil moisture content during the rainfall event (Figure 6).

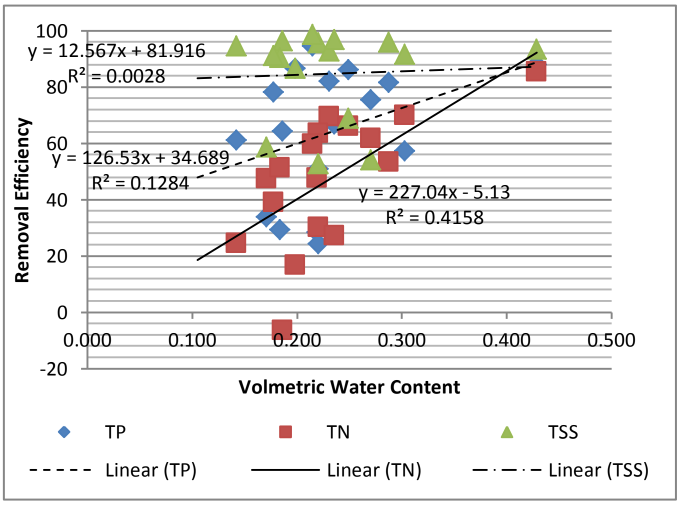

Figure 6. Influence of maximum soil moisture on removal efficiency

One possible removal mechanism of TN was denitrification process. This process is facilitated by facultative anaerobic bacteria. At high soil moisture, the soil may be in anoxic condition which facilitates denitrification process. Higher soil moisture also reduces water potential, i.e. the amount of energy plants and microbes need to exert to absorb water. With higher soil moisture, it would be easier for plants and microbes to absorb water along with the dissolved nutrients. This allowed for better dissolved pollutants removal.

Removal efficiency of TP and TSS were less affected by maximum soil moisture. As higher percentage of TN was dissolved compared to TP (50.2%) and TSS, the removal of TN may be more affected by soil moisture as higher soil moisture would allow for better plants and microbial uptake. Removal of TP and TSS could be mainly driven by physical filtration which is less affected by soil moisture. The effectiveness of soil filtration process is mainly determined by the inter-particle pore sizes of the filter. Thus, soil moisture had little effect in the removal of particulate pollutants. It can be observed in Figure 3 that soil moisture had a weak influence on the removal efficiency of TP. This could be due to a fraction of the pollutant being dissolved.

D. *Air Temperature*

A positive relationship between air temperature and nutrients removal was observed (Figure 7). This could be due to increased microbial activities due to higher temperature. However, the r^2 value of the curve obtained was relatively small showing that air temperature did not have a significant impact on nutrients removal efficiency. The small r^2 value could also be due to small variation in air temperature observed.

TSS removal efficiency was observed to decrease with air temperature. The different trend observed for TP and TN could be due to the possible influences from other pollutant mechanisms such as sorption and plants and microbial uptake. TSS participates little in chemical and biological processes and was mainly removed via physical filtration through the soil media. Rapid sand filtration process is affected by temperature [15]. Increased temperature can lead to poorer sedimentation due to increased diffusion and Brownian motion.

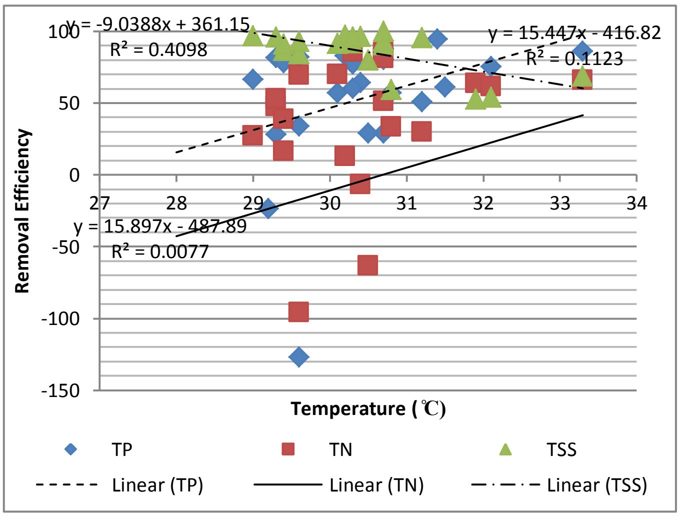

Figure 7. Influence of temperature on removal efficiency

IV. Conclusion

In conclusion, the bioretention system constructed worked well to remove nitrogen, phosphorus and suspended solid from stormwater runoff to mitigate the effects of urbanization and industrialization. Effluent samples collected met stormwater treatment quality set by local environmental agency. Effluent TN, TP and TSS concentrations were observed to be 0.05 to 1.18 ppm, 0.02 to 0.12 ppm and 0.1 to 20.0 ppm respectively. Nitrogen leaching was observed for 8 months. Long leaching period could be due to prolonged dry and hot weather after the completion of the modular bioretention swale. The addition of soil amendments to the engineered soil used as filter media for the swale has proven to help in preventing phosphorus leaching and improve phosphorus removal. TSS removal efficiency (83.8%) was significantly higher than that observed for nutrients removal (50.7% for TN and 52.6% for TP) possibly due to relatively simpler removal mechanism that are less influenced by environmental parameters.

A few of environmental influences were identified in the research. It was found that pollutant loading lead to higher removal efficiency of TN, TP and TSS. However, there is no strong relationship between pollutant loading and effluent quality. The distribution of pollutants between dissolved and particulate form also affected the performance of the bioretention system. Higher removal efficiencies were observed when influent samples contained lower fraction of dissolved pollutant for TN and TP.

Maximum soil moisture influenced nitrogen removal but not phosphorus or suspended solid removal. Air temperature also displayed differing effect on nutrients and TSS removal. However, the influences are weak and not very significant

Acknowledgment

The authors would like to acknowledge PUB, Singapore's National Water Agency for its funding support of the project (R-706-000028-490) and for providing the WTR used in the project.

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