Analysis of Biofiltration Efficiency for Treating Stormwater Runoff from a Parking Facility

by

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Abstract

Biofiltration units (e.g. bioswales and rain gardens) are depressed landscape areas that are designed to receive and filter stormwater runoff. They are applicable in residential and commercial environments with grass, shrubs and perennials plants. The top soils are usually covered with shredded hardwood bark and mulch. The benefits of biofiltration applications include decreased surface runoff, increased groundwater recharge, and pollutant treatment through a variety of processes.

The use of the biofiltration as a BMP (Best Management Practices) for treating stormwater runoff has been advocated for in many parts of the world. However, results from many installed units show that biofiltration application for water quality improvements has not always been positive due to inappropriate design and poor maintenance. This is evident in the limited and inconsistency in available data for biofiltration application performance from different studies.

It is against this background that this study was undertaken to evaluate the performance of the rain garden and the bioswales (biofiltration swales) constructed on the campus of Youngstown State University to treat stormwater runoff from a parking facility. Stormwater samples were taken from biofiltration inlets, outlets and along the biofiltration units after rain events over a period of ten months. Samples were analyzed for a variety of water quality parameters including nutrients (ammonia-nitrogen, total phosphorus and nitrate-nitrogen), metals, oil and grease, conductivity as well as pH. Parameters were analyzed according to the American Standard Methods. Laboratory results were then analyzed using SPSS statistical software (repeated measures) to compare concentration changes along the biofiltration units. Results from the study

indicated that the biofiltration units on Youngstown State University campus is efficient in removing 81.3% total suspended solids (TSS) , 39.1% total phosphorus (TP), 58.1% ammonia (NH_3-N), 7.4% reduction in conductivity and 28.5% reduction in chemical oxygen demand.

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Chapter 1 Introduction

Bioswales (biofiltration swales) and rain gardens are vegetated filtering systems used in treating stormwater runoff. They are recommended by the United States Environmental Protection Agency (U.S. EPA) as best management practices (BMPs) in reducing groundwater and surface water (streams, rivers, and lakes) pollution (Jurries 2003). Bioswales and rain gardens are examples of biofiltration units under structural BMPs which are commonly constructed along streets (*streetscape*), parking lots and landscapes of residential, industrial and commercial sites.

Examples of stormwater pollutants that biofiltration units treat include ammonia-nitrogen (NH_3-N), nitrite and nitrate-nitrogen (NO_3-N), phosphorus (P), dissolved metals (such as Zn, Cu, and Pb), total suspended solids (TSS), oil and grease and total petroleum hydrocarbon (TPH). According to Tchobanoglous et al. (1991), biofiltration was first introduced in 1893 in the United Kingdom as a trickling filter for treatment of contaminated water bearing biodegradable organic compounds. Its application in stormwater treatment began in the late 1980's and 1990's in Europe (Waag et al. 2008). In recent years, individuals, municipalities and organizations are incorporating the technology into landscape and streetscape designs to prevent surface water pollution downstream from non-point sources.

Overview of Biofiltration Units on Youngstown State Campus

As a means of incorporating environmentally friendly and pollution prevention measures on its campus, Youngstown State University constructed two bioswales and a rain garden on one of its parking lots in 2005 to treat stormwater runoff prior to discharge into a combined sewer. Although there were two bioswales and one rain garden examined, they will be referred to as biofiltration units throughout (except when necessary). The stormwater runoff infiltrates through the biofiltration units during rainfall; although, their pollutant removal capabilities and overall efficiency are not known. Therefore the main questions that this research seeks to answer are:

1. Are the bioswales and rain garden really working as designed?
2. What are the working efficiencies?
3. What are the best available maintenance plans?

These questions call for evaluation and analysis of the biofiltration unit's performance and the unit's contribution towards reducing water pollution from non-point sources.

Protecting Natural Waters

Water is one of the most abundant natural resources on the surface of the earth. It covers about 70 percent of the surface of the earth (Masters 1991). Water plays an important role in the lives of living things and the environment as a whole. It has the ability to dissolve more substances than any other solvent. Due to this property, it serves as an effective medium for transporting dissolved nutrients to tissues and organs in living things as well as eliminating their waste. In the natural environment, water transports dissolved substances throughout the biosphere. Surface water contributes significantly to the world's climate (humidity) through the hydrologic cycle. It also supports terrestrial and aquatic life, just to mention a few of its functions.

The functions of water in the environment are dependent on its chemical, biological and physiological properties. Alteration in the chemical and biological properties of water affects its natural quality and ability to function to support life and other living organisms in the food chain. Both human and natural activities contribute to the deteriorating of water quality and functions. Excessive weathering, volcanic eruptions, snowmelt and heavy rain falls (stormwater) are examples of natural phenomena that generate substances that deteriorate water quality. Human activities such as agriculture, construction, manufacturing, illicit and improper disposal of materials and wastes also contribute to water contamination. These sources of contamination may be from a known and specific point (point source) or may be untraceable and from unspecific points (non-point sources). Surface and ground waters are humans', as well as other living organisms', main source of water, but they are susceptible to contamination and, therefore, need to be protected. Water changes that can cause deterioration of water quality include excessive nutrients, high salts, metals or organic compounds.

Excessive amounts of chemical elements (nutrients) such as nitrogen, phosphorus, carbon, sulfur and potassium lead to eutrophication and deterioration in water quality. The excessive nutrients change the natural chemistry of water and enhance the growth of aquatic plants and algae (particularly nitrogen and phosphorus). When these aquatic plants and algae die, they increase the amount of organic material in the water; this then increases decomposition rate and the rate of dissolved oxygen consumption. This process greatly depletes the amount of oxygen available for other aquatic organisms such as fish and macroinvertebrates and decreases biodiversity. In addition to reducing available oxygen, algae and decaying organic matter in surface water contribute to color, turbidity, odors and taste in surface water.

Water has the ability to dissolve minerals (solids or salts) from surfaces that it flows over or comes in contact with. The concentration of dissolved solids is an indicator of water salinity. Sodium, calcium, potassium and bicarbonates contribute to water salinity. A measure of total dissolved solids (TDS) is an indicator of the conductivity of the water. Beyond certain concentration (150 and 500 µmhos/cm) of salt in water, it becomes toxic for aquatic life (C&WQ 2008).

Besides nutrients and salts from land runoff, anthropogenic activity can lead to increases in organic compounds and heavy metals. Activity from mining, leather tanning, and many other industrial activities add elevated metals; even stormwater from homes and parking lots have been identified as having higher levels of metals. Metals such as aluminum, arsenic, beryllium, bismuth, chromium, lead, nickel and a variety of others contaminate surface waters, causing toxicity for many aquatic organisms. Another group of water contaminants are organic compounds which are insoluble in water. Petroleum hydrocarbons (oil and grease) and vinyl chloride are examples of organic compounds that contaminate surface and ground water. Many of these contaminants come from parking facilities, roof runoff, atmospheric deposition and industrial processes.

Stormwater

Stormwater discharges are generated by runoff from land and impervious surfaces (streets, parking lots and rooftops) during rainfall and snow events. They often contain pollutants in quantities that could adversely affect surface water quality. According to the United States Environmental Protection Agency (EPA), most stormwater discharges, if they originate from known source, are considered point sources and require coverage by an NPDES (National Pollutant Discharge Elimination System) permit (US EPA 1980).

Stormwater is primarily a non-point source of pollutant if it originates from diffuse source. It can contain a variety of pollutants including pesticides, fertilizers, debris, particles and nutrients (including nitrogen and phosphorus). The type of pollutants varies from location to location depending on activities undertaken in the immediate environment such as fertilizer application on lawns, farmlands, commercial landscaping, golf courses and recreational facilities. Rusting and wearing parts of vehicles, buildings, roofs and commercial sites have also been found as sources of heavy metals contribution in stormwater. Oil and grease from leaking cars onto parking lots and industrial sites and salts from deicing occur in areas receiving water from surfaces of parking lots or streets where vehicular traffic is common. Stormwater runoff carries these pollutants into city drain systems during rain events. In some municipalities, stormwater runoff flows directly into local streams or lakes with its contents.

In most municipalities, the drainage systems are designed to receive stormwater runoff. The runoff usually flows into combined sewer systems to a publicly-owned treatment works (POTW) for treatment prior to discharge into a receiving water body. In the events of heavy downpours, combined sewer systems capacities can be exceeded and this can result in stormwater overflow into receiving water bodies without treatment. As part of stormwater management programs to protect waters from pollution, the EPA has authorized states to establish and implement regulations, practices and technologies that protect water bodies (Clean Water Act 1972).

The Clean Water Act

The Clean Water Act (CWA) has a history of a series of enactments, spanning from 1899 which aim at preventing discharge of pollutants into natural waters (US EPA 1972).

The early enactments prohibited the discharge of any type of refuse other than liquids from streets and sewers into navigable waterways without a permit (US EPA 1986). Human waste, the primary cause of waterborne disease, was also the major issue in the earlier days. As the years went by, water pollution regulations were amended to cover all aspects and sources of water pollution including agriculture, manufacturing and construction industries.

Currently, the objective of the CWA is "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters'' (US EPA 1986). There are several regulatory frameworks and programs that incorporate permit systems; BMPs, Water Quality Criteria and Standard programs are geared towards the achievement of the CWA objectives. In 1987, the US Congress amended the federal Clean Water Act to require stormwater discharge permits under the EPA's National Pollutant Discharge Elimination System (NPDES). This amendment, which is known as the Phase I of NPDES, is intended to minimize polluted discharge from stormwater runoff into combined sewer overflows. It calls for permits for stormwater discharge from municipalities with populations over 100,000, construction sites and specific industrial activities.

Phase II of NPDES was an expansion of Phase I to include stricter regulations and the regulation of additional sources of stormwater to protect water quality. To achieve the objectives of the NPDES, the EPA has established six minimum control measures under the BMPs approach for small municipalities. The six minimum control measures are:

1. *Public Education and Outreach Program* on the impacts of stormwater on surface water, and possible steps that can be taken to reduce stormwater pollution. The

program focuses on the general community, commercial, industrial and institutional discharges.

2. *Public Involvement and Participation* in developing and implementing the stormwater management plan.
3. *Elimination of Illicit Discharge to* municipal separate stormwater systems (MS4s) to prevent unauthorized discharge of wastes other than stormwater.
4. *Construction Site Stormwater Runoff Ordinance* that requires the use of appropriate BMPs' pre-construction reviews of stormwater pollution prevention plans (SWP3s), site inspections during construction for compliance with the SWP3 and penalties for non-compliance.
5. *Post-Construction Stormwater Management Ordinance* requires the implementation of structural and non-structural BMPs within new development and redevelopment areas, including assurances of the long-term operation of these BMPs.
6. *Pollution Prevention and Good Housekeeping* for municipal operations such as efforts to reduce stormwater pollution from the maintenance of open space, parks and vehicle fleets.

The establishment and expansion of the NPDES policy was the result of a joint collaboration of the EPA, environmental groups, and municipalities. The policy contains a presumptive clause with emphasis on meeting water quality standards (Roesner and Traina 1994).

Water Quality Standards

Water quality standards (WQS) are the EPA's ways of translating the broad goals of the CWA into waterbody-specific objectives. According to the EPA, WQS should be expressed in terms that allow quantifiable measurements. The three major components of the WQS are

1. *Designated Uses (DUs)*, the assigned use of a water body by society such as recreational, agricultural, or industrial purposes.
2. *Antidegradation Policies* are established sets of rules that should be followed with respect to activities that could lower the quality of high quality waters.
3. *Water Quality Criteria* are scientific descriptions of the levels of individual pollutants or water quality characteristics of a waterbody necessary to support designated uses. Water quality criteria are expressed as concentrations of pollutants, temperature, pH, turbidity units, toxicity units or other any quantitative measures. It can be narrative statements for instance, “no toxic chemicals in toxic amounts”.

In addition to regulatory frameworks, the EPA supports the utilization of engineered technologies to treat and restore contaminated waters and treat contamination at the source of generation.

Due to the implementation of regulatory programs over the past three decades, pollutants from point sources of pollution, such as industrial facilities and municipal sewage systems, are no longer the major cause of surface water pollution. The major cause of pollution is now associated with diffuse (non-point) sources (US EPA 1986).

Best Management Practices

Best Management Practices (BMPs), both structural and non-structural, are useful practices (engineered and non-engineered) in protecting natural waters from the effect of stormwater runoff and other non-point sources. They are used to provide preliminary treatment of runoff that has the potential to cause a change in the quality of the receiving water body. Nonstructural BMPs programs focus on activities such as Pollution Prevention, Watershed Management Plans, Preventive Construction Techniques, Outreach and Educational Programs and Riparian Areas. On the other hand, structural BMPs involve design and engineering techniques that incorporate natural means of treating stormwater runoff.

Structural BMPs of treating stormwater pollutants include but are not limited to Infiltration Basins, Infiltration Trenches, Sand Filters, Grassed Swales, Vegetative Filter, strips, Vegetated Natural Buffers, Open Spaces, Extended Detention Dry Basins, Wet Ponds, Constructed Wetlands, Porous Pavement and Concrete Grid Pavement, Oil/Grit Separators or Water Quality Inlets, Level Spreaders, French Drains, Dry Wells or Roof Downspout Systems, Ex-filtration Trenches, Rain Gardens, Vegetated Buffers and Bioswales. Under these practices, stormwater runoff is directed into these facilities and allowed to infiltrate through the plants, mulch and soil/sediment environment for assimilation of the pollutants in the runoff.

Biofiltration Technology

Biofiltration processes employ the principles of phytoremediation, infiltration, absorption, ion-exchange and microbial actions (microorganisms). A well designed biofiltration unit with the appropriate plants, soil and rock arrangements absorb, filter and purify stormwater runoff as it infiltrates through the unit. The EPA encourages states, counties and owners and managers of facilities to identify and implement effective BMPs for improving stormwater runoff. Rain gardens and bioswales are typical examples of vegetated filtering systems that utilize the process of biofiltration in treating stormwater runoff. They are designed to trap nutrients, sediments, petroleum products and other related pollutants while allowing unrestricted flow of water into drainage systems. They are incorporated in recreational parks, residential, industrial and commercial landscapes and streetscapes.

Bioswales and Rain Gardens

Basically, bioswales and rain gardens perform the same functions. The major differences lie in the design parameters and site of location. A bioswale is a constructed vegetated swale, ditch or depression that transports stormwater runoff. Pollutants are immobilized, broken down and retained while infiltrating through the vegetation and sediments.

Bioswales fall under two categories based on the degree of vegetation and cross sectional shape. Under the degree of vegetation, they are described as fully vegetated and open channel vegetation. In terms of cross sectional shape, bioswales are categorized as ‘U’, ‘V’, and ‘trapezoid’ (Jurries 2003).

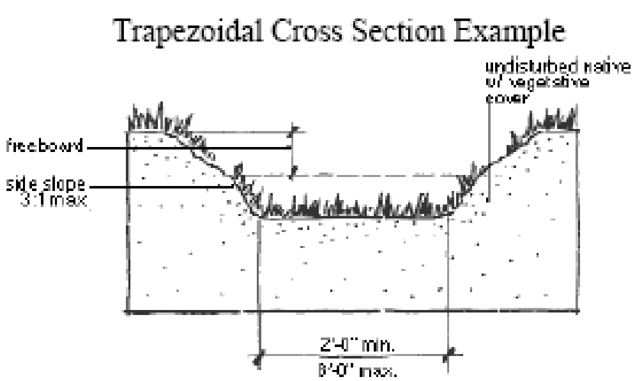


Figure 1-1 Cross sectional view of a trapezoidal bioswale

Rain gardens are shallow swales and depressions that hold water temporarily rather than let it flow quickly. Rain gardens serve as bioretention basins that collect and hold stormwater runoff. They are noted for improving water quality through high retention rate, capturing and absorbing pollutants in stormwater runoff. A properly designed rain garden can hold stormwater for a maximum of 48 hours (Geauga 2006).

Bioswales and rain gardens are biofiltration units designed and constructed to perform three main functions:

1. *Improve stormwater runoff quality*:

   They are designed and constructed to physically filter pollutants and enhance chemical and biological processes that remove pollutants from stormwater runoff. Sedimentation, filtration, absorption and biological uptake are the processes by which biofiltration units remove stormwater pollutants.

2. *Stormwater Detention:*

   Biofiltration units serve as stormwater detention ponds for flood control. Stormwater detention reduces peak flows from sites, thereby mitigating possible downstream flood hazards. Decreased flow rates due to detention promote the sedimentation of particulates and associated pollutants. Furthermore, lower flow rates reduce and elongate pollutant loading to downstream receiving waters (Cunningham et al. 1997).

3. *Aesthetic Purposes:*

   Though the primary purpose of biofiltration units is to improve stormwater quality, they also enhance the beauty of the environment with the plant features (Geauga 2006).

The application of biofiltration systems to promote water quality has been advocated for many years. The rate of application of the technology has increased worldwide over the past decade, specifically in the area of stormwater management practices and incorporation of sustainable designs in landscaping and streetscaping. The increase in the application is primarily due to the eco-friendly and cost-effectiveness of the technology compared to conventional treatment methods (Srivastava and Majumder 2008). In a research report on the performance of grass filters used for stormwater treatment, the technology is regarded as the simplest and most cost-effective form of stormwater control measures (Deletic and Fletcher 2006).

Design parameters that affect biofiltration system performance include: unit capacity, surface area, bed media, porosity, slope, channel bottom width, flow depth, flow velocity, retention time, roughness co-efficient and length of channel. Design specifications may differ from one geographical location to another or according to local EPA standards. The following are examples of recommended design parameters for high efficiencies of biofiltration unit performance by the city of Salem, Oregon and other sources.

- *Slope.*

  Slope should be steep enough to prevent ponding and shallow enough to slow water velocity. Soils must not readily drain water; the goal is to get cleaner water to flow downstream. Recommended slopes range: 1.0% to 4.0%.

  Deletic and Fletcher (2006) comment that swale designs which create a thin-film flow and maximize potential for soil sorption of orthophosphate may enhance phosphorus (TP) removal. They suggests that buffers will not work effectively with slopes of greater than 5%.

- *Channel Bottom Width.*

  A wider channel allows for maximum filtering surface and for slower water spreading throughout the system. Maximum widths prevent shallow flows from concentrating and gullying. This leads to maximizing the filtering as the runoff flows through the vegetation structure on the bed.

- *Roughness coefficient.*

  Roughness coefficient is a parameter that varies with the type of vegetative cover and flow depth. There should be sufficient roughness to slow water velocity and to allow water to contact vegetation within its journey through the bioswale.

- *Flow depth.*

  Flow depths should not be taller than the vegetation (grass). Maximum depth of 4" is recommended.

- *Flow Velocity*.

  Flow should be sufficiently low enough to provide adequate residence time within the channel. A maximum flow velocity of 1.0 feet per second for water quality treatment is required. 2-year storm events should be non-erosive, usually having not greater than 4-5 feet per second (ft/s) velocity.

- *Length of Channel.*

  It is recommended that the channel lengths of biofiltration units should be long enough to provide approximately 10 minutes of residence time.

- *Vegetation and Soil Conditions*

According to a report by Clean Washington Center (1997) on a “Study of Compost use in Bioswales for Compost Market Expansion” the vegetation and soil on biofiltration units play an important role. They employ filtration, absorption and ion exchange mechanisms in reducing pollutant concentration in stormwater runoff. The report emphasized that the appropriate vegetation and soil arrangement is an important factor in achieving good results in the remediation processes.

Chapter 2 : Literature Review

In the United States, bioswales and rain gardens have been installed in many locations including but not limited to Fort Bragg, NC; City of Livermore, California; Parknoll Elementary school in Berea, Ohio; Fairfax County, Virginia; Kings County, Washington; Prince George’s County, Maryland. There has been an increase in the application of the technology in different parts of the world too. Notably, the United Kingdom (Scholz 2004), Sweden (Persson et al. 2005), Australia (Read et al. 2008), China (Wang et al. 2008), South Africa (Braune and Wood 1999) and India (Srivastava and Majumder 2008).

In spite of the eco-friendliness, cost-effectiveness and simplicity in treating stormwater runoff, reported results from different studies in different locations show lack of consistency in biofiltration performance data worldwide. Because of the inconsistency, very minimal sound scientific data is available for urban and stormwater managers in making decisions about the most effective biofiltration system conditions, design parameters and operations to optimize stormwater runoff handling and pollutant treatment (Wong et al. 2006).

A study by Dennis Jurries (2003) indicates that there are two ways of measuring the effectiveness of bioswales. The first is by measuring the pollutants of interest by their concentrations in the runoff entering and exiting the bioswale and calculating the difference. The second method involves performing a mass balance of pollutant in the bioswale throughout the length of the bioswale. Jurries comments that measuring the concentration of the inlet and outlet of particular pollutants of interest alone is not enough to evaluate a bio-filtration system because it does not account for the infiltration of the pollutants along the length of the bioswale which may be released at some future time or have to be remediated in the future. Therefore, in addition to measuring the differences in the inlet and outlet concentrations, Jurries recommends a mass balance of pollutants throughout the length of bioswales when calculating efficiencies of pollutant removal.

Another school of thought in search of establishing reliable data is to combine field studies, laboratory analysis and computer programming to create predictive softwares and models that can be applied across a range of geographical locations under different climate conditions. The purpose of this approach is to enable prediction of the general performance of stormwater treatment units. This approach has led to evaluation of performance involving the use of computer models, tools and empirical relationships to describe quantitative estimates of pollutant removal.

The issue with this approach (model application) as pointed out by Bouraoui et al. (1996) is that most of the models require very detailed site-specific data which are unlikely to be practical for use by the stormwater management industry. For example, a stormwater treatment prediction based on a user-defined first order-decay rate, or sedimentation theory may need particle-size and specific settling velocity distribution for pollutants as input data (Huber et al. 1987). Other Stormwater Management Models (SWMM) user-input require data that is based on whether flow is completely mixed, or plug flow to predict the overall level of treatment for a pollution control pond (Deletic and Fletcher 2006).

In 1989, Flanagan et al. (1989) developed equations for predicting the performance of buffer strips in removing sediment in agricultural environments. The widely cited Kentucky model (Munoz-Carpena et al. 1999) was developed using artificial media instead of real grass. This model has generally proven unsatisfactory in simulating low sediment inflow concentrations and small particles that are characteristic of urban runoff (Delectic 2000).

Delectic (2001, 2005) developed a deterministic model (named TRAVA) of sediment transport over grass filter strips and swales in focusing on their application in urban stormwater control. The model was based on the Aberdeen Equation (name derived from the site where the study was done, Aberdeen, Scotland) for trapping particles by grass medium. The TRAVA is described as a complex hydrodynamic model that was primarily designed for simulating transport for a single rain event (Deletic 2000).

Regarding the statistical approach, Duncan et al. (1997) related observed performance at a range of temporal scales to parameters which describe treatment levels and it catchments or the relationship between them for efficiency evaluation.

Greg Mazer et al. (2001) estimated the efficiencies of bioswale treatment with respect to total suspended solids, dissolved metals and total phosphorous. The percentage removals of these parameters are shown in Table 2.1. Table 2.2 shows obtainable reductions of pollutants in bioswales presented by the State of Oregon Department of Environmental Quality (Jurries 2003). This efficiency was based on the following specific design parameters: “at least 200 feet in Length with a maximum runoff velocity of 1.5 ft/sec., a water depth of one to four inches, a grass height of at least 6 inches, and a minimum contact (residence) time of 2.5 minutes.”

Table 2-1: Obtainable reductions of pollutants in bioswales (Mazer 2001)

Pollutant	Percentage Reduction, %
Total Suspended Solids	60 to 99
Dissolved Metals	21 to 91
Total Phosphorus	7.5 to 80

Table 2-2: Obtainable reductions of pollutants in bioswales (Jurries 2003)

Pollutant	Percentage Reduction, %
Total Suspended Solids	83 to 92
Turbidity (with 9 minutes of residence)	65
Lead	67
Copper	46
Total Phosphorus	29 to 80
Aluminum	63
Total Zinc	63
Dissolved Zinc	30
Oil/Grease	75
Nitrate-N	39 to 89

From grassed swale study in Melbourne, Australia, pollutant removal efficiency was investigated by dosing the system with known concentrations of total suspended solids (TSS), PO_4 and NO_x (Deletic and Fletcher 2006). A flow corresponding to 3 month ARI (21/s) was used. The system was dosed with a synthetic sediments and pollutants. The result from the investigation based on a 35m length of swale is presented in table 2.3. The low removal rate of phosphorus was attributed to usage of soluble reactive phosphorus in the dosing mix.

Table 2-3: Obtainable reductions of pollutants in bioswales (Lloyd 2001)

Pollutant	**Percentage Reduction, %**
Total Suspended Solids	74
Total Phosphorus	55
Total Nitrate	No effective removal

Hvitved-Jacobsen et el (1987) studied swale performance along highways in Maitland and EPCOT, Florida. Results from the study indicated 25% and 30% efficiencies for swales at Maitland and EPCOT respectively. The level of total nitrogen removal was low averaging 11% from one site and 7% from the other. Dissolved metals removal was relatively high but with less of the dissolved fraction removed. In terms of dissolved metals, it was deduced that the removal of metals will be greater for those species present as charged ions. The dominant removal mechanism of dissolved metals was identified as adsorption of the ions onto particles.

An investigation into the performance of a grass swale receiving stormwater from a residential subdivision in Florida reported a 99% removal of TSS and varying percentages for total phosphorus (TP), total Kjeldahl nitrogen (TKN), total nitrate (TN) as well as total iron and biochemical oxygen demand (BOD) (Deletic and Fletcher 2006).

A research report on bioretention by Davis et al. (2003), focused primarily on laboratory prototypes. The report shows high concentration reductions (>90%) for copper (Cu), Lead (Pb) and Zinc (Zn). The report indicated reduction in nutrient concentrations as follows: total Kjeldahl-nitrogen (TKN) retention was 68%, and ammonia-nitrogen (NH_3-N) retention was 87%. Retention of nitrite + nitrate-nitrogen (NO_3-N) was 24%.

The low retention of NO_3-N was attributed to the fact that the negatively charged NO_3^- ion does not adsorb well unto soil particles. They concluded that this was due to the creation of NO_3-N through mineralization and nitrification of other forms of nitrogen in-between infiltration, an event which has also been cited as a possible mechanism for the low retention of NO_3-N (Davis et al. 2001).

In a study by Deletic and Fletcher (2006), a controlled field tests, on a grass filter strip in Aberdeen, Scotland and a grass swale in Brisbane, Australia was performed. The emphasis on the Aberdeen study was on performance in relation to different sediment particle sizes. On the other hand, the Brisbane study was on treatment performance for total nitrogen (TN), and total phosphorus (TP). In both studies, TSS concentrations were recorded along the grass as well as artificial inflow of water and sediment of different flow rates and sediment concentrations. They also had an unsteady input of pollutants. Results from the study shows that the Aberdeen strip reduced sediments by 61-86%, while the Brisbane Swale removed an average of 69%, 46% and 56% of the total loads of TSS, TP and TN, respectively. The TRAVA model was used in this study. They concluded that grass swales and filter strips are effective in removing sediments from urban stormwater runoff. The TSS removal was attributed to physical processes based on flow rate, grass density and particle size.

In a Master's degree thesis study, a group of students from the University of California, Santa Barbara analyzed the efficiency of a bioswale for treating surface runoff from a new project development site (Camino Real Project) in Goleta, California (Groves et al. 1999). While their results indicated that there were decreases in concentrations between bioswale inlet and outlet, statistical data revealed that the decreases were not very significant. The result was based on limited field data from a few stormwater samplings.

A “Field evaluation of rain garden flow and pollutant treatment” report, by Michael E. Dietz and John C. Clausen (2006) published the result of a rain garden installed to retain pollutants and reduce stormwater runoff in Prince George’s County, Maryland. The report shows that rain garden reduced the peak flow rate and increased the lag time of influent water. In the analysis, they found out that the only pollutant that was well retained was NH_3-N. The concentration of NH_3-N from the under drain was significantly lower than the inlet concentrations. They observed that the rain garden provided runoff control rather than water quality improvement.

Causes of Variations in Biofiltration Performances

Though most of the results from the studies show some evidence of removal of TSS, phosphorus, nitrates and dissolved metal, the level of pollutants removal in all the studies vary. The causes of variation in most instances are attributed to chemical and biological processes, appropriate vegetation (plants), sediments (soil, gravels and rock arrangements), design parameters (retention time, hydrologic properties etc), construction and maintenance practices.

Srivastava and Majumder (2008) attributed the variation to results to other parameters that affect biofiltration performance. They explained that removal efficiency is affected by other physiological parameters such as pH, temperature, O_2 content, initial concentration of the ‘pollutant of concern’ in the runoff.

A publication by Jennifer Read et al. (2008) on “Variation among plant species in pollutant removal from stormwater in biofiltration systems,” indicates that while there is evidence that the presence of plants improve effluent quality, it does not clearly show how specific plant traits influence pollutant removal and which species or types of species are most suitable for use in biofiltration systems. The report emphasized that plants selection must be based not only on their treatment performance but also on their capacity to survive in potentially stressful growth conditions such as seasonal weather conditions.

With respect to design, Vlotman et al. (2007), commented that though it is acknowledged that biofiltration systems improve water quality, past experiences have not always been positive due to inappropriate design with systems that are either too steep (causing localized erosion) or too flat (poor construction leading to localized ponding for excessive duration following a storm event).

A good maintenance practice is another essential factor in maintaining a lasting biofiltration treatment performance. Regular maintenance activities outlined by the State of Oregon Department of Environmental Quality include mowing, irrigation, pruning and replacement of plants. The Department recommends trimming of vegetation on biofiltration units every year or two to prevent woody species from taking over. Other recommended maintenance practices include:

- Regular inspection of surface drainage systems before or after each major storm and first seasonal rains to ensure removal of sediment and trash build up.
- Repair of surfaces that have been damaged by erosion, rodents and other causes.

Good maintenance practices prevent restricted flow that causes localized flooding, erosion, sediment buildup, odor and aesthetic problems.

The establishment of reliable scientific data, incorporation of recommended design and maintenance practices from biofiltration performance investigations is not only for prediction purposes but also for operating and maintenance guidelines to optimize future designs for specific geographical locations. It is anticipated that urban waterway managers and professionals in stormwater management will find these data, software and models (from biofiltration application researches) useful in prioritizing and implementation of stormwater treatment systems.

Chapter 3 Youngstown State University's Biofiltration Units

The Gateway Project

Two bioswales and a rain garden were constructed on a parking lot on Youngstown State University's campus in fall 2005. The installation was part of an institutional BMP initiative project (The Gateway project) to treat stormwater runoff from parking facilities on the campus. The units were constructed for the following purposes:

- Receive and filter stormwater from the adjoining parking lots
- Provide flood containment
- Improve water quality and
- Beautify the parking lot

The units were designed and constructed such that the stormwater runoff will flow into the bioswales through several inlets on the uphill side of the bioswales. Storm water overflows on the bioswales and excess runoff from the parking lot will flow unto the rain garden. The effluent of the rain garden is connected to the City of Youngstown's combined sewage system where the stormwater flows into the Youngstown Waste Water Treatment Plant (YWWTP) for treatment prior to discharge into the Mahoning River. When the capacity of the combined system is exceeded as a result of heavy rainfall or snow melt, stormwater runoff overflows directly into Mahoning River without treatment. Under such circumstances, an efficient biofiltration system plays a significant role in reducing surface water pollution.

Site Description

The biofiltration units on YSU campus were constructed on parking lot F1. The 1.73 acre (75,359ft^2) parking lot surface area provides 120 parking spaces for students, staff and visitors to the university. It is located approximately at the mid-eastern section (41° 06°25 .48N, 80° 38° 45.09W) of the University campus as shown on Figure 3.1. The bioswales are installed in the middle of the parking lot while the rain garden is located on the edge of the southeast corner, outside the parking lot as shown on Figure 3.2 and Figure 3.4.

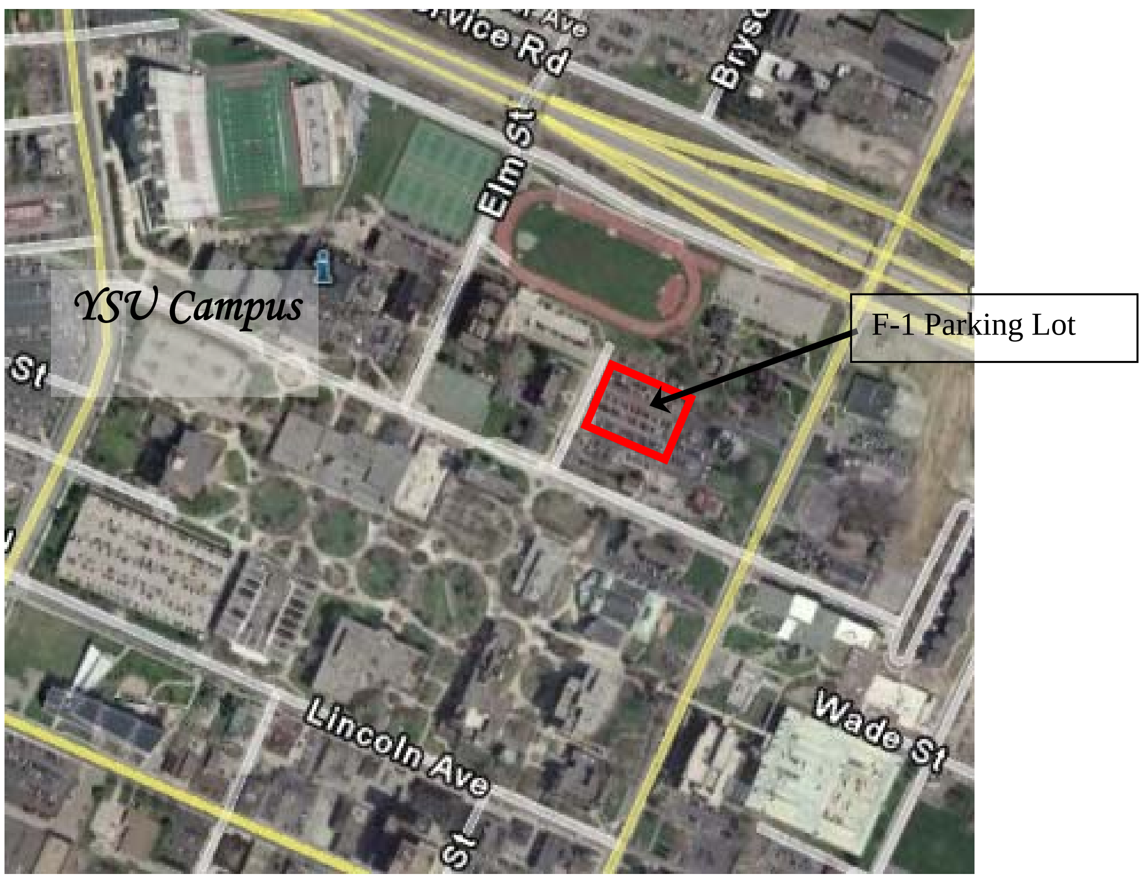


Figure 3-1: Location of F-1 Parking lot on YSU campus

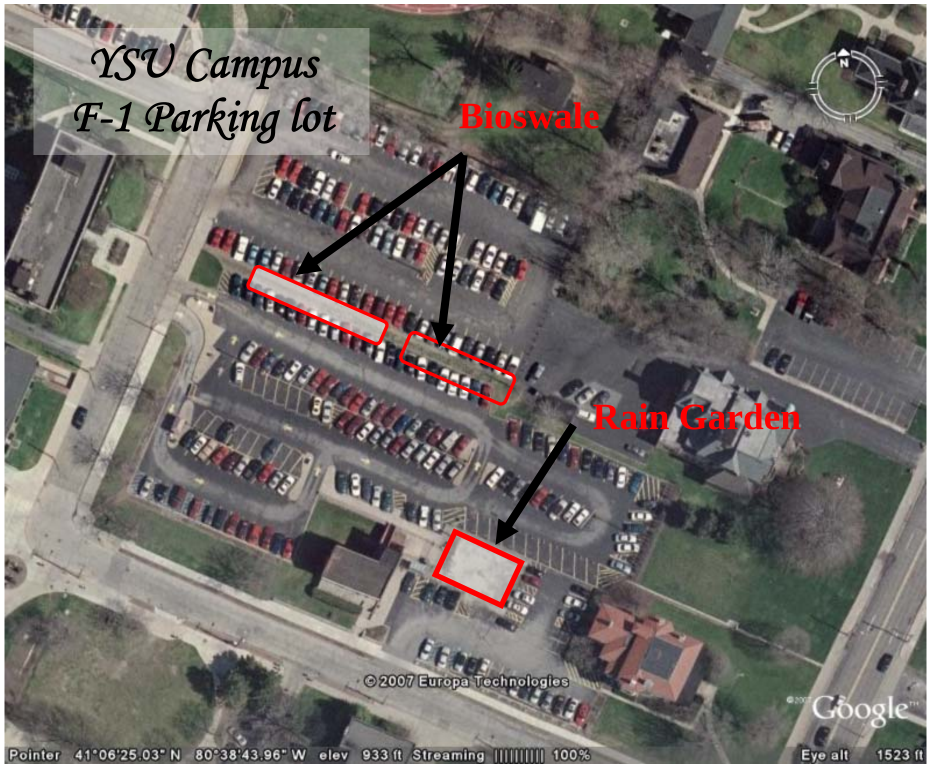


Figure 3-2: Location of biofiltration Units on YSU campus

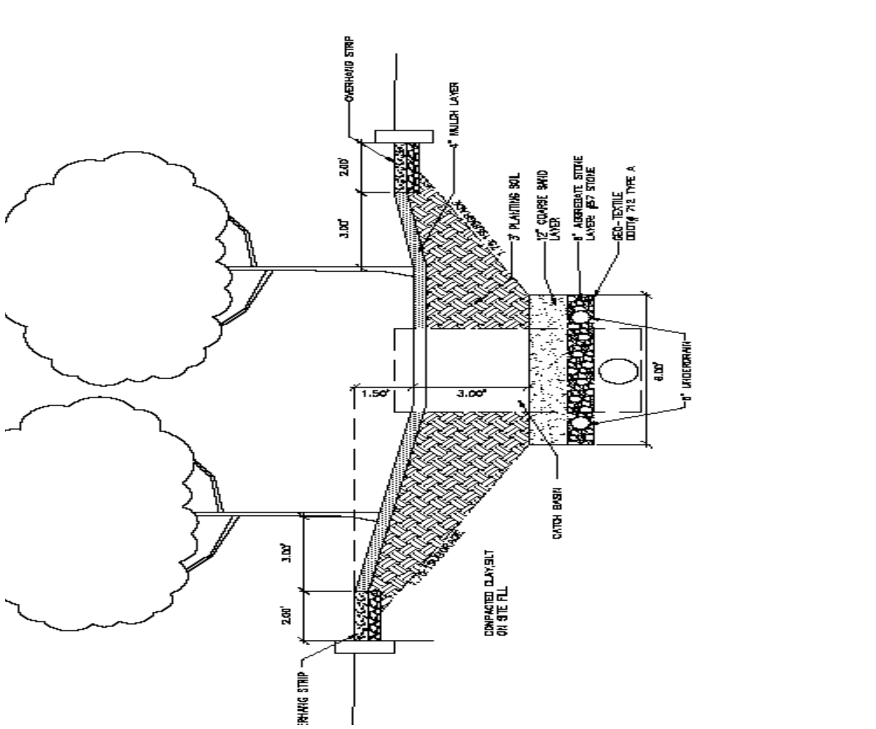


Figure 3-3: Cross sectional view of YSU's Bioswale

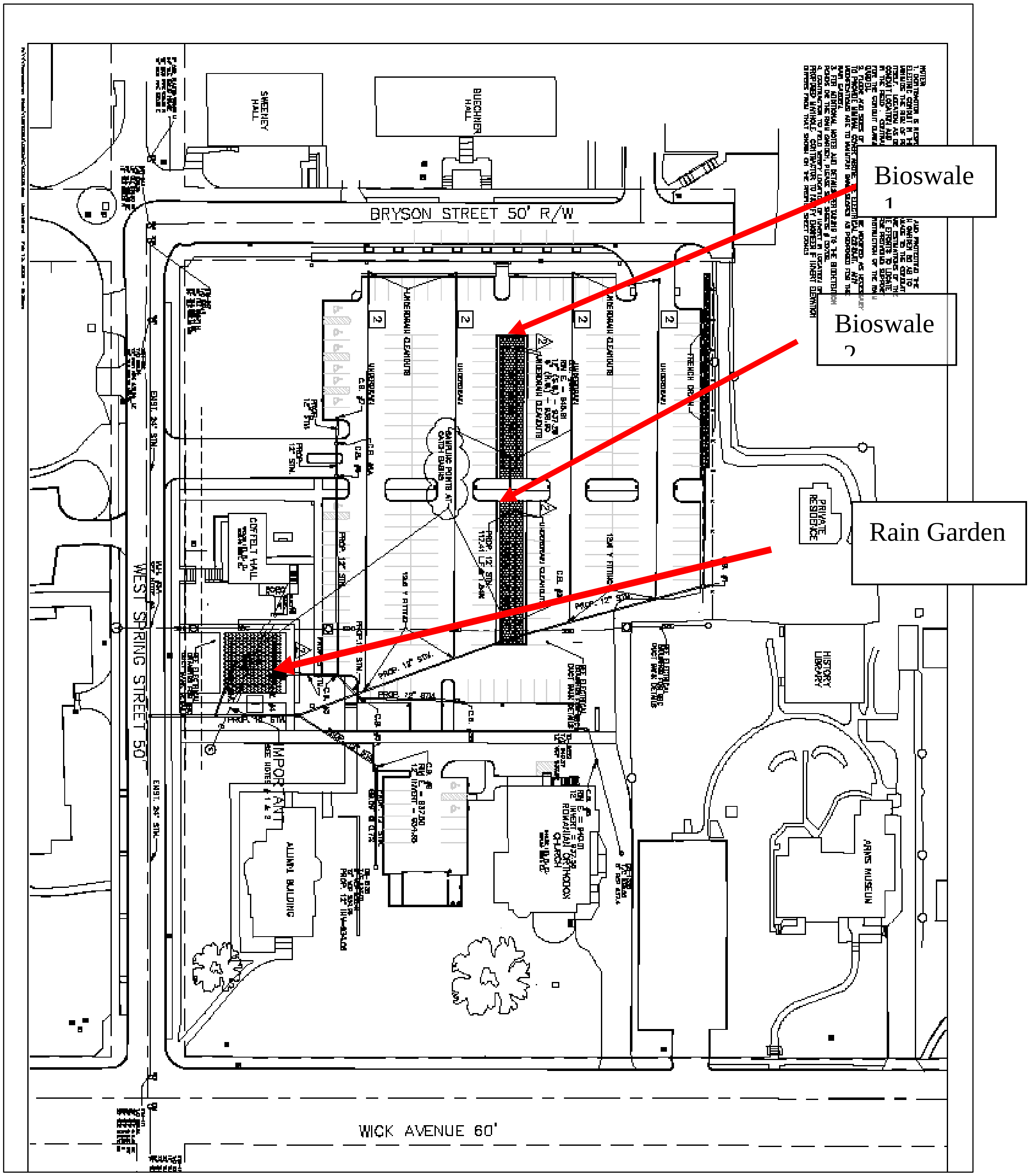


Figure 3-4: Locations of bioswale and rain gardens on Parking lot F-1

A 6ft wide concrete sidewalk separates the two bioswales at the center of the parking lot. Each bioswale is of 16 ft wide and 99 ft long and has a total surface area of 1,584ft^2. The surface area of the parking lot above bioswale-1 (north-western part of the parking lot) is 14,374.8 ft^2. In the event of rainfall, stormwater flows from this area onto bioswale-1 (bioswale-1 influent). Bioswale-2 influent is from an area of 6,098.4 ft^2 of the parking lot on the north side of the bioswale. The rain garden receives stormwater from the southeastern section of the parking lot, overflows from the drains and filtrates from the bioswales.

Information available at the time of this study indicated that, the YSU biofiltration units were designed with the following specifications: 4 inch mulch layer, 4 feet depth of sandy loam soil for planting bed and 12 inches coarse sand layer. The area was planted with a variety of landscape plants. The infiltration rate of the soil was designed to be 0.5 inches per hour and a soil pH between 5.5 and 6.5. Figure 3.3 shows a cross sectional view of the bioswales and Figure 3.4 shows the locations of the bioswales and rain garden.

Since the completion of the biofiltration units in 2005, stormwater has been flowing through the system. However, the extent to which the units treat stormwater runoff is not known. Therefore, this study was undertaken in 2007 to investigate the functionality of the biofiltration units specifically to:

1. Identify changes in water quality when using biofiltration units.
2. Identify potential loss of efficiency.
3. Suggest maintenance practices based on the results to improve efficiency

Chapter 4 : Methods and Procedures

To assess the effectiveness of the biofiltration units, stormwater runoff samples were collected during rainfall events and analyzed. Samples were analyzed by following all water quality analytical procedures for the selected parameters according to Standard Methods (APHA 1998) procedures. Laboratory results were statistically analyzed using SPSS (repeated measures) and MS excel Pivot software packages.

The samples were collected from the inlets and outlets of the biofiltration units as well as from an open area of the parking lot as shown on Figure 4.1 and 4.2. Sampling was done during the first flush (30 to 60 minutes) of a rain event when there had been no rain for about a period of two weeks and at least once per month (depending on weather conditions) from March 2007 to December 2007.

Sampling locations included:

- **B-1-I** : Bioswale-1 inlet sampling point for stormwater runoff from parking lot surface area of 14,374.8 ft^2 before infiltration through bioswale-1.
- **B-1-D**: Sampling point for bioswale-1 drain located at the center of bioswale-1. It is the sub-surface drain. This sample represents filtered runoff from bioswale-1 before joining filtered runoff from bioswale-2.
- **B-2-D**: Sampling point for bioswale-2 drain located at the center of bioswale-2 . This sample is a combination of filtered runoff from bioswale-1 and bioswal-2 prior to joining rain garden.
- **PL**: Parking lot sampling point. Runoff collected directly from parking lot surface joining another conduit before entering the rain garden.

- **R-G-I**: Sample point for rain garden inlet. Sample from this point represents a combination of filtered runoff from bioswale-1 and bioswale-2 as well as runoff from parking lot surface area south of bioswales as shown on Figure 4.1 and 4.2.
- **R-G-E**: Sampling point for rain garden effluent. Sample from this location is percieved as the treated sample entering the combined sewer system.

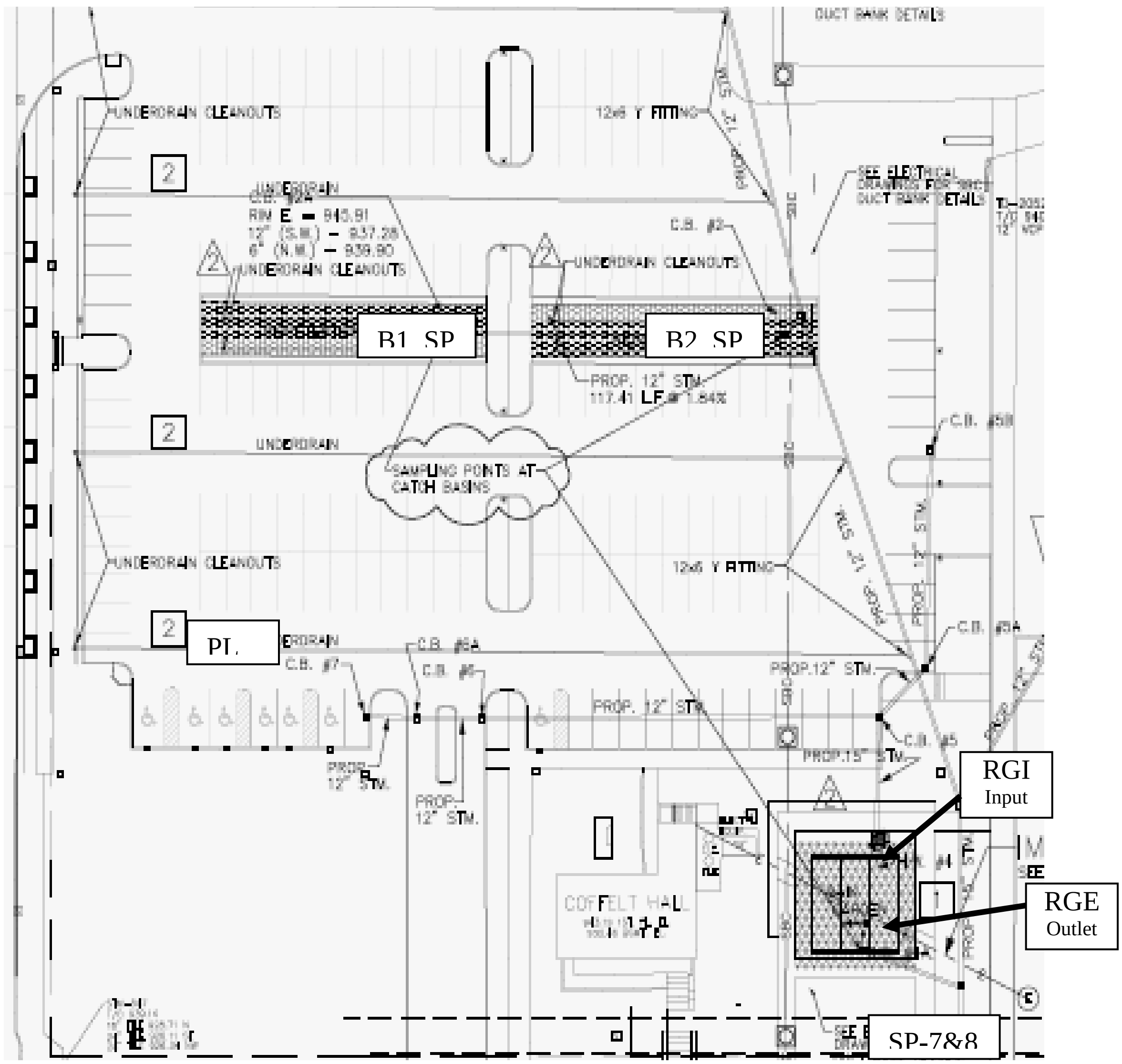


Figure 4-1 Schematic of sampling points in the YSU F-1 parking areas containing the biofiltration units

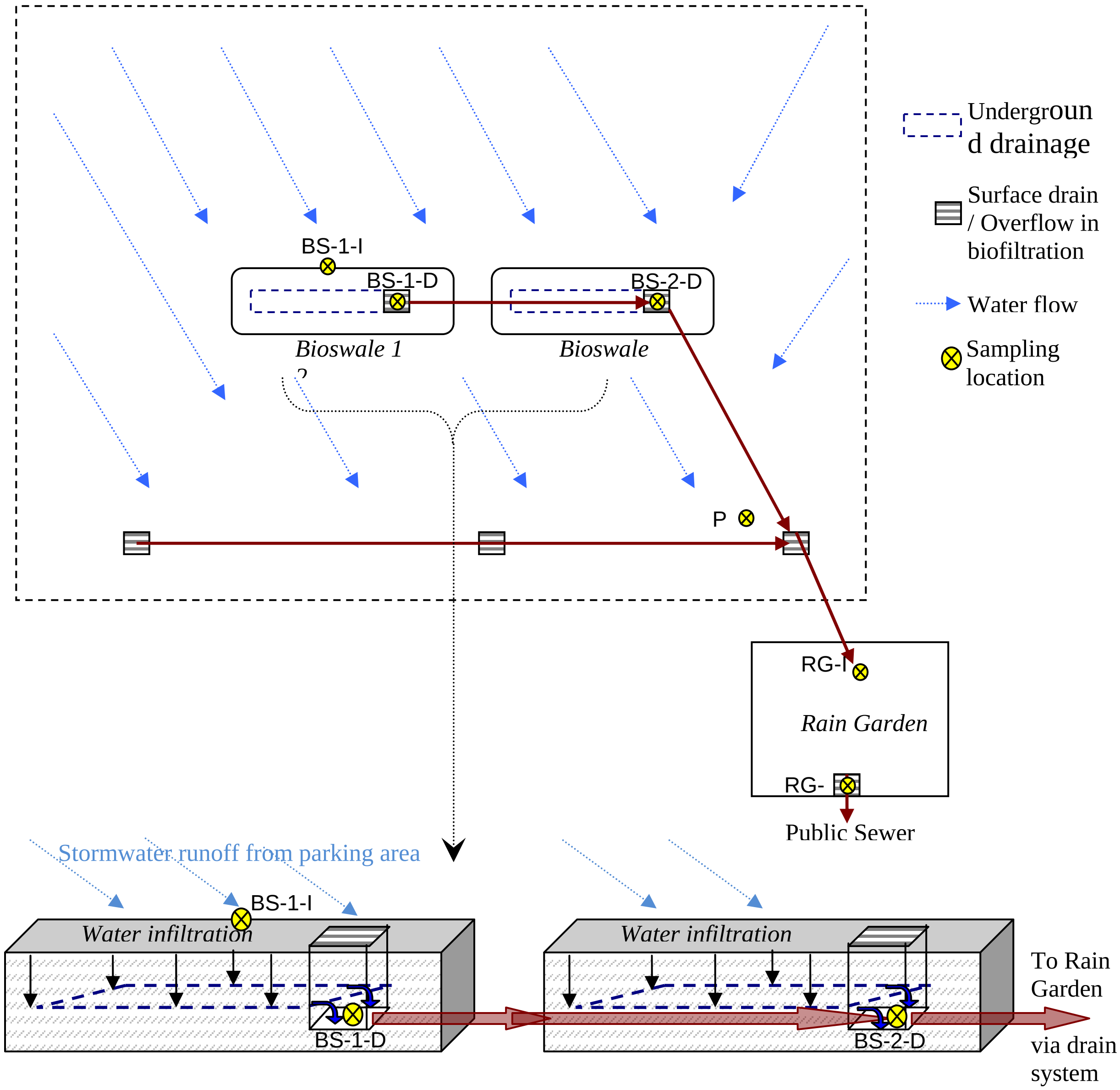


Figure 4-2 Schematic of flow of runoff and collection points along the biofiltration units.

Storm water runoff samples were collected from six locations as described above. Runoff were collected with the aid of sampling equipment (long-handled dippers, later replaced by telescopic dippers) into prepared 1 liter sampling bottles. All laboratory supplies were pre-washed with phosphate-free soap, acid washed and rinsed with distilled water. Sampling locations were selected to provide representative data of runoff concentrations as the runoff flowed through the biofiltration system. The selection was based on flow, drainage areas and accessibility. There were multiple inlets through which storm water runoff flowed from the parking lot to the bioswales. The inlets are open spaces of the curb along the edge of the bioswales at the center of the parking lot. The flow rates from the inlets vary depending on the amount of rainfall. The flow rates, most of the time, were from multiple inlets and were too low to measure with a flow meter. This made the measurement of a single or cumulative flow rate to represent the overall inlet flow rate of stormwater runoff during rainfall event impossible. However, three inlet locations were selected for bioswale-1. Analytical results from all three locations were averaged (arithmetic mean) to represent the inlet concentration of bioswale-1. In the case of bioswale-2, stormwater runoff from the parking lot does not flow directly into the bioswales most of the time. This made sampling from the inlet of bioswale-2 also impossible.

There was occasional flooding of bioswale-1 and the rain garden. The drain cover located in these areas were low resulting in overflow of runoff and with debris deposited directly into the drain instead of infiltrating through it. This situation did not occur on bioswale-2. Runoff from bioswales and the lower section of the parking lot area flow into the rain garden through an extended polyvinylchloride (PVC) pipe. The pipe extends about 2feet from one end of the edge of a concrete slab. The PVC pipe is about 2 feet high above the surface of the rain garden. During heavy down pours, the rain garden becomes flooded and submerges the PVC. In such situations, sampling from the pool of standing water was used. In the events of flooding, runoff overflowed directly into the rain garden outlet drain. It was envisioned that concentration of samples taken during heavy rainfall events will be affected due to the submerging of the inlet pipe and direct overflow of runoff into the outlet drain as a result of the flooding.

Water Quality Analysis

The collected samples were filtered and acidified with sulfuric acid for nutrient and metal analyses. The samples were stored in a refrigerator until they were analyzed. The holding times were within 28 days and 6 months for nutrient and metals respectively.

The collected samples were analyzed for total phosphorus (TP), total suspended solids (TSS), ammonia-nitrogen (NH_3-N), nitrate-nitrogen (NO_3-N), oil and grease, chemical oxygen demand (COD), dissolved oxygen (DO), and dissolved metals (Al, Ba, Cr, Cu, Fe, Ni, Pb, Ti, and Zn). An YSI-85 combination field meter was used to measure conductivity, temperature and DO on site throughout the study. Table 4.1 presents a summary of all the analytical procedures followed (as outlined in the *Standard Methods for the Examination of Water and Wastewater*) for the selected parameters of concern. Analyses of dissolved metals and oil and grease were performed by staff at the YWWTP. Stormwater samples were collected for ten rain events during the period of the study. However, samplings from specific locations on certain rain events were not possible due to very low flow. Dissolved metals and oil and grease concentration were not routinely measured for all the sampling events. Arithmetic mean concentration was calculated for each sampling location for all parameters analyzed during each sampling event.

Table 4-1: Pollutants of Concern and Analytical Methods

Parameter	**Preservative**	**Method Reference**	**Holding Time**
pH	On-site	pH Meter	Immediately
Temperature	On-site	probe	immediately
Conductivity	Cool 4°C	Probe	28days
Total Suspended Solids	N/A	Standard Methods 2540-D	28days
COD	H_2SO_4 pH<2	Standard Methods 5220 A	28 days
Ammonia	Cool 4°C H_2SO_4 pH<2	Standard Methods 4500-NH_3 (Phenate Method)	28 days - 6 month
Nitrate-Nitrite	Cool 4°C H_2SO_4 pH<2	Standard Methods 4500-NO_3^- E (Cadmium Reduction Method)	28 days - 6 month
Phosphorus	Filter, Cool 4°C H_2SO_4 pH<2	Standard Methods 4500-P (Dissolved-Ascorbic Acid Method)	28 days - 6 month
Dissolved Metals (Zn, Pb, Al, and Cu)	Filter, Cool 4°C H_2SO_4 pH<2	ICP – courtesy Youngstown Waste Water Treatment	6 months
Oil and Grease	Filter, Cool 4°C H_2SO_4 pH<2	Courtesy Youngstown Waste Water Treatment	

Chapter 5 Results and Discussion

To estimate the amount of pollutants retained in the biofiltration units, SPSS "repeated measures" statistical software was used to evaluate the laboratory results. The software was used to determine if significant differences existed in the measured concentrations and also to analyze the trend changes in concentration of the runoff along the sampling points during the course of the study.

Rainfall and Stormwater Runoff Volumes

The amount of rainfall for each sampling event was obtained from the YWWTP records. Since runoff were too low to determine with a flow meter in the course of the study, estimated runoff volume entering bioswale-1 and bioswale-2 were calculated based on the surface area where the stormwater flowed from the parking lot and amount of rainfall. Table 5.1 presents the amount of rainfall for each of the sampling dates and the corresponding volume of stormwater that infiltrated through bioswale-1 and bioswale-2 throughout the study. The highest amount of rain fall of 2 inches was recorded on June 2. This yielded 2396 ft^3 and 1016 ft^3 of stormwater runoff that infiltrated through bioswale-1 and bioswale-2 respectively. The least amount of rain fall of 0.38 inches was recorded on September 26, yielding volumes of 455 ft^3 and 193 ft^3 infiltrating through bioswale-1 and bioswale-2 respectively.

Table 5-1: Amount of rainfall and sampling dates

Sampling Dates	**Amount of Rainfall, inches**
March 14, 2007	0.62
April 25, 2007	0.9
June 2, 2007	2
June 13, 2007	0.94
July 11, 2007	0.59
July 27, 2007	0.5
August 20, 2007	1.7
September 26, 2007	0.38
October 23, 2007	1.45
December 9, 2007	0.64

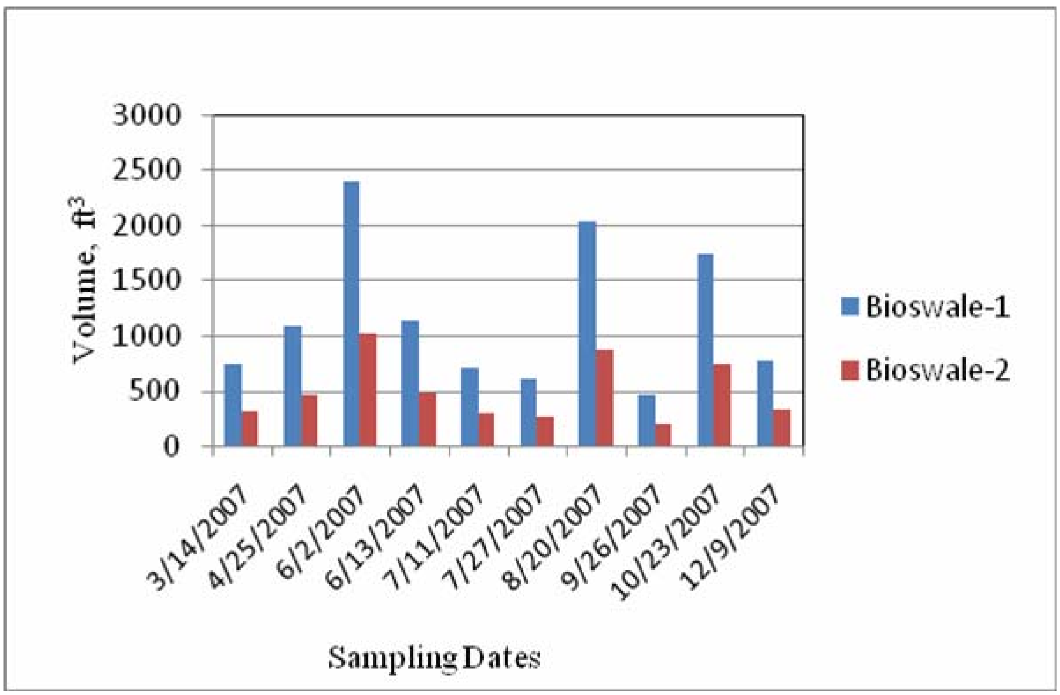


Figure 5-1 : Estimated volume of stormwater infiltrating through bioswale units

Total Suspended solids (TSS)

TSS are inorganic (silts, clays, etc) and organic (algae, zooplankton, bacteria and detritus) fractions that are carried along by water as it flows over impermeable surfaces. In surface waters, TSS contributes to turbidity and siltation (sediment deposition). The physical effects of TSS on aquatic environment include: reduction of light penetration in water columns, which interferes with visual feeding and photosynthesis; clogging of fish gills and destruction of natural habitat of bottom-dwelling organisms by covering their breeding areas. DO, temperature and pH are water properties that are indirectly affected by TSS (US EPA 1983). A report by the Kentucky Water Watch states that, the National Academy of Sciences has recommended that the concentration of TSS should not reduce light penetration by more than 10%. In a study in which TSS were increased to 80 mg/L, the macroinvertebrate population was decreased by 60% (C&WQ 2008).

In this study, concentrations of TSS were measured for each sampling event to assess the effectiveness of removing TSS from parking lot runoff when using the biofiltration units. Results from laboratory analysis of TSS are presented in Figure 5.2 and 5.3. Graphs for individual sampling dates are shown in Appendix A (TSS).

Total Suspended Solids Removal

Graphs for July 2 and September 26 (Figure 5.2) indicate a consistent decline in TSS concentration from bioswale-1 through the rain garden effluent. The inlet stormwater volumes for those dates are 706.8ft^{3}and 455.2ft^3 for bioswale-1 respectively. April 25, June 2, June 13 and August 20 graphs show a similarity in trend. For these days, the bioswale-1 initial TSS influent concentrations were low, followed by a high concentration in the bioswale-1 drain and then a consistent decline in the bioswale-2 drain to the rain garden inlet. These sampling dates are associated with high inlet stormwater volumes. The inlet stormwater volumes for these days were 1,078.1 ft^3, 2395.8 ft^3, 1126.0 ft^3 and 2036.4 ft^3 respectively as shown in Figure 5.1.

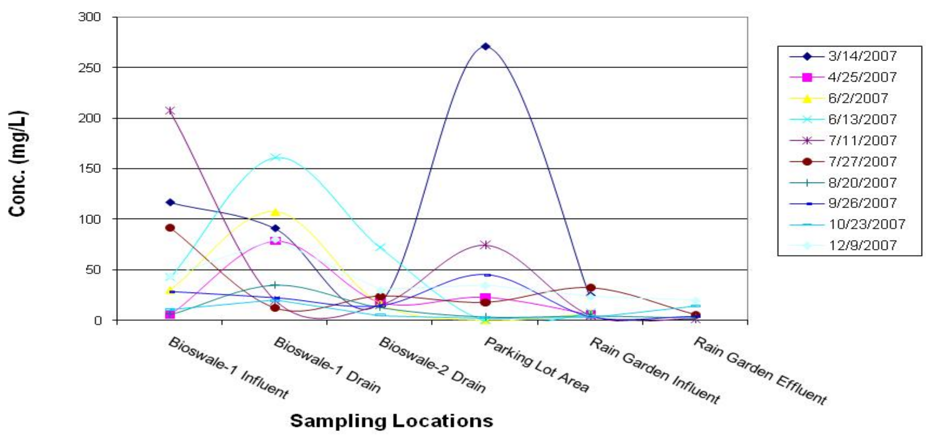


Figure 5-2 Total suspended solids concentrations for all sampling dates and locations.

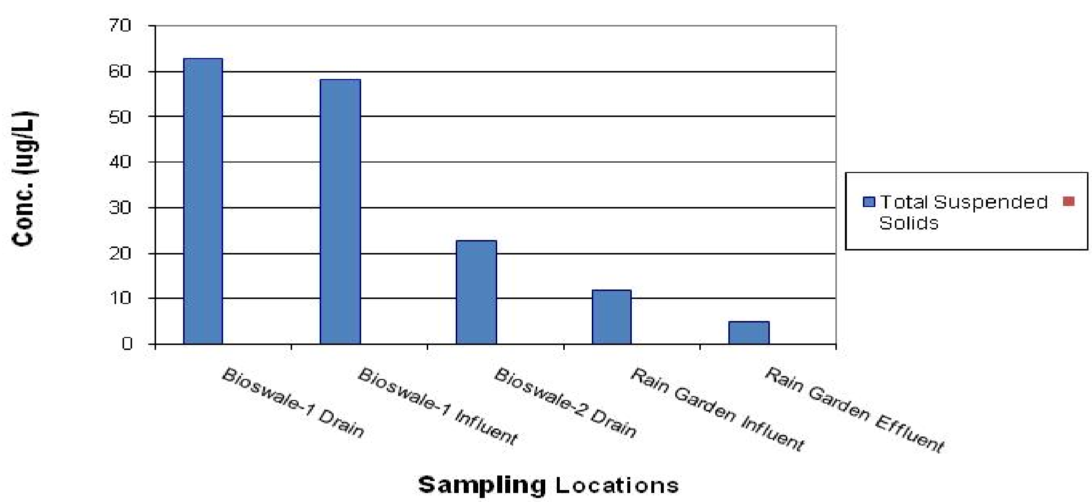


Figure 5-3 Average total suspended solids concentrations for all sampling dates and locations along biofiltration units.

TSS concentrations for sampling dates July 27 and October 23 follow a different trend. TSS concentrations were high for the bioswale-1 inlet, increased in the bioswale-1 drain, bioswale-2 drain and rain garden inlet then decreased in concentration for the outlet of the rain garden. Variations in TSS concentration for October 23 sample is irregular with bioswale-1 inlet, and the bioswale-1 drain concentrations were high then declined in the bioswale-2 drain and rain garden inlet concentrations. The rain garden outlet concentration was, however, higher, exceeding the bioswale-1 inlet concentration; this was unexpected. This unexpected change in concentration is attributed to the flooding of the rain garden and overflow of stormwater directly through the rain garden outlet sampling location.

Figure 5.2 show the variation of TSS concentrations for all the sampling dates. The result of the overall analysis processed using SPSS is presented in Figure 5.3. The Figure shows that there was a large difference between the bioswale inlet concentration of 62.72 mg/L and the rain garden outlet concentration of 4.8 mg/L. It can be deduced from the concentrations that the biofiltration units retained 57.9 mg/L of the initial TSS concentration.

Reduction of TSS concentration was expected since the use of the biofiltration units is a physical removal process that relies mostly on dense vegetation and filtration medium as shown in different related studies discussed under literature review.

The SPSS analysis chart shows that TSS concentration decreased along the biofiltration units. The decrease in concentration along the units was more consistent when the inlet flow volume was low (September 26 sampling). At high runoff volumes, stormwater overflows into the bioswale-1 drain and rain garden outlets, carrying with it debris and sediments which deposit directly into the underdrain pipe instead of infiltrating through the units. High TSS concentrations in the bioswale-1 drain and rain garden outlets occurred in the events of high runoff volumes. These occurred on April 25, June 2, June 13, and August 20 for the bioswale-1 drain and October 23 for the rain garden effluent.

From the annual TSS analysis, it is estimated that the biofiltration units are effective in treating TSS, retaining about 92.3% of suspended solids. This is to be expected because it is a physical treatment based on particle filtration. The estimated percentage coincides with study results presented by Juries (2003), Hvitved-Jacobsen et al. (1987) and Mazer (2001).

Nutrients

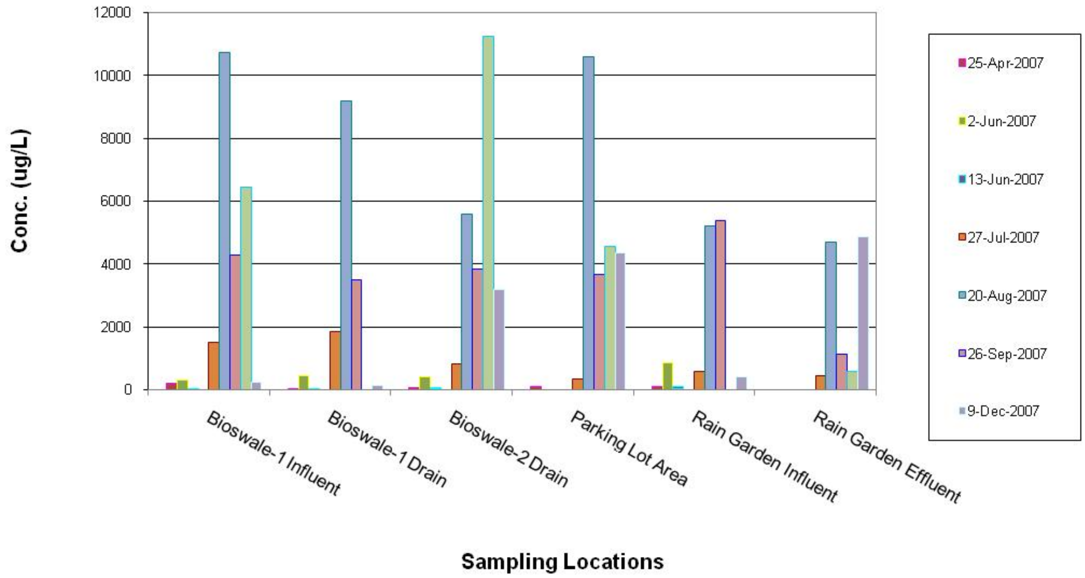
Ammonia, Nitrogen and phosphorus are examples of nutrients that are essential for plant growth. However, excess amounts of these nutrients in aquatic environments can cause adverse effects on aquatic organisms. In the aquatic environment, excess amounts of nutrients enhance growth of aquatic vegetation. Algal blooms may occur, which reduces light penetration in water columns, causing plants to die and generate organic matter. Organic matter in aquatic environments leads to the depletion of dissolved oxygen due to the increase in decomposition of organic matter which utilizes available oxygen and also loss of habitat for aquatic animals.

Potential sources of nutrients on the parking lot include; deposits from the atmosphere and runoff from nearby landscapes where fertilizers and nutrients had been applied. In this study, inlet and outlet concentrations of ammonia-nitrogen, nitrite/nitrate-nitrogen and TP were measured to evaluate the capability of the biofiltration units to prevent nutrients from the parking lot's runoff to enter receiving waters. Analytical results and graphs of individual sampling events are presented in Appendix A&B respectively.

Seven sampling events were analyzed for ammonia. Ammonia was measured as ammonia nitrogen (NH_3-N). Plotted graphs of ammonia's analytical results for each of the dates show a varying trend of ammonia concentrations along the units. Results for April 25, June 2 and June 13 show a steady increase trend in ammonia concentrations along the biofiltration units (particularly June 13). Results for July 27 and August 20, however, show an opposite trend in concentration changes with respect to April 25, June 2 and June 13. Ammonia concentration for these dates declined steadily along the biofiltration units. The September 26 result shows high concentrations from the upstream then a substantial reduction in the rain garden effluent. The December 9 result shows low concentration levels upstream with high concentration levels at the bioswale-2 drain and rain garden effluent. The change might be due to infiltration of runoff from the bioswale-2 inlet and decomposition of dead plants on the units during the fall season.

With the exception of December 9 sampling, results for the rain garden show that the rain garden reduced ammonia concentration in the stormwater runoff. However, the overall SPSS results show high concentrations at the bioswale-1 inlet (2966.4 µg/L), bioswale-2 drain (3150.2 µg/L) and a relatively low rain garden outlet concentration (2344 µg/L). It can be deduced from both the rain garden results and the overall annual graphs that the biofiltration units retained 805.6 µg/L of ammonia in the stormwater runoff flowing through the biofiltration unit. The high concentration values in the bioswale-2 drain is expected due to the unaccountable inlet concentraion.

(a)



(b)

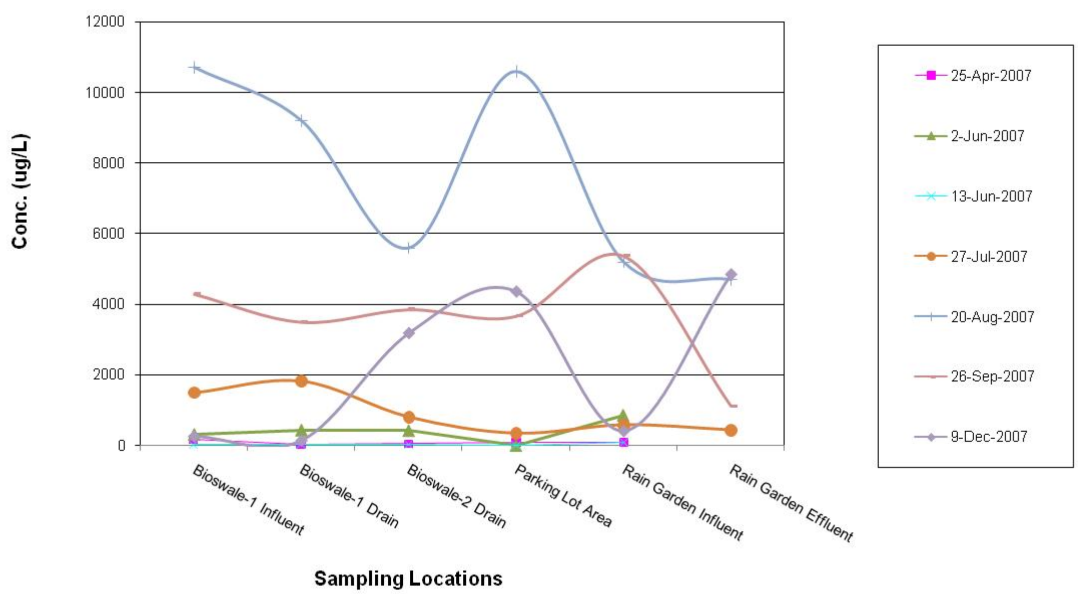


Figure 5-4 Ammonia concentrations for all sampling dates and locations

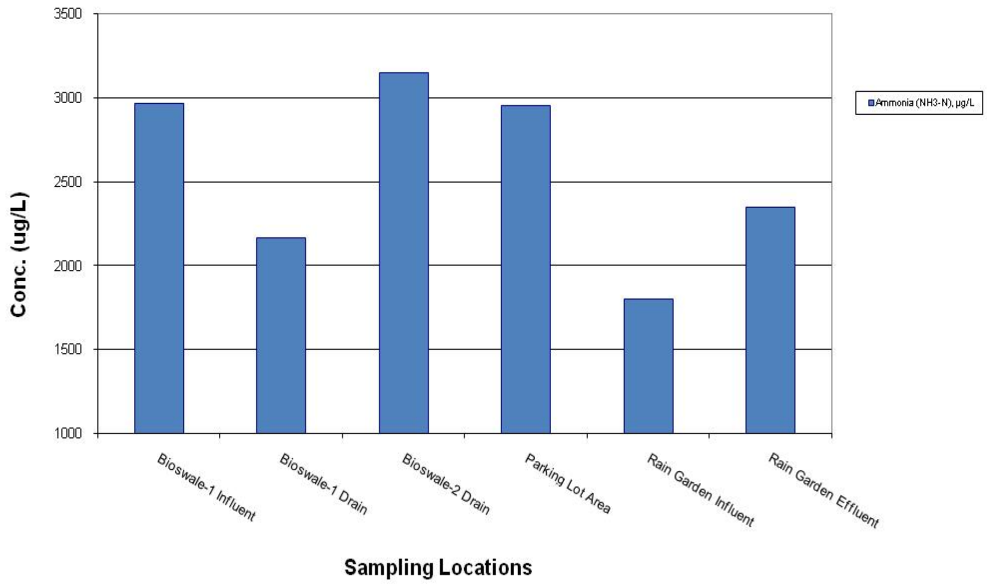


Figure 5-5 Average annual variations of ammonia along biofiltration units

Figure 5.4b depicts that ammonia contents in the runoff were highest in the July 11 sample followed by September 26, July 27 and June 2. Ammonia concentration was very low in June 13 and April 25. This observation may be attributed to the increase in plant and microbial activity in the spring and summer seasons respectively. The December 9 concentration along the unit varied from low to high then low again at the rain garden inlet and then high again in the outlet concentration. Unlike TSS concentrations, the changes in the ammonia concentration levels do not necessarily correlate with the runoff volumes. However, concentration levels were relatively high in most of the summer samplings (July 11, September 26 and July 27) compared with late fall (December 9) and early spring (April 25). Contrary to that, the lowest concentraiton levels ocurred in June 13 when the runoff volume was relatively high. The potential reason for the differences between TSS and ammonia variations could be the fact that TSS removal is a physical filtration process while ammonia is a chemical process with active microbial denitrification or ammonification processes. Futher research would have to be done to identify the process affecting the ammonia levels.

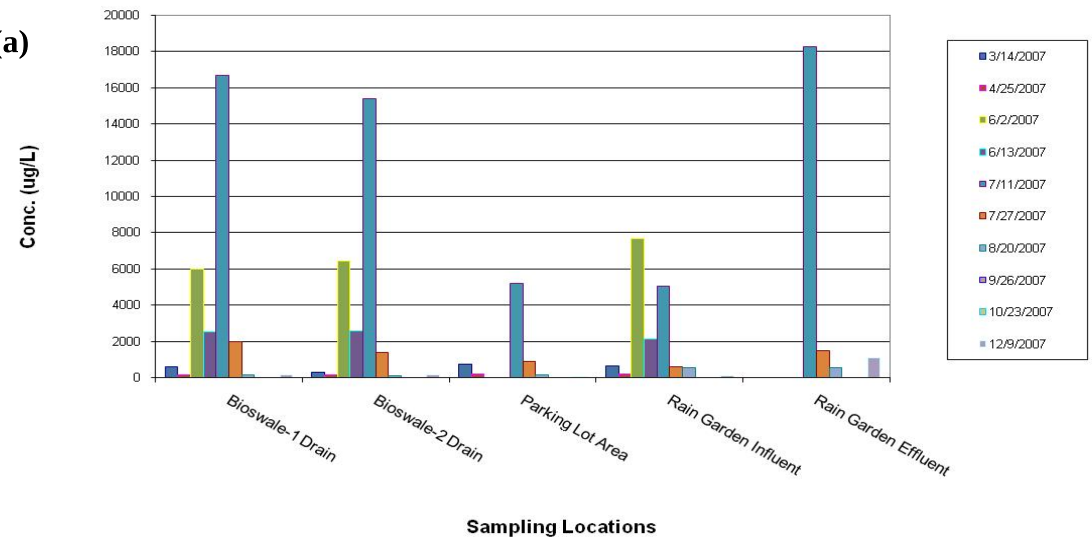
Nitrate/Nitrite-Nitrogen

The results for nitrate analysis were similar to the variation in ammonia concentrations. The nitrate results are presented in graphs 5.6 and 5.7. Graphs of June 2 and April 25 show a steady increase in concentration along the bioswale units (except April 25, which has high inlet concentration). The results from June 13 and December 9 analyses show a decrease in concentration along the units (excepting the higher concentration of the outlet of December 9). Results for the remaining dates show a different trend of concentration changes along the units.

With the exception of August 20 rain garden results, the results from four rain garden samplings indicate an increase in rain garden outlet concentrations. Figure 5.7 show that the average rain garden influent concentration was 1692.4 µg/L while the effluent was 2139.83 µg/L. An increase in nitrate concentration is contradictory to what was expected, since a rain garden's function is to reduce nitrate concentration.

Figure 5.6a depicts that nitrate contents in the runoff was highest in the July 11 sample (same as ammonia) followed by June 2 and June 13. The lowest concentration levels measured during the study were in the April 25, March 14 and August 20 analyses. Similar to ammonia, the inconsistency in the variation of nitrate concentration along the units can be attributed to microbial activities in the units, seasonal changes, decomposition of plants on the units and overflow of runoff. With respect to the high nitrate concentrations in the effluents, it can not be said in the study that the biofiltration units retained nitrates in the runoff.

(a)



(b)

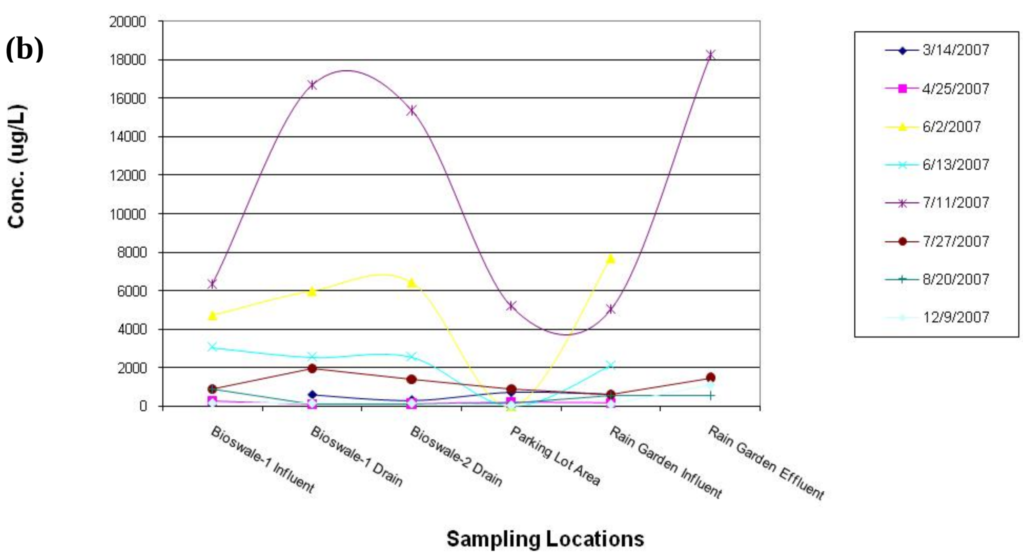


Figure 5-6 Nitrate/Nitrite-nitrogen concentrations for all sampling dates and locations

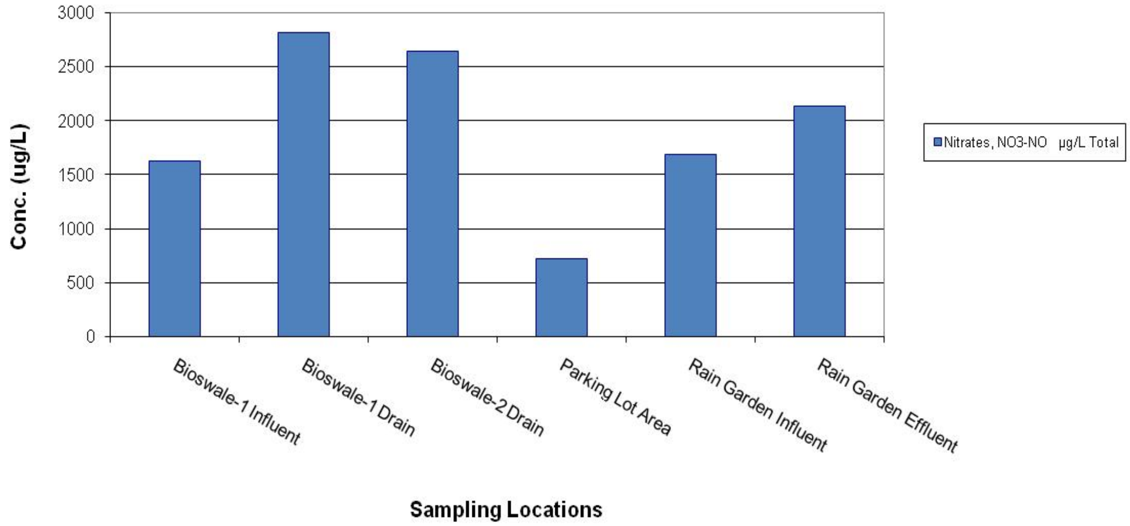
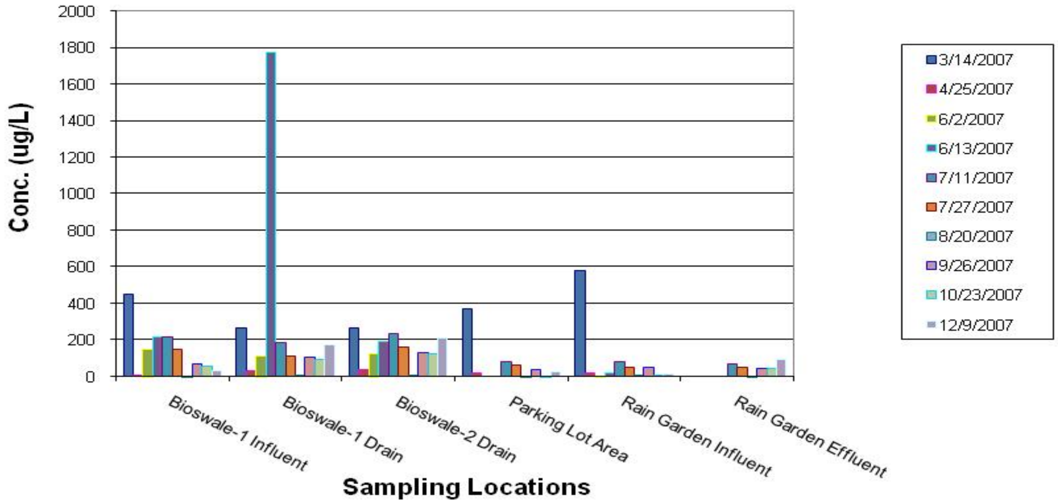


Figure 5-7 Average annual nitrate concentrations along biofiltraion units

Phosphorus

A variation of phosphorus concentration over the period of the study follows the pattern of ammonia and nitrate concentrations as discussed previously. June 2, July 11 and July 27 sampling dates show a decreasing trend of phosphorus concentrations along the biofiltration units (Figure 5.8). For April 25, August 20, September 26, October 23 and December 9 results, phosphorus concentrations increased gradually along the two bioswales. However, the inlet and outlet concentrations of the rain garden are lower compared to the bioswales' concentrations. The overall annual graph (Figure 5.8c) depicts higher phosphorus concentrations in the bioswales and lower concentrations in the rain garden. Results for the individual sampling events can be found in Appendix A & B

(a)



(b)

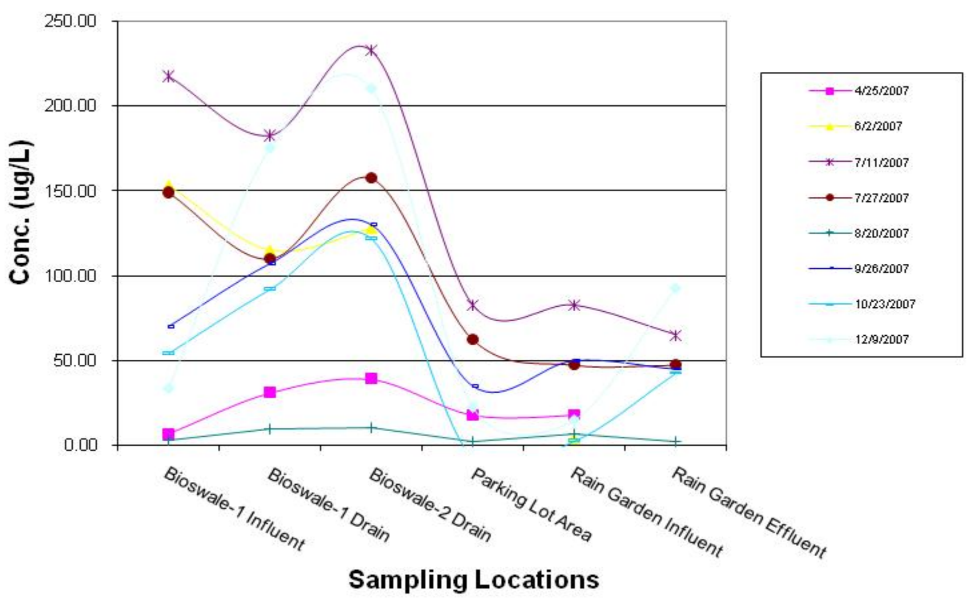


Figure 5-8 (a)&(b) Total phosphorus concentrations for all sampling dates and locations

(c)

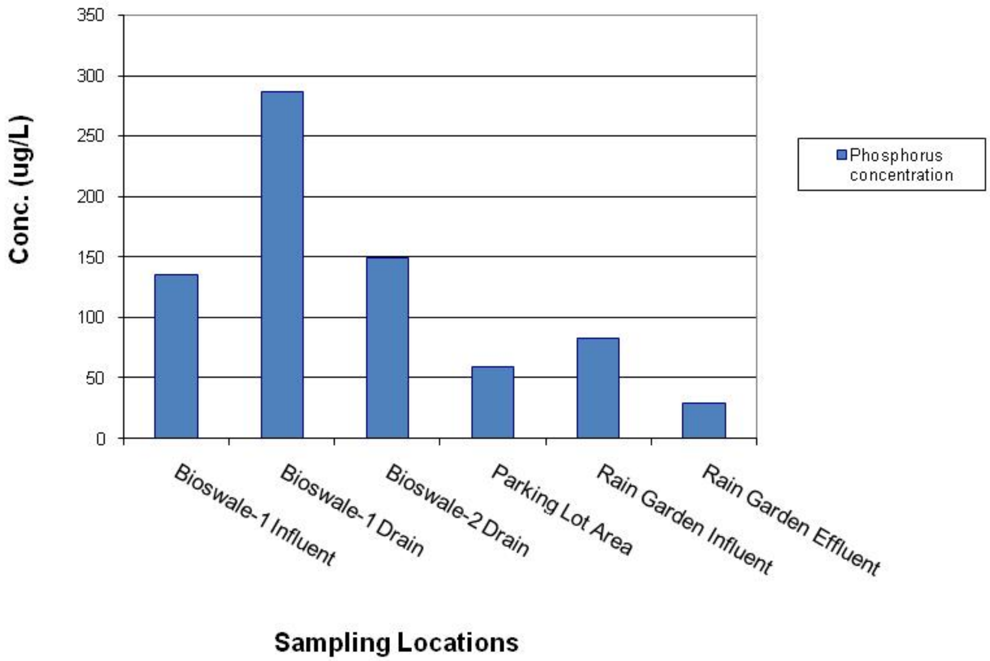


Figure 5-9 (c) Average phosphorus concentrations for all sampling dates and locations

Phosphorus analysis on the rain garden alone also showed varying trends. The inlet phosphorus concentration was higher than the outlet concentration for July 2 sampling and the reverse for October 23 sampling and December 9. Results for July 27 show no substantial changes in concentration. The consistent increase of phosphorus concentration at the bioswale-2 drain can be ascribed to the unaccountable bioswale-1 phosphorus concentration from the parking lot.

Figure 5.8b shows that phosphorus contents in the runoff were high in the July11, June 2 and July 27 samples and low in the April 25, August 20 and December 9 samples. The reason for these changes is associated with decomposition of vegetation and release of nutrients in the fall season (LID 2003). It was estimated from the overall annual average data that the biofiltration units reduced 256.92 μg/L of phosphorus in stormwater runoff from the parking lot. This is approximately an 89% reduction.

Nutrient Removal

Figure 5.9 shows the relative nutrient concentrations along the bioswales on the sampling dates. Phosphorus concentrations were the lowest compared to ammonia and nitrates. Both ammonia and total phosphorus concentrations decreased along the bioswale. The increase in concentration at bioswale-2 is an indication of an external source of nutrients from the bioswale-2 inlet. All three parameters recorded high concentrations during the summer season (June 6 – August 20). Concentrations of NH_3-N and NO_3-N did not change significantly as stormwater runoff infiltrated through the biofiltration units. The occasional elevated concentration levels of TP, NH_3-N and NO_3-NO suggest a source of nitrogen within the soil medium. There was a similar trend in a study by Jennifer Read et al. (2008).

High concentrations of nutrients during the summer season are attributed to the decomposition of vegetation as suggested by the Low Impact Development Center (LID 2003). According to LID, decomposition in the fall season releases nutrients as plants die. Less vegetation (and frost) on the biofiltration units in the winter season also contribute to a decrease in pollutant removal. A higher runoff velocity is another factor that has the potential to induce erosion and sediment release if the biofiltration design is not stable. Leaching of mulch and organic soil media also contribute to nutrient export in biofiltration units (LID Center, updated 2008)

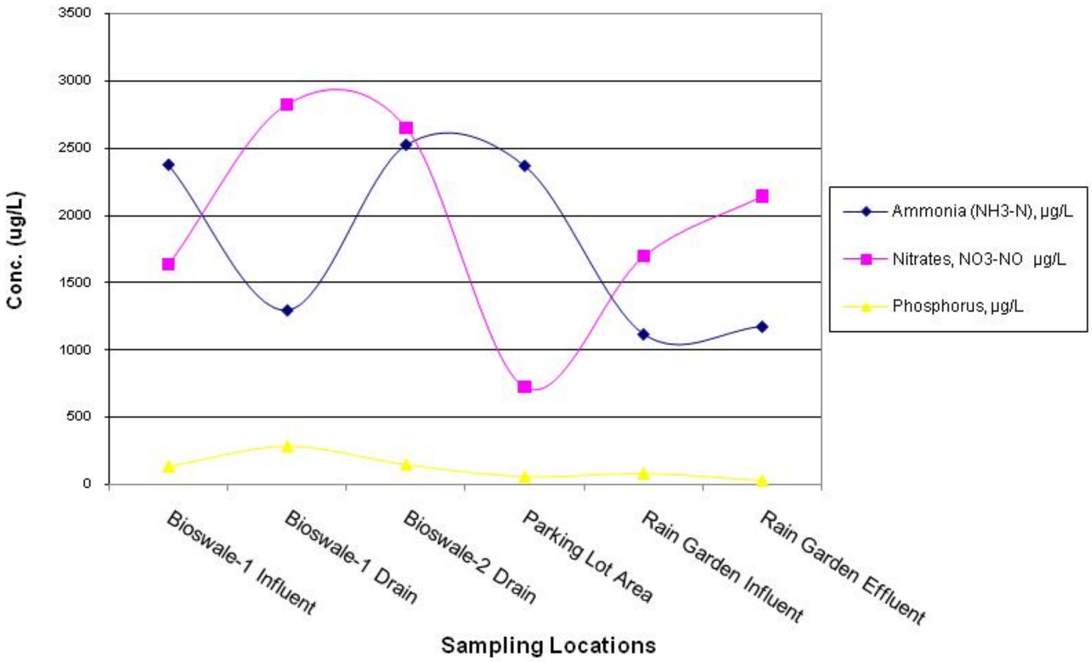


Figure 5-10 Variations of nutrient concentration along, ammonia, nitrate and phosphorus along the biofiltraion units

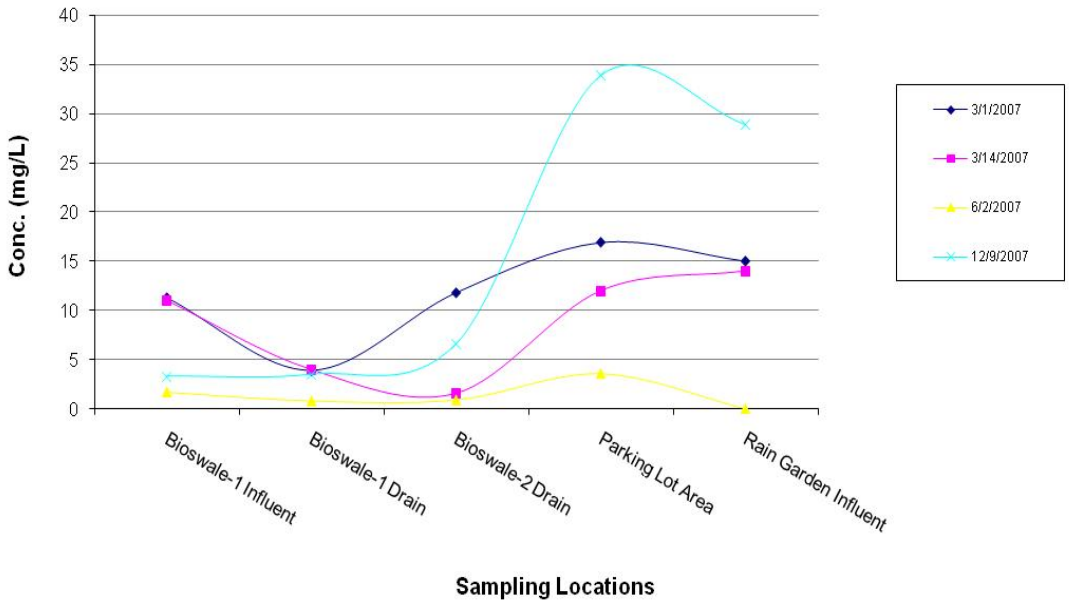
The NH_3-N and NO_3-NO curves present inconsistency in ammonia removal in the biofiltration units. This occurrence is attributed to seasonal changes and the effect of runoff velocities. The decrease in phosphorus effluent concentrations in this study is similar to a study by Hvitved-Jacobsen et al. (1987). The decrease was attributed to the fact that TP has the potential to be attached to fine sediment due to soil adsorption of the orthophosphate. It was noted in the report by Hvitved-Jacobsen et al. (1987) that swale designs which create thin-film flow and maximize the potential for soil sorption of orthophosphate may enhance TP removal.

Oil and Grease

Leaked oil and petroleum products on parking lots from vehicles are washed down into sewers during rainfall. Petroleum products in surface waters are harmful to the aquatic environment. Oil and grease is an indicator of petroleum products in runoff. In studying the uptakability of oil and grease by biofiltration units, only three sampling events (March 1, March 14 and June 2) were measured for oil and grease concentrations in the runoff from the parking lot. The analysis was performed by staff at the YWWTP. The analytical results are presented in Figure 5.10. There was no analytical results for the rain garden outlet for these sampling dates because the rain garden outlet sampling began on July 11, after a longer piece of sampling equimpment was acquired. Figure 5.10 shows the variation in terms of concentraion levels for the sampling dates. The overall SPSS analysis shows an increase in oil and grease concentration along the bioswale units. This is unexpected and might be due to overflow or external sources of runoff containing oil and grease.

The oil and grease graph indicated reduction in concentration between the bioswale-1 inlet concentration and bioswale-1 drain. The increase in concentration between the bioswale-1 drain and bioswale-2 drain is attributed to additional concentration of oil and grease from bioswale-2 inlet (which was not analyzed for).

(a)



(b)

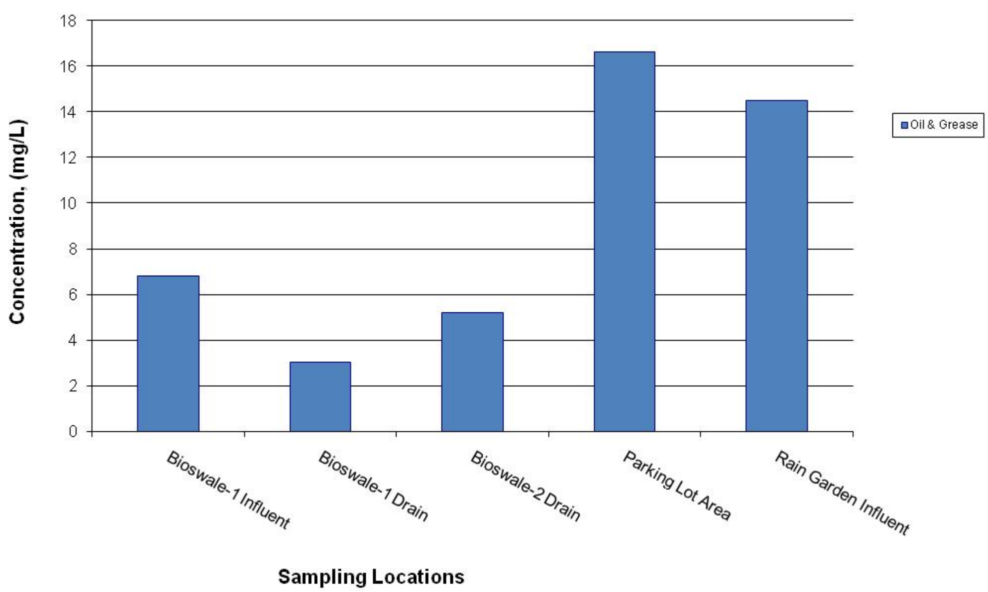


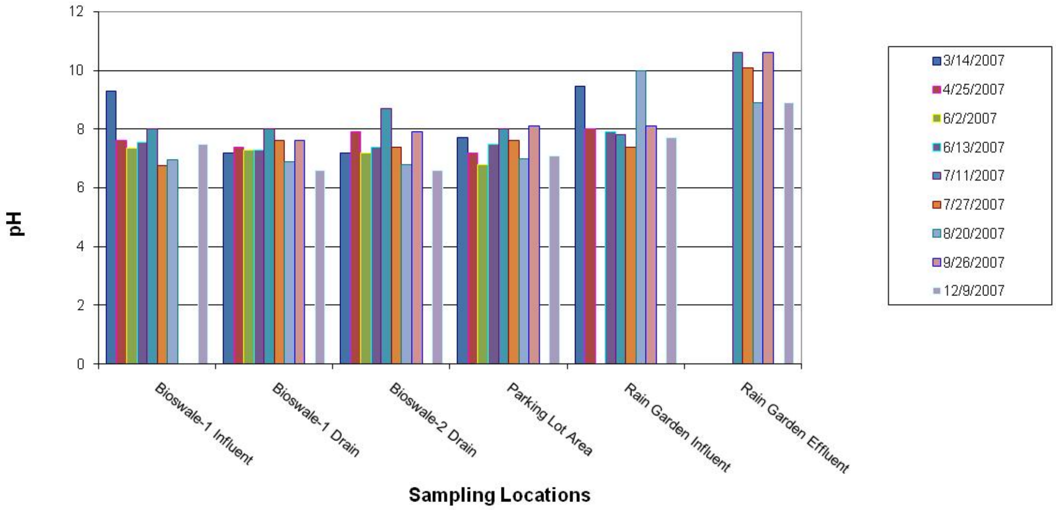
Figure 5-11 Oil and grease concentrations form biofiltration units on YSU F-1 parking area.

The same reason applies to the increase in concentration between the bioswale-2 drain and rain garden influent. With respect to the rain garden inlet, runoff from the parking lot surface area combined with the bioswale-2 effluent resulting in a higher concentration. Due to the low number of sampling events tested and exclusion of rain garden outlet sampling, this result might not be a accurate representative of oil and grease treatment in the units.

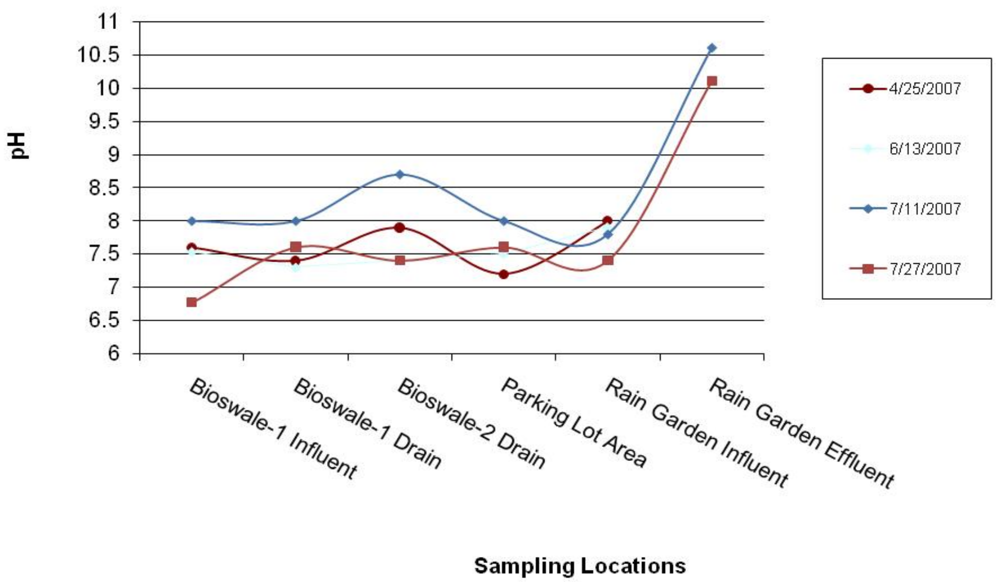
pH and Conductivity

pH is an indicator of the acidic conditions (low pH) or basic conditions (high pH) of water bodies. Runoff carry many insoluble and soluble substances. One of the most significant environmental impacts of pH is the effect that it has on the solubility and, thus, the bioavailability of other substances. The pH of water affects the toxicity of these substances. At a lower pH, many insoluble substances (i.e. metals) become more soluble and, thus, available for absorption by organisms. A pH range of 6.0 to 9.0 appears to provide protection for the life of freshwater fish and bottom dwelling invertebrates. The pH criteria for aquatic life is, therefore, between 6.0 and 9.0 pH units to protect aquatic ecosystem. (US EPA 1983)

Plotted recordings of pH readings along the biofiltration units indicated a steady increase in pH values of the runoff from the bioswale influent through the rain garden influent then a decrease in the rain garden effluent as shown in Figure 5.11. The recorded pH readings ranged from 6.7 (lowest pH recorded on July 27 from the bioswale-1 influent) and 10.6 (highest pH recorded on September 26 from rain garden effluent). The potential cause for the pH increase in the outlet runoff may be attributed to bicarbonates ions (HCO_3^-) or limestone ($Ca(OH)_2$) in related construction materials or other sources of OH^+ in the soil medium.

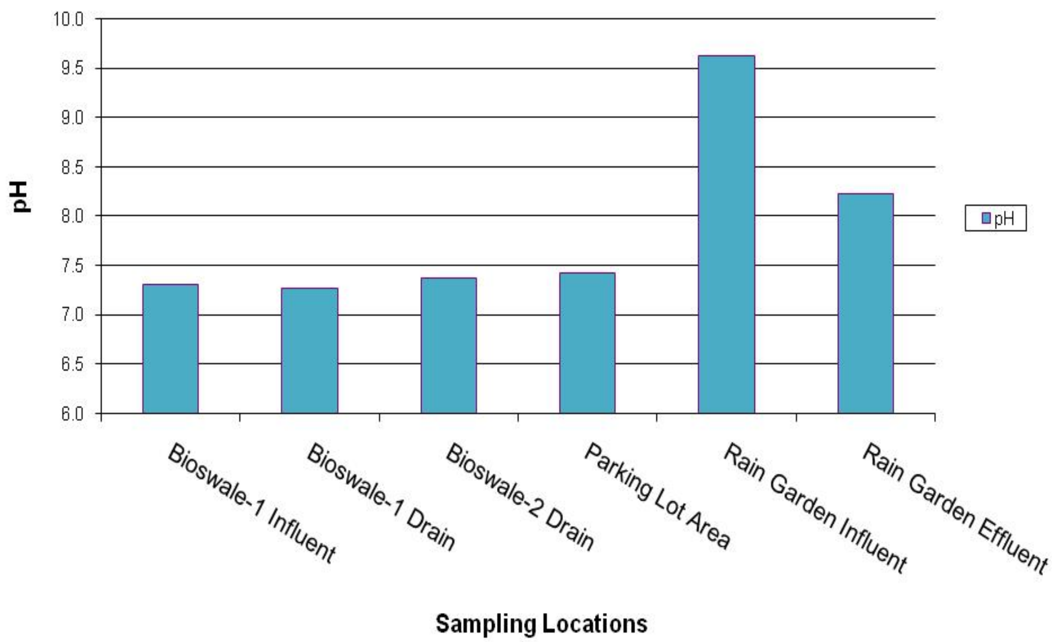


a. Recorded pH readings along the biofiltration units for all sampling days



b. Recorded pH readings along the biofiltration units for four sampling days

Figure 5-12 Variations of pH readings along the biofiltration units



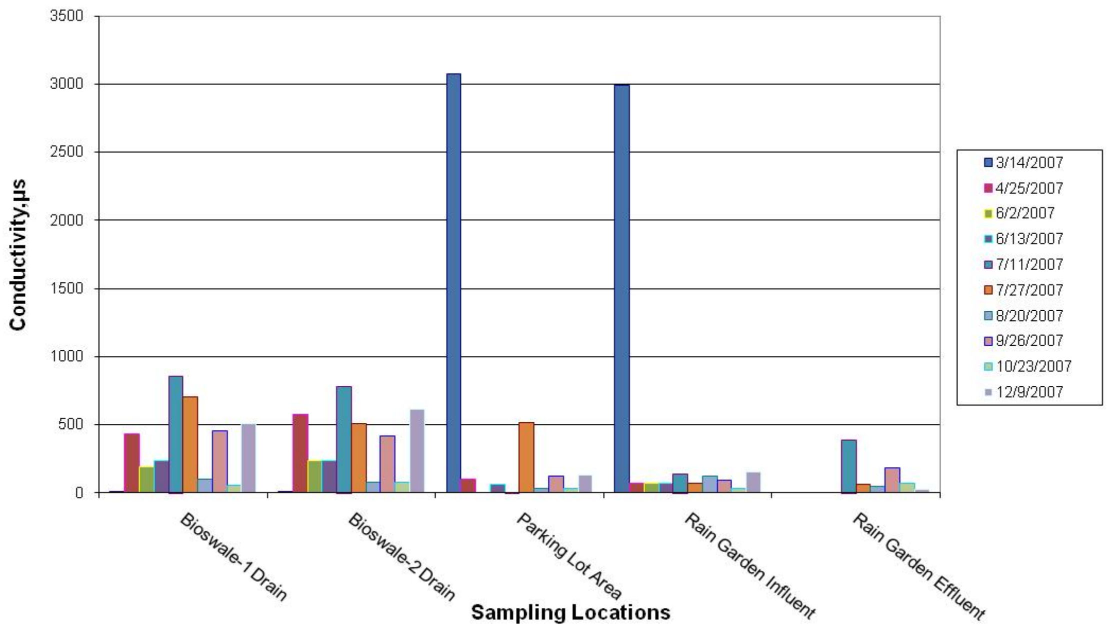
c. Annual average pH readings along the biofiltration units

Figure 5-13 Variations of pH readings along the biofiltration units

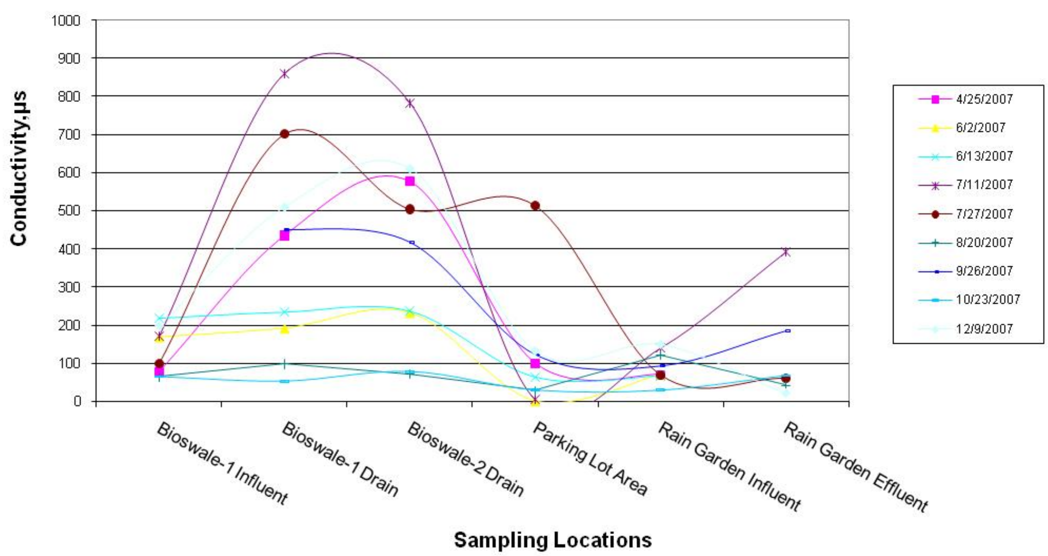
Conductivity, a parameter for assessing total dissolved solids (mineralization) or the overall ionic effect in water source, was analyzed and presented in Figure 5.12. In water, soluble substances break apart, forming aqueous solution of ions. Such solutions have the ability to carry electrical current. Conductivity is a measure of the ability of an aqueous solution to carry an electrical current. It is used to determine a number of applications related to water quality such as determining the overall ionic effect in a water source and its effects on plants and animals. Conductivity was measured in this study to determine the ability of biofiltration units to control conductivity of stormwater runoff from parking lots.

Analytical results presented on Figure 5.12 show that conductivity was relatively low in runoff from the parking lot into the biofiltration unit as indicated in the bioswale-1 influent. The curves show an increase in conductivity along the biofiltration units specifically the bioswale-1 drain and bioswale-2 drain. However, conductivity declined at the rain garden inlet and again increased in the rain garden effluent for the individual sampling days. The increase at the bioswale-1 drain and bioswale-2 drain is likely to be associated with release of ions in the soil medium or other parameters such as nutrients. Overflow of runoff into the drain could also be a possible reason. The annual average analysis, however, indicated a substantial decrease in the overall conductivity measurement depicting that dissolved ions (H^+) were adsorbed through surfaces in the rain garden soil medium. This observation corresponds to the increase in pH measurement on the annual average graph in Figure 5.11 indicating that pH and conductivity have similar trends.

The similarity in trend is attributed to the decrease (adsorption) in H^+ ions in the runoff, resulting in the release of OH^+ ions, thereby increasing the pH (more basic) and decreasing conductivity since conductivity is dependent on H^+ ions. It can therefore be deduced that the biofiltration units reduced total dissolved solids in the runoff from the parking lot.

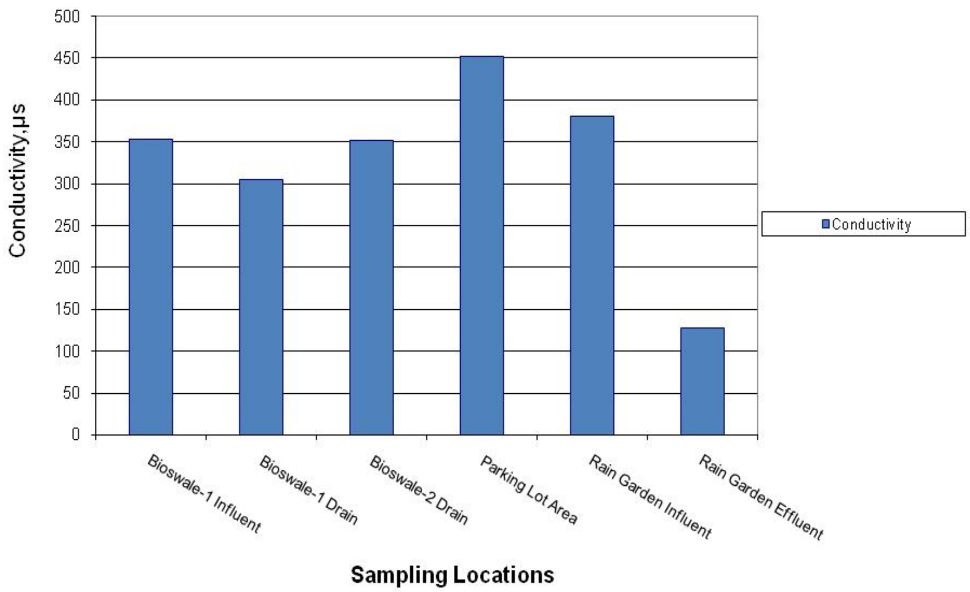


a. Recorded conductivity readings along the biofiltration units for all



b. Variation of conductivity readings along the biofiltration units

Figure 5-14(a) & (b)Variations of conductivity measurements along the biofiltration units



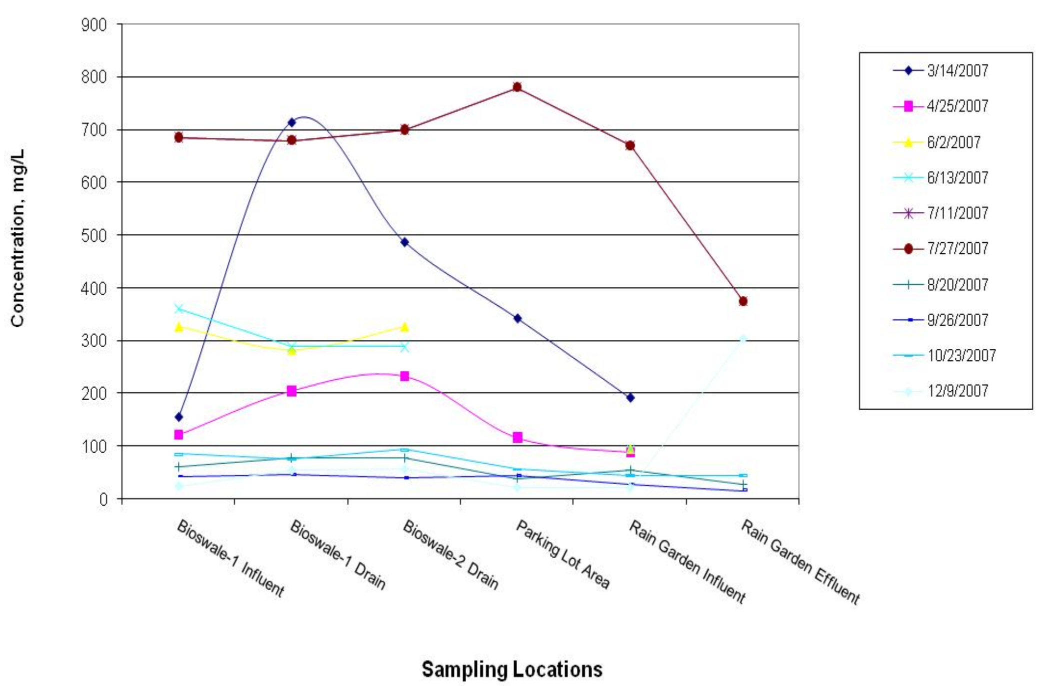
c. Annual average conductivity readings along the biofiltration units

Figure 5-15 (c) Variations of conductivity measurements along the biofiltration units

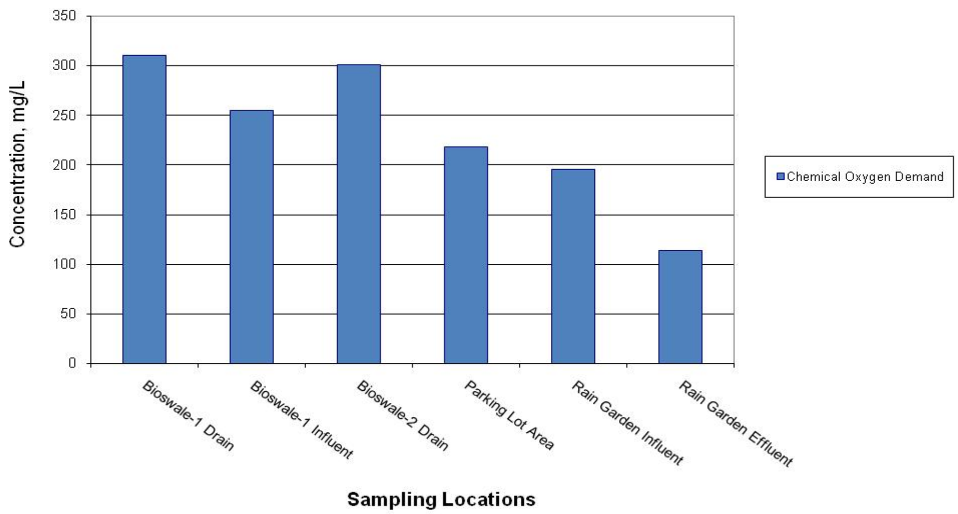
Chemical Oxygen Demand (COD)

Chemical Oxygen Demand (COD), a parameter used to indirectly measure the amount of organic materials in water was also measured throughout the course of the study. Oxygen demand is an important parameter for determining the amount of organic matter in water. Biological Oxygen Demand (BOD) measures the amount of oxygen consumed by microbial oxidation (Water and Wastes Digest 2003) while COD measures the capacity of water to consume oxygen during the decomposition of organic matter and the oxidation of inorganic chemicals such as ammonia and nitrite. Both COD and BOD tests are useful in measuring water quality. BOD testing uses microorganisms that consume oxygen while feeding on organic compounds in a wastewater sample over a five-day period. A COD test is a faster test for determining COD levels and is preferred for more rapid results. Since there are no identifiable biological activities upstream of the biofiltration units, COD tests were performed in this study to measure the extent of organic matter removal when using the biofiltration units.

Figure 5.13a shows that COD concentration was highest in July 27 samples when the inlet runoff volume was low. Overall, Figure 5.13b indicates that COD concentration decreased along the biofiltration unit except in the bioswale-2 drain. The decrease in COD concentration based on the overall inlet and outlet measurements was from 310.7mg/L to 114.5mg/L representing an estimated reduction of 28.5% % of the initial concentration. Decreasing COD concentration means that the amount of organic matter that will consume oxygen is decreasing. This indicates that the biofiltration unit enhances removal of organic matter in stormwater runoff.



a. Variation of COD along the biofiltration units



b. Annual average COD along the biofiltration units

Figure 5-16 Variations of COD along the biofiltration units

Dissolved Metals

Sources of metals in runoff from parking lots are mainly wearing parts of vehicles and rusts. Dissolved metals in water are toxic to aquatic organisms. A selected number of metals tested were chosen based on the chances of being deposited on parking lots. These were aluminum (Al), barium (Ba), copper (Cu), nickel (Ni), chromium (Cr), titanium (Ti), iron (Fe), zinc (Zn), and lead (Pb). The test was performed by staff at the YWWTP in Youngstown, Ohio.

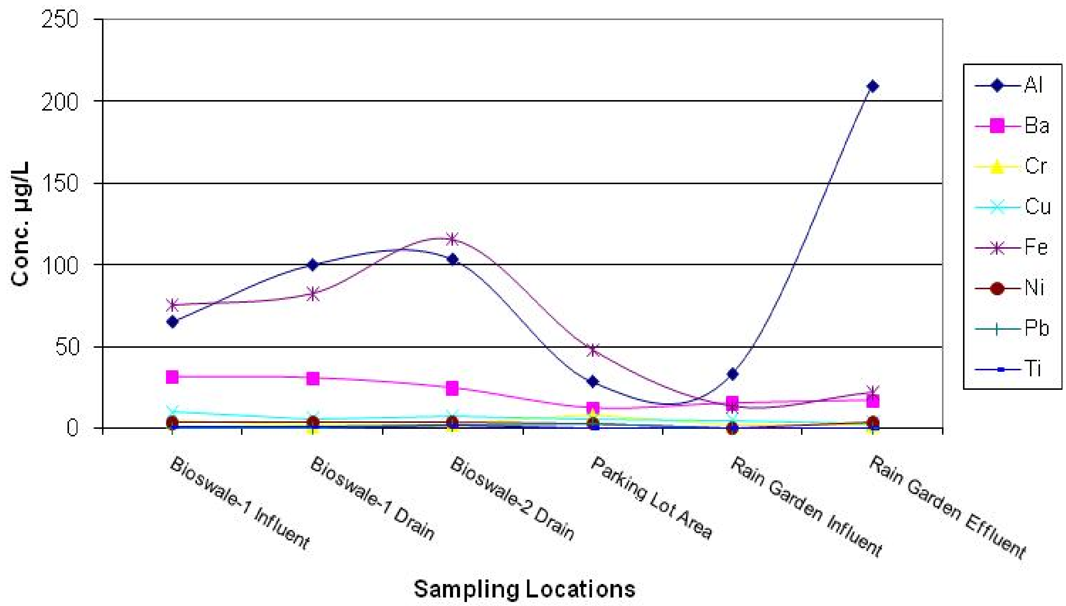


Figure 5-17 Variation of dissolved metals along the biofiltration units

The analytical results presented in Figure 5.14 indicate that aluminum (Al) and iron (Fe) were more prominent in the stormwater compared to barium (Ba), copper (Cu), nickel(Ni), chromium (Cr), titanium (Ti) and lead (Pb). Ti, Pb, Cr and Cu concentrations were too low. From the results, dissolved metal concentrations of all the metals decreased along the biofiltration units, except Al and Ba

Under normal circumstances, it is expected that the application of biofiltration units should result in the reduction of dissolved metal concentration in the stormwater runoff as shown in all the metals analyzed except Al and Ba. Therefore, increased Al and Ba concentration along the biofiltration units predicts the availability of Al^{3+} and Ba^{2+} ions in solution. This might be from other sources that are not accounted for. It could also be that the Al^{3+} and Ba^{2+} ions are not being adsorb (adsorbs to surfaces). Another possible reason for these occurrences can be attributed to flooding and overflow of stormwater runoff on the biofiltration units. With the exception of Al and Ba, it can be deduced from this study that the biofiltration units reduced dissolved metals in the runoff.

Chapter 6 Conclusion

The focus of the study was to assess changes in concentrations of water quality parameters in stormwater runoff as it infiltrates through the biofiltration units. After field sampling, laboratory analysis and statistical data evaluation, results obtained indicate different trends for different parameters. Comparison of concentrations along the sampling points and estimation of extent of treatment based on volume weighted average (appendix B) indicated reduction of total suspended solids (Figure 5.2), ammonia (Figure 5.4), total phosphorus (Figure 5.8), conductivity (Figure 5.12), COD (Figure 5.13) and dissolved metals (except Al, Figure 5.14). These decreased trends indicate that the bioswales and rain garden, to some extent, are operating as intended (to filter pollutants). On the other hand, concentrations of some parameters like NO_3-N (Figure 5.6), oil and grease (Figure 5.10) and Al (Figure 5.14) increased along the units. These increases may indicate leakage of the filtration system by outside sources or incomplete filtration.

Accurate analytical results could be obtained if all inlets and outlets were sampled and analyzed. However, due to several constraints, sampling from certain locations was not possible. Constraints encountered in this study include; low stormwater flow for bioswale-2 inlet sampling, frequent flooding and overflowing of runoff on bioswale-1 and rain garden, direct rainfall unto unit surfaces during heavy rainfall, and inaccessible inlet sources into the rain garden. These constraints have potential impacts on the results.

A review of the data shows some inconsistencies in the ability of the different biofiltration units to function properly. Some concentrations (TSS, COD, and oil and grease) decreased between the bioswale-1 influent and bioswale-1 drain and again between the rain garden influent and rain garden effluent. On the contrary, other parameters such as total phosphorus (TP) showed an increase in concentrations between the bioswale-1 influent and bioswale-1 drain but a decrease in concentration between the rain garden influent and rain garden effluent. Nitrate analysis showed a decrease in concentration between the bioswale-1 influent and bioswale-1 drain but an increase in concentration between the rain garden influent and rain garden effluent. Most of the samples analyzed for dissolved metals were at non-detectable limits for all the biofiltration units, indicating a low source of metals. There was no substantial difference in pH readings between the bioswale-1 inlet and drain, but there was an increase in pH between the rain garden influent and rain garden effluent. This may be due to substrate differences in the biofiltration units.

The variability in the amount of rainfall on different sampling dates yielded different flow velocities (Figure 5.1) and yielded occasional flooding and overflow into effluent sampling points; this could be one source of inconsistency in the trend of treatment efficiencies along the biofiltration units. Another factor includes seasonal changes, resulting in decomposition of plants in the fall season thereby adding nutrients (ammonia, phosphorus, and nitrate) to the soil medium. In the winter, frost (snow) renders plants and microorganisms dormant. This may decrease the units' efficiency (LID 2003).

Analyzing the overall efficiency of the rain garden alone was not possible due to the occasional flooding which submerged the PVC pipe and the overflow of stormwater directly unto the rain garden effluent man-hole (rain garden outlet sampling point) instead of infiltrating.

Notwithstanding the limitations in this study, statistical results indicate that the biofiltration units (overall) are efficient in treating total suspended solids (81.3%), total phosphorus (39.1%), ammonia (58.11%), conductivity (7.37%), chemical oxygen demand (28.5%), and a few of dissolve metals (Cr-37.0 %, Cu -15.1%, Fe-44.0%, Ti-73.9%, Zn-53.9%). The percentage of removal of these parameters were calculated based on volume weighted concentration of bioswale-1 inlet and rain garden effluent from July to December 2007. The results in this study were not tested for statistical significance.

Based on the field study and observations, it is recommended that several modifications would increase the efficiencies of the biofiltration units. Increasing the height of the drains (man-hole) in all the biofiltration units would allow greater holding volume before the stormwater would overflow. As the units operate now, the runoff, soil, mulch, and debris flow into the drains with little infiltration. The addition of native plants would reduce the need for re-planting, and weeding, and it would provide a positive example for the public of how to use native plants for landscaping. Native plants have better tolerance for the local climate, soil conditions and seasonal changes. Lastly, there is a loss of usable rain garden area directly behind the influent piping. Either altering the water flow so that more area is available to treat the stormwater before it overflows or moving the influent pipe would greatly enhance the filtration process. In addition, basic maintenance such as periodically removing deposited soil and debris from under-drain pipes to prevent clogging would benefit the infiltration rate and flow of stormwater. With or without these modifications, continued assessment of the biofiltration units would be useful. Additional sampling from all the inlets, time interval sampling during rain events, and better flow rate estimates would improve the understanding of the efficiency of each of the biofiltration units.

Despite these obstacles, the data collected has indicated that there is a high possibility that the bioswales and rain garden on Youngstown State University campus are effective in treating COD, conductivity, some dissolve metals (Cr, Cu, Fe, Ti, and Zn), TP, ammonia and reducing TSS in stormwater runoff from the parking lots. It is anticipated that the biofiltration performance is higher than estimated. Overall, it is observed from this study that well designed and properly maintained biofiltration units have the potential to provide significant benefits in treating stormwater runoff from parking lots and protecting receiving waters from pollution while beautifying the environment.

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Chapter 8 : Appendix

A: Arithmetic mean Concentrations of Analyzed selected Parameters

Ammonia (NH_3-N), µg/L

Location	4/25/2007	6/2/2007	6/13/2007	7/27/2007	8/20/2007	9/26/2007	10/23/2007	12/9/2007
Bioswale-1 Influent	183.6	311.8	16.5	1503.3	10716.7	4292.9	6452.9	253.8
Bioswale-1 Drain	25.1	435	25.8	1835	9200	3500	NS	138.5
Bioswale-2 Drain	45.6	418.6	33.8	810	5600	3857.1	11247.1	3189.7
Parking Lot Area	88.1	NS	NS	350	10600	3671.4	4570.6	4369.2
Rain Garden Influent	77.6	852.1	93.5	590	5200	5371.4	NS	407.7
Rain Garden Effluent	NS	NS	NS	445	4700	1121.4	600	4856.4

Chemical Oxygen Demand (COD)

	3/14/2007	4/25/2007	6/2/2007	6/13/2007	7/11/2007	7/27/2007	8/20/2007	9/26/2007	10/23/2007	12/9/2007
Bioswale-1 Influent	155	122.2	327.8	361.1	685	685	61.1	43	85.4	25
Bioswale-1 Drain	715	205.6	283.3	288.9	680	680	77.8	46.5	75	55
Bioswale-2 Drain	487.5	233.3	327.8	288.9	700	700	77.8	40	93.8	57.5
Parking Lot Area	342.5	116.7	NS	NS	780	780	38.8	44.5	56.3	22.5
Rain Garden Influent	191.7	88.9	94.4	94.4	670	670	55.6	28	43.8	22.5
Rain Garden Effluent	NS	NS	NS	NS	375	375	27.8	16	43.8	304

Conductivity,µs

	3/14/2007	4/25/2007	6/2/2007	6/13/2007	7/11/2007	7/27/2007	8/20/2007	9/26/2007	10/23/2007	12/9/2007
Bioswale-1 Influent	1692.0	77.0	168.3	217.0	170.5	100.1	63.7	NS	63.5	197.2
Bioswale-1 Drain	4.8	434.3	191.3	233.1	860.0	702.0	98.6	450.0	51.9	509.0
Bioswale-2 Drain	4.8	576.0	232.2	235.6	783.0	505.0	72.0	416.7	77.0	610.0
Parking Lot Area	3078.0	98.8	NS	64.1	4.0	514.0	28.5	123.1	28.3	130.7
Rain Garden Influent	2995.0	69.5	70.4	68.0	139.0	69.6	121.4	93.4	28.0	148.0
Rain Garden Effluent	NS	NS	NS	NS	391.0	61.0	42.0	184.9	66.5	20.4

Nitrates, NO3-NO µg/L

Location	3/14/2007	4/25/2007	6/2/2007	6/13/2007	7/11/2007	7/27/2007	8/20/2007	12/9/2007
Bioswale-1 Influent	NV	272.8	4726.0	3050.0	6345.8	866.1	887.0	160.4
Bioswale-1 Drain	600.5	129.5	5986.0	2544.4	16683.3	1973.2	127.4	156.7
Bioswale-2 Drain	312.9	152.0	6426.0	2558.3	15375.0	1385.1	100.3	160.8
Parking Lot Area	731.3	209.5	NV	NV	5191.7	903.0	145.7	53.3
Rain Garden Influent	623.0	186.2	7686.0	2125.0	5050.0	597.7	558.9	97.5
Rain Garden Effluent	NS	NS	NS	NS	18266.7	1484.1	542.5	1105.0

Oil and Grease, mg/L

Location	3/1/2007	3/14/2007	6/2/2007	12/9/2007
Bioswale-1 Influent	11.3	11.0	1.7	3.3
Bioswale-1 Drain	3.9	4.0	0.8	3.5
Bioswale-2 Drain	11.8	1.6	0.9	6.6
Parking Lot Area	16.9	12.0	3.6	33.9
Rain Garden Influent	15.0	14.0	0.0	28.9
Rain Garden Effluent	NS	NS	NS	NS

NS=No sampling

Dissolved Metals, µg/L

Locations	Al	Ba	Cr	Cu	Fe	Ni	Pb	Ti
Bioswale-1 Influent	65.09	31.15	3.82	9.66	75.33	3.21	ND	0.68
Bioswale-1 Drain	100.01	30.58	1.38	5.68	82.42	3.43	ND	0.72
Bioswale-2 Drain	103.42	24.50	2.38	7.20	115.80	3.52	1.55	1.30
Parking Lot Area	28.39	12.23	7.81	5.17	47.99	2.79	2.93	0.14
Rain Garden Influent	32.99	15.25	1.51	5.01	13.08	ND	ND	0.07
Rain Garden Effluent	209.65	16.92	1.80	2.91	21.55	3.24	0.42	0.28

ND= below detection limit

B: Annual Average Concentrations

Chemical Oxygen Demand (COD)

Location	COD, mg/L
Bioswale-1 Drain	310.7
Bioswale-1 Influent	255.1
Bioswale-2 Drain	300.7
Parking Lot Area	218.1
Rain Garden Influent	195.9
Rain Garden Effluent	114.2

Oil & Grease

Location	Oil & Grease, mg/L
Bioswale-1 Drain	3.1
Bioswale-1 Influent	6.8
Bioswale-2 Drain	5.2
Parking Lot Area	16.6
Rain Garden Influent	14.5

Total Suspended Solids

Location	Total Suspended Solids, mg/L
Bioswale-1 Drain	62.72
Bioswale-1 Influent	58.18
Bioswale-2 Drain	22.63
Rain Garden Influent	11.68
Rain Garden Effluent	4.80

Nutrients

	Parameter		
Location	Ammonia (NH3-N), µg/L	Nitrates, NO3-NO µg/L	Phosphorus, µg/L
Bioswale-1 Influent	2373.15	1630.82	135.65
Bioswale-1 Drain	1293.58	2820.11	286.38
Bioswale-2 Drain	2520.19	2647.05	148.80
Parking Lot Area	2364.93	723.45	58.73
Rain Garden Influent	1116.29	1692.43	82.33
Rain Garden Effluent	1172.28	2139.83	29.46

C: Dissolved Metals

Aluminum

Dissolved Metals

Average of Conc, µg/L	Date				
Location	3/14/2007	4/25/2007	9/26/2007	10/23/2007	12/9/2007
Bioswale-1 Influent	1165.57	1164.89	52.42	77.76	121.58
Bioswale-1 Drain	701.81	641.69	133.17	66.84	117.17
Bioswale-2 Drain	548.63	375.85	88.08	118.76	65.18
Parking Lot Area	1676.16	356.20	29.98	26.80	51.19
Rain Garden Influent	760.34	147.74	36.65	29.32	73.53
Rain Garden Effluent	NS	Ns	204.46	214.84	144.56

Barium

Average of Conc, µg/L	Date				
Location	3/14/2007	4/25/2007	9/26/2007	10/23/2007	12/9/2007
Bioswale-1 Influent	51.73	42.40	30.99	31.31	40.06
Bioswale-1 Drain	230.80	86.42	35.49	25.67	71.61
Bioswale-2 Drain	283.95	77.86	28.13	20.86	45.90
Parking Lot Area	49.64	26.30	14.09	10.37	33.82
Rain Garden Influent	63.60	16.97	18.80	11.69	37.47
Rain Garden Effluent	NS	NS	18.29	15.55	172.27

Chromium

Average of Conc, µg/L	Date				
Location	3/14/2007	4/25/2007	9/26/2007	10/23/2007	12/9/2007
Bioswale-1 Influent	6.81	5.94	6.09	1.54	ND
Bioswale-1 Drain	3.96	4.03	2.75	ND	1.61
Bioswale-2 Drain	3.71	2.83	3.11	1.65	ND
Parking Lot Area	19.07	5.17	13.68	1.93	ND
Rain Garden Influent	Ns	1.58	3.02	ND	ND
Rain Garden Effluent	NS	NS	2.20	1.40	6.51

Copper

Average of Conc, µg/L	Date				
Location	3/14/2007	4/25/2007	9/26/2007	10/23/2007	12/9/2007
Bioswale-1 Influent	21.24	19.26	16.01	3.31	5.21
Bioswale-1 Drain	12.73	11.80	8.34	3.02	5.88
Bioswale-2 Drain	12.81	10.18	8.73	5.66	4.16
Parking Lot Area	24.46	7.45	10.34	ND	3.46
Rain Garden Influent	15.39	9.71	10.01	ND	4.63
Rain Garden Effluent	NS	NS	3.48	2.34	11.48

Iron

Average of Conc, µg/L	Date				
Location	3/14/2007	4/25/2007	9/26/2007	10/23/2007	12/9/2007
Bioswale-1 Influent	954.24	718.87	75.14	75.52	113.85
Bioswale-1 Drain	574.21	656.70	115.96	48.88	131.01
Bioswale-2 Drain	934.78	192.59	126.71	104.89	34.56
Parking Lot Area	1391.15	352.18	31.73	64.25	47.43
Rain Garden Influent	1047.64	384.66	26.16	ND	67.88
Rain Garden Effluent	NS	NS	20.99	22.10	122.16

Nickel

Average of Conc, µg/L	Date				
Location	3/14/2007	4/25/2007	9/26/2007	10/23/2007	12/9/2007
Bioswale-1 Influent	9.97	8.82	6.41	ND	3.47
Bioswale-1 Drain	6.18	6.87	4.20	2.66	ND
Bioswale-2 Drain	6.48	6.39	4.05	2.99	ND
Parking Lot Area	9.77	4.34	5.57	ND	ND
Rain Garden Influent	6.50	3.08	ND	ND	ND
Rain Garden Effluent	NS	NS	3.54	2.93	4.25

ND = below detection limit, NS = No sampling or recorded value

Titanium

	Ti				
Average of Conc, µg/L	Date				
Location	3/14/2007	4/25/2007	9/26/2007	10/23/2007	12/9/2007
Bioswale-1 Influent	14.02	12.36	0.27	1.09	0.79
Bioswale-1 Drain	4.51	4.30	0.97	0.47	0.29
Bioswale-2 Drain	3.02	1.21	1.35	1.24	0.28
Parking Lot Area	17.93	5.18	0.13	0.14	0.35
Rain Garden Influent	7.42	ND	0.14	ND	0.31
Rain Garden Effluent	NS	NS	0.35	0.21	0.21

ND = below detection limit, NS = No sampling or recorded value

Lead

Average of Conc, µg/L	Pb				
	Date				
Location	3/14/2007	4/25/2007	9/26/2007	10/23/2007	12/9/2007
Bioswale-1 Influent	29.41	26.49	ND	ND	4.26
Bioswale-1 Drain	14.09	5.15	ND	ND	ND
Bioswale-2 Drain	10.86	4.70	3.10	ND	ND
Parking Lot Area	94.72	14.81	ND	5.86	ND
Rain Garden Influent	33.49	5.49	ND	ND	4.57
Rain Garden Effluent	NS	NS	0.84	ND	19.34

ND = below detection limit, NS = No sampling or recorded value

Zinc

Average of Conc, µg/L	Zn				
	Date				
Location	3/14/2007	4/25/2007	9/26/2007	10/23/2007	12/9/2007
Bioswale-1 Influent	139.19	186.53	36.84	27.70	39.23
Bioswale-1 Drain	73.94	74.38	33.59	28.42	33.84
Bioswale-2 Drain	90.91	72.46	45.67	24.47	18.89
Parking Lot Area	185.25	45.48	33.81	13.09	18.59
Rain Garden Influent	97.83	46.68	25.86	22.32	20.41
Rain Garden Effluent	NS	NS	8.31	13.71	21.16

ND = below detection limit, NS = No sampling or recorded value

Appendix B: Efficiency Estimation based on volume weighted concentration

Chemical Oxygen Demand

Date	Rainfall (r) (inches)	Bioswale In Concentration of X (mg/L)	Bioswale In r_iC_i	Rain Garden Out Concentration of X (mg/L)	Rain Garden Out r_iC_i
7/11/2007	0.59	685.00	404.15	375.00	221.25
7/27/2007	0.5	685.00	342.50	375.00	187.50
8/20/2007	1.7	61.11	103.89	27.78	47.23
9/26/2007	0.38	43.00	16.34	16.00	6.08
10/23/2007	1.45	85.42	123.85	43.75	63.44
12/9/2007	0.64	25.00	16.00	304.00	194.56
Σ =	**5.26**		**1006.74**		**720.05**

Volune Weighted Concentration

$$Conc_{BS\ in} = \frac{\Sigma r_iC_i}{\Sigma r_i} \qquad \frac{1006.74}{5.26} \qquad 191.39$$

$$Conc_{RG\ out} = \frac{\Sigma r_iC_i}{\Sigma r_i} \qquad \frac{720.05}{5.26} \qquad 136.89$$

$$\text{Efficiency} = \frac{(Conc_{in} - Conc_{out})}{Conc_{in}} * 100 \qquad \underline{\mathbf{28.5\ \%}}$$

Ammonia

Date	Rainfall (r) (inches)	Bioswale In Concentration of X (ug/L)	Bioswale In r_iC_i	Rain Garden Out Concentration of X (ug/L)	Rain Garden Out r_iC_i
7/27/2007	0.5	1503.33	751.67	445.00	222.50
8/20/2007	1.7	10716.67	18218.33	4700.00	7990.00
9/26/2007	0.38	4292.86	1631.29	1121.43	426.14
10/23/2007	1.45	6452.94	9356.76	600.00	870.00
12/9/2007	0.64	253.85	162.46	4856.41	3108.10
Σ =	**4.67**		**30120.51**		**12616.75**

Volune Weighted Concentration

$$Conc_{BS\ in} = \frac{\Sigma r_iC_i}{\Sigma r_i} \quad \frac{30120.51}{4.67} \quad 6449.79$$

$$Conc_{RG\ out} = \frac{\Sigma r_iC_i}{\Sigma r_i} \quad \frac{12616.75}{4.67} \quad 2701.66$$

$$\text{Efficiency} = \frac{(Conc_{in} - Conc_{out})}{Conc_{in}} *100 \quad \underline{\mathbf{58.11\%}}$$

Nitrate

Date	Rainfall (r) (inches)	Bioswale Influent Concentration of X (ug/L)	Bioswale Influent r_iC_i	Rain Garden Effluent Concentration of X (ug/L)	Rain Garden Effluent r_iC_i
7/11/2007	0.59	6345.83	3744.04	18266.67	10777.33
7/27/2007	0.5	866.15	433.07	1484.09	742.05
8/20/2007	1.7	886.95	1507.82	542.54	922.32
12/9/2007	0.64	160.42	102.67	1105.00	707.20
Σ =	3.43		5787.60		13148.90

Volune Weighted Concentration

$$Conc_{BS\ in} = \frac{\Sigma\, r_iC_i}{\Sigma\, r_i} \quad \frac{5787.60131}{3.43} \quad 1687.35$$

$$Conc_{RG\ out} = \frac{\Sigma\, r_iC_i}{\Sigma\, r_i} \quad \frac{13148.90469}{3.43} \quad 3833.50$$

$$\text{Efficiency} = \frac{(Conc_{in} - Conc_{out})}{Conc_{in}} *100 \quad \mathbf{-127.2\ \%}$$

Phosphorus

Date	Rainfall (r) (inches)	Bioswale In Concentration of X (ug/L)	Bioswale In r_iC_i	Rain Garden Out Concentration of X (ug/L)	Rain Garden Out r_iC_i
7/11/2007	0.59	217.50	128.33	65.00	38.35
7/27/2007	0.5	149.17	74.58	47.50	23.75
8/20/2007	1.7	3.05	5.19	2.14	3.64
9/26/2007	0.38	70.00	26.60	45.00	17.10
10/23/2007	1.45	54.17	78.54	42.50	61.63
12/9/2007	0.64	33.50	21.44	92.50	59.20
Σ =	5.26		334.68		203.66

Volune Weighted Concentration

$$Conc_{BS\ in} = \frac{\Sigma r_iC_i}{\Sigma r_i} \qquad \frac{334.675}{5.26} \qquad 63.6$$

$$Conc_{RG\ out} = \frac{\Sigma r_iC_i}{\Sigma r_i} \qquad \frac{203.663}{5.26} \qquad 38.7$$

$$\text{Efficiency} = \frac{(Conc_{in} - Conc_{out})}{Conc_{in}} * 100 \qquad \underline{\mathbf{39.1\%}}$$

Conductivity

Date	Rainfall (r) (inches)	Bioswale In Concentration of X (ug/L)	Bioswale In r_iC_i	Rain Garden Out Concentration of X (ug/L)	Rain Garden Out r_iC_i
7/11/2007	0.59	170.50	100.60	391.00	230.69
7/27/2007	0.5	100.13	50.07	61.50	30.50
8/20/2007	1.7	63.73	108.35	42.00	71.40
10/23/2007	1.45	63.45	92.00	66.50	96.43
12/9/2007	0.64	197.20	126.21	20.40	13.06
Σ =	**4.88**		**477.22**		**442.07**

Volune Weighted Concentration

$$Conc_{BS\ in} = \frac{\Sigma r_iC_i}{\Sigma r_i} \quad \frac{477.22}{4.88} \quad 97.79$$

$$Conc_{RG\ out} = \frac{\Sigma r_iC_i}{\Sigma r_i} \quad \frac{442.07}{4.88} \quad 90.59$$

$$\text{Efficiency} = \frac{(Conc_{in} - Conc_{out})}{Conc_{in}} * 100 \quad \underline{\mathbf{7.37\%}}$$

Total Suspended Solids

Date	Rainfall (r) (inches)	Bioswale In Concentration of X (mg/L)	Bioswale In r_iC_i	Rain Garden Out Concentration of X (mg/L)	Rain Garden Out r_iC_i
7/11/2007	0.59	207.04	122.15	1.20	0.71
7/27/2007	0.5	91.43	45.71	5.60	2.80
8/20/2007	1.7	5.93	10.09	2.80	4.76
9/26/2007	0.38	28.47	10.82	4.10	1.56
10/23/2007	1.45	10.78	15.63	14.30	20.74
12/9/2007	0.64	43.70	27.97	20.00	12.80
Σ =	**5.26**		**232.37**		**43.36**

Volune Weighted Concentration

$$Conc_{BS\ in} = \frac{\Sigma\, r_iC_i}{\Sigma\, r_i} \qquad \frac{232.37}{5.26} \qquad 44.18$$

$$Conc_{RG\ out} = \frac{\Sigma\, r_iC_i}{\Sigma\, r_i} \qquad \frac{43.36}{5.26} \qquad 8.24$$

$$\text{Efficiency} = \frac{(Conc_{in}-Conc_{out})}{Conc_{in}} *100 \qquad \mathbf{\underline{81.34\%}}$$

Dissolved Metals

AL

Date	**Rainfall (r) (inches)**	**Bioswale In Concentration of X (ug/L)**	**Bioswale In r_iC_i**	**Rain Garden Out Concentration of X (ug/L)**	**Rain Garden Out r_iC_i**
9/26/2007	0.38	52.42	19.9196	204.46	77.6948
10/23/2007	1.45	77.76	112.756833	214.84	311.518
12/9/2007	0.64	121.58	77.808	144.56	92.5184
Σ =	2.47		210.484433		481.7312

Volune Weighted Concentration

$Conc_{BS\ in} = \frac{\Sigma r_iC_i}{\Sigma r_i}$ $\frac{210.4844333}{2.47}$ 85.2

$Conc_{RG\ out} = \frac{\Sigma r_iC_i}{\Sigma r_i}$ $\frac{481.7312}{2.47}$ 195.0

Efficiency $= \frac{(Conc_{in} - Conc_{out})}{Conc} * 100$ **-128.9%**

Ba

Date	**Rainfall (r) (inches)**	**Bioswale In Concentration of X (ug/L)**	**Bioswale In r_iC_i**	**Rain Garden Out Concentration of X (ug/L)**	**Rain Garden Out r_iC_i**
9/26/2007	0.38	30.99	11.78	18.29	6.95
10/23/2007	1.45	31.31	45.40	15.55	22.55
12/9/2007	0.64	40.06	25.64	172.27	110.25
Σ =	2.47		82.81		139.75

Volune Weighted Concentration

$$Conc_{BS\ in} = \frac{\Sigma r_iC_i}{\Sigma r_i} \quad \frac{82.8141}{2.47} \quad 33.5$$

$$Conc_{RG\ out} = \frac{\Sigma r_iC_i}{\Sigma r_i} \quad \frac{139.7505}{2.47} \quad 56.6$$

$$\text{Efficiency} = \frac{(Conc_{in} - Conc_{out})}{Conc} * 100 \quad -68.8\%$$

Cr

Date	Rainfall (r) (inches)	Bioswale In Concentration of X (ug/L)	Bioswale In r_iC_i	Rain Garden Out Concentration of X (ug/L)	Rain Garden Out r_iC_i
9/26/2007	0.38	6.09	2.3142	2.2	0.836
10/23/2007	1.45	1.54	2.233	1.4	2.03
Σ =	1.83		4.5472		2.866

Volune Weighted Concentration

$$Conc_{BS\ in} = \frac{\Sigma r_iC_i}{\Sigma r_i} \quad \frac{4.5472}{1.83} \quad 2.5$$

$$Conc_{RG\ out} = \frac{\Sigma r_iC_i}{\Sigma r_i} \quad \frac{2.866}{1.83} \quad 1.6$$

$$\text{Efficiency} = \frac{(Conc_{in}-Conc_{out})}{Conc_{in}} *100 \quad \underline{\mathbf{37.0\%}}$$

Cu

Date	Rainfall (r) (inches)	Bioswale In Concentration of X (ug/L)	Bioswale In r_iC_i	Rain Garden Out Concentration of X (ug/L)	Rain Garden Out r_iC_i
9/26/2007	0.38	16.01	6.08	3.48	1.32
10/23/2007	1.45	3.30	4.79	2.34	3.39
12/9/2007	0.64	5.21	3.33	11.48	7.35
Σ =	2.47		14.21		12.06

Volune Weighted Concentration

$$Conc_{BS\ in} = \frac{\Sigma\ r_iC_i}{\Sigma\ r_i} \qquad \frac{14.21286667}{2.47} \qquad 5.8$$

$$Conc_{RG\ out} = \frac{\Sigma\ r_iC_i}{\Sigma\ r_i} \qquad \frac{12.0626}{2.47} \qquad 4.9$$

$$\text{Efficiency} = \frac{(Conc_{in} - Conc_{out})}{Conc_{in}} * 100 \qquad \underline{\mathbf{15.1\%}}$$

Fe

Date	Rainfall (r) (inches)	Bioswale In Concentration of X (ug/L)	Bioswale In r_iC_i	Rain Garden Out Concentration of X (ug/L)	Rain Garden Out r_iC_i
9/26/2007	0.38	75.14	28.55	20.99	7.98
10/23/2007	1.45	75.52	109.50	22.1	32.05
12/9/2007	0.64	113.85	72.86	122.16	78.18
Σ =	2.47		210.92		118.20

Volune Weighted Concentration

$$Conc_{BS\ in} = \frac{\Sigma r_iC_i}{\Sigma r_i} \quad \frac{210.9212}{2.47} \quad 85.4$$

$$Conc_{RG\ out} = \frac{\Sigma r_iC_i}{\Sigma r_i} \quad \frac{118.2036}{2.47} \quad 47.9$$

$$\text{Efficiency} = \frac{(Conc_{in} - Conc_{out})}{Conc_{in}} * 100 \quad \textbf{44.0\%}$$

Ti

Date	**Rainfall (r) (inches)**	**Bioswale In Concentration of X (ug/L)**	**Bioswale In r_iC_i**	**Rain Garden Out Concentration of X (ug/L)**	**Rain Garden Out r_iC_i**
9/26/2007	0.38	0.27	0.10	0.35	0.13
10/23/2007	1.45	1.09	1.58	0.21	0.30
12/9/2007	0.64	0.79	0.51	0.21	0.13
$\Sigma =$	2.47		2.19		0.57

Volune Weighted Concentration

$$Conc_{BS\ in} = \frac{\Sigma r_iC_i}{\Sigma r_i} \qquad \frac{2.1887}{2.47} \qquad 0.9$$

$$Conc_{RG\ out} = \frac{\Sigma r_iC_i}{\Sigma r_i} \qquad \frac{0.5719}{2.47} \qquad 0.2$$

$$\text{Efficiency} = \frac{(Conc_{in} - Conc_{out})}{Conc} *100 \qquad \mathbf{73.9\%}$$

Zn

Date	Rainfall (r) (inches)	Bioswale In Concentration of X (ug/L)	Bioswale In r_iC_i	Rain Garden Out Concentration of X (ug/L)	Rain Garden Out r_iC_i
9/26/2007	0.38	36.84	14.0	8.31	3.16
10/23/2007	1.45	27.7	40.17	13.71	19.89
12/9/2007	0.64	39.23	25.11	21.16	13.54
Σ =	2.47		79.27		36.58

Volune Weighted Concentration

$$Conc_{BS\ in} = \frac{\Sigma r_iC_i}{\Sigma r_i} \qquad \frac{79.2714}{2.47} \qquad 32.1$$

$$Conc_{RG\ out} = \frac{\Sigma r_iC_i}{\Sigma r_i} \qquad \frac{36.5797}{2.47} \qquad 14.8$$

$$\text{Efficiency} = \frac{(Conc_{in}-Conc_{out})}{Conc_{in}} * 100 \qquad \mathbf{53.9\%}$$