

FDEP Contract Number WM 910
Management of Source Area Runoff Using In-situ Controls

Final Report Draft

University of Florida
Department of Environmental Engineering Sciences
218 Black Hall
Gainesville, FL 32611, USA

01 September 2009

TABLE OF CONTENTS

CHAPTER 1: Introduction

CHAPTER 2: Literature Review for Stormwater Filter Systems

CHAPTER 3: Nutrients Partitioning and Transport in Rainfall Runoff from an Institutional
Source Area

CHAPTER 4: Testing of Engineered Soil Media for Phosphorus Adsorption or Desorption

CHAPTER 5: Field-Scale Testing of the Engineered Soil Media Filter System

CHAPTER 6: Retrofitting Impervious Urban Infrastructure with Green Technology for
Rainfall-Runoff Restoration, Indirect Reuse and Pollutant Load Reduction

CHAPTER 7: Recommendations

APPENDIX A: Literature Review for Stormwater Filter Systems

CHAPTER 1: INTRODUCTION

Over the last four decades many studies have demonstrated the delivery of nitrogen (N) species, phosphorus (P) species, and particulate matter (PM) in rainfall-runoff impacted by anthropogenic and biogenic sources at the built urban interface. Runoff resulting from impervious surfaces and catchment urbanization has long been recognized as one of the significant sources of pollutants and identified by the USEPA as a leading cause of water quality impairment (USEPA, 1996). The magnitude of this delivery into a municipal separate storm sewer conveyance system, a combined system, a best management practice (BMP) or receiving waters is significantly increased due to the modification of the relationship between rainfall and runoff through increasing imperviousness. The intensity of such imperviousness in constructed environs is the result of land use changes, pavements, buildings, associated infrastructure, construction, compaction of cohesive soils, densification of non-cohesive soils and alteration of cover conditions. In fact, the increased delivery of N, P, PM, metals, runoff and thermal loads are due to alterations of the natural nutrient, chemical, particulate and hydrologic cycles which are coupled phenomena in the urban environs.

In addition to PM, nutrients (phosphorus and nitrogen) represent major ecological concerns and are recognized as constituents with concentrations and loads must be reduced in stormwater runoff (or snowmelt runoff in northern climates). Many studies, for example, USEPA (1999) have pointed out that excessive nutrients can cause nuisance algae blooms and consequently, negative aesthetic, eutrophic or hyper-eutrophic conditions in receiving waters. For example, P is the primary limiting nutrient in most lakes and reservoirs; although the debate between N and P limitations is still an active topic. Intensive anthropogenic activities and related enhancement of biogenic activities alters P cycling and dispersion. The challenge of controlling N, P and PM is significant given modern anthropogenic processes such as urbanization, transportation, industrialization, current land development practices, and intensive agriculture (even in urban environs) that have placed a tremendous ecological stress on the receiving water bodies. The most recent process of reclaimed wastewater used for urban irrigation adds an additional input of nutrients and chemicals that range from metals to endocrine disrupting compounds (EDC). Many conventional site development design practices exacerbate the problem, while paradoxically simple alterations such as the use of depressed vegetated medians as opposed to elevated curbed medians or engineered cementitious permeable pavement can provide stormwater benefits at equal or lower cost to conventional development practices. With respect to nutrients, for example, N species such as nitrate-rich runoff produce algal blooms in receiving. Another common species of N in stormwater, ammonia-nitrogen ($\text{NH}_3\text{-NH}_4^+$), can generated in oxidation-reduction processes with degradation of organic matter, for example in many common BMP systems such as hydrodynamic separators and in below-grade runoff storage in BMPs such as vaults or tanks. Depending on the pH and concentration; ammonia-nitrogen is potentially toxic to aquatic species. Unlike nitrate, ammonium can be partially removed from stormwater through adsorptive-filtration (infiltration) interactions with soil media.

Recent studies have demonstrated that LID or in-situ practices such as bio-swales, bio-infiltration, engineered soil media systems or engineered cementitious permeable pavement receiving source area runoff from urban areas, specifically impervious pavement can greatly reduce runoff amounts and help restore the pre-developed hydrology. For example, engineered

in-situ soil media filter systems can be a multifunctional passive control to serve as a water chemistry and hydrologic buffer for source area runoff from impervious surfaces. With proper design and application, such in-situ soil media systems which can be vegetated and integrate shallow volumetric capacity for chemistry and hydrologic enhancement for urban source waters; helping restore components of the hydrologic cycle towards pre-constructed conditions. Such systems provide depth filtration, surficial straining, adsorption, ion exchange, infiltration, storage, hydrologic attenuation, evapotranspiration and redox cycling with depth.

A variety of BMPs and low impact development (LID) practices that are designed for infiltration and some degree of exfiltration to surrounding soil have been developed. Several studies reported variable levels of success in lowering particulate matter (PM) fractions such as suspended PM, metal and hydrocarbon concentrations through such systems but nutrient concentrations were weakly lowered and often increased. More research and testing is required, in order to document pollutant load reduction and to examine the hydrologic pathways for these systems. Such techniques have not always reduced nutrient loads, and better design and testing are required to enhance the reduction of nitrogen and removal of phosphorus.

Given this background and framework, the main objective of the project is a quantitative investigation of stormwater media with a commensurate selection from these media for application in an in-situ stormwater control system for PM and nutrients removal. The adopted methodology consisted of a four-phase approach and implementation.

The first phase is a literature review and compilation for in-situ controls (or as identified in the literature nominally as LID). These literature studies have been collected, examined and organized in a formal review. As part of this review, focus was given to cases studies of in-situ systems, any applications of engineered soils, media systems, and applications of vegetated volumetric controls such as swales receiving pavement runoff. The focus was hydrologic control, nutrient control or conversion, and particulate control by in-situ systems. The literature review is reported in Chapter 2 and Appendix A of the present Report.

The second phase was a detailed examination of an urban paved Gainesville catchment supporting surface parking with raised vegetated islands to establish the interaction between hydrology, chemical and particulate matter (PM) and nutrients in rainfall-runoff. Rainfall and runoff were examined separately. Results indicate that both loads and event concentrations from the asphalt-paved catchment were significant for nutrients (N and P) and to a lesser extent PM. PM was examined based on pragmatic nominal size and phenomenological fractions; dissolved, suspended, settleable and sediment fractions. Additionally, more fundamental properties of PM were examined through laser diffraction. Both analysis methodologies for PM provide practical and fundamental insight into the in-situ soil media filter design component of the project. The PM fractions were also examined with respect to N and P association to assess partitioning and transport behavior across the urban paved surface before the filter and for size fractionation of N and P for the in-situ filter design. The findings of four fully-monitored storm events, reported in Chapter 3, provided the necessary knowledge to perform the third and four phase of the research consisting respectively in a bench-scale testing of amended or engineered soils for nutrient control or conversion, and particulate control (Chapter 4) and the field test of the selected media (Chapter 5).

To date very few quantitative tools evaluating adsorptive-filter media for phosphorus adsorption have been implemented. Additionally, there continues to be limited information available and divergent performance claims for phosphorus removal for both manufactured and natural filtration systems using un-quantified media. Media applications that do exist with reported information tend to experience high performance variability (Davis et al. 2006, Heieh et al. 2007) or result in exporting phosphorus, or leaching of other indices such as metals. Again, these challenges are due to the limited quantitative information of the behavior of the filter material. Moreover, availability and rapid replacement costs are concerns when media of lower capacity or longevity is employed for commercial use. Some materials have abundant sources and relative low cost, such as sand, peat, perlite or organic based materials made from different types of waste, but their performance for phosphorus or nitrogen removal does not satisfy the requirements imposed by regulatory agencies or public communities or meet TMDLs or discharge criteria under many conditions.

Thus, the purpose of the third phase of the project is to quantitatively examine the phosphorus removal performance of the soil filter media. These filter media were examined based on standard engineering methods of adsorption phenomena and requirements of adsorption behavior for media. These requirements include a quantitative description of (1) equilibrium isotherms (how much phosphorus can media uptake), (2) kinetics (how rapidly can phosphorus be taken up by the media), (3) breakthrough (under flow-through hydraulic loading rates, what is the removal level and how long does the media lasts before performance diminishes, i.e. maintenance frequency), and (4) potential media desorption. Successful deployment of any media system requires the comparison of media behavior on a rigorous and equal basis through these quantitative descriptions; in addition to desorption or leaching quantification. With such a methodology, media comparisons are clearly illustrated in Chapter 4 as a series of equilibria, kinetics and breakthrough results; providing a much-needed rigorous and defensible basis to predict media performance. The detailed investigation of the engineered soil media resulted in the choice of a clay-based Al-oxide media as compared to a suite of other media. This media was prepared and a treatment system based on the engineered soil was designed and constructed to undergo the field test that represented the fourth phase of the Project.

The scope of the field testing included the in-situ intra-event data collection and analysis of 15 rainfall-runoff events from February 2007 to October 2008, treatment thereof, and drainage management. Specifically, Chapter 5 assesses the intra-event transport and fate of phosphorus and particulate matter (PM), and the inter-event fate of nitrogen species as well as the treatment and fate of these constituents through the clay-based oxide media filtration that provided surface complexation (ion exchange-adsorption-chemical precipitation) for dissolved phosphorus species and filtration of PM-bound TP. The inter-event behavior of the engineered soil filter media system was examined after each captured event for a period of up to 13 days between captured events in order to examine the water chemistry drainage management strategies where the water surface in the soil filter system was maintained under two separate conditions: (1) a retention runoff level below the soil filter system resulting in an unsaturated soil filter condition, but with sufficient retention to saturate the settled sludge layer at the bottom of the system, or (2) a retention runoff level above the soil filter system resulting in prolonged saturated conditions for the entire system.

To demonstrate the potential of LID and green infrastructure design to manage pollutant loads and reduce water resource stresses, the data collected during the field test of the media

were used for a design project that aimed at retrofitting the Reitz Union Surface Parking Area of the University of Florida with a series of design elements. The proposed design is presented in Chapter 6 of the present report. The design presented quantitatively demonstrates that hydrology and pollutant load can be managed on site with site re-design; illustrating the goal of no net load increase for a long-term time series of rainfall-runoff events from 1999 through 2008. A biofiltration area reactor (BAR) is lined with a bounding clay liner for localized perched water table management and managed denitrification. The BARs are downstream of a linear infiltration reactor (LIR) combining the infiltration/evaporation potential and filtration of PM by cementitious permeable pavement (CPP) that includes oxide admixture for adsorption of phosphorus and/or metals. Monthly pavement sweeping was included for source control and infiltration capacity of the CPP. Continuous simulations using SWMM (surface water) and VS2DTI (subsurface water), time series data, site geometrics and soil properties as well as a pollutant loading database indicate that design options can achieve no net load increase from pre-developed conditions. Cost estimates demonstrate that re-design is comparable to conventional construction costs while also incorporating Florida-friendly landscape. Additionally, design options yield a lower cost per pound for nitrogen and phosphorus treated, as compared to conventional Florida BMPs.

CHAPTER 2: LITERATURE REVIEW FOR STORMWATER FILTER SYSTEMS

List of Tables	2-ii
ABSTRACT.....	2-1
INTRODUCTION	2-1
SWALES.....	2-2
SAND FILTERS.....	2-2
UNDERGROUND INFILTRATION/EXFILTRATION SYSTEMS.....	2-3
EFFLUENT FILTRATION	2-4
BIORETENTION	2-4
GRAVEL BED FILTERS.....	2-5
FILTER STRIPS.....	2-6
LABORATORY AND FIELD SCALE EXPERIMENTS.....	2-6
ACKNOWLEDGEMENTS.....	2-7
REFERENCES	2-8

List of Tables

Table 1 Decrease or Increase of Nutrient Concentrations Measured in Swales	2-17
Table 2 Decrease or Increase of Concentrations of Runoff Nutrients or PM in Filtration/Exfiltration Systems.....	2-18
Table 3 Decrease or Increase of Concentrations of Nutrients in Bioretention	2-19
Table 4 Decrease or Increase of Concentrations of Nutrients in Laboratory or Field Tests That Evaluated Soil Amendments Designed to Improve Performance.....	2-20
Table 5 Decrease or Increase of Concentrations of Metals in Laboratory or Field Tests	2-21

ABSTRACT

Low impact development (LID) is a stormwater management method designed to mimic the pre-development hydrology at the urban interface. One goal of LID is to restore the pre-development components of the hydrologic cycle; for example to provide infiltration opportunities for storm runoff. This chapter summarizes a large number of research projects that have studied infiltration techniques for the past 20 years. For this chapter over 175 papers (mainly from archival journals) were reviewed and papers report variable levels of success in lowering particulate matter (PM) fractions such as suspended PM, metal and hydrocarbon concentrations in infiltration systems, but nutrient concentrations were weakly lowered and often increased. This chapter examines these findings but emphasizes findings for nutrients. Hydraulic conductivity is also identified, if reported, since infiltration is one of the most important processes for LID practices. Infiltration reduces surface runoff pollutant loads even when concentrations are not reduced. Research indicates that with soils or media of high adsorptive capacity for a specific constituent under competitive conditions, groundwater contamination by that contaminant is not a problem. Common exceptions include nitrates and the more mobile metal species such as Zn or Cd. Also, included in the review are the many laboratory experiments and pilot studies that have tested soil amendments and engineered soil or media systems designed to reduce pollutant concentrations. Many reports reviewed did not include efficiency data, material balances, or QA/QC, but provided useful information and some of this is discussed in the narrative.

Key Words: stormwater, filtration, low impact development, rainfall-runoff, adsorption

INTRODUCTION

Pollution from storm runoff has long been identified as a serious threat by mobilizing polluted material during rain events and transporting pollutants to receiving waters or soils. In the urban landscape, this process has been exacerbated by the altered watershed hydrology created by impervious land surfaces. The challenge of abating both runoff volumes and pollutant loads have resulted in a great number of research efforts designed to solve these problems. Low Impact Development (LID) is a current practice that focuses on designs that restore the pre-development hydrology and helps reduce runoff pollution impacts. Among one of the most important LID practices is the use of small decentralized techniques designed to infiltrate storm runoff near the source. Infiltration is not a new technique for stormwater control, but LID is the first time that these concepts have been combined as a unified system. The purpose of the review is to summarize much of the monitoring performed on infiltration methods with emphasis on the hydrology and water quality aspects. Over 125 research papers have been identified to date. The bibliography has concentrated on landscape techniques and does not include the extensive research effort for green roofs or pervious pavement. The specific techniques included are: bioretention, swales, infiltration trenches, vegetated filter strips, sand filters, effluent filtration, packed bed filters and miscellaneous studies useful for a stakeholder. Also included is the large effort to test soil amendments and engineered soil/media in laboratory or pilot scale experiments which have been developed to improve the performance of infiltration systems. One problem with analyzing the data from this research has been the practice of reporting efficiencies by two methods: 1) as reduction of concentrations and 2) as a reduction in mass loads.

SWALES

A swale is a shallow, linear surface depression that is vegetated, usually with grass. A swale is used for conveyance and possibly storage of stormwater runoff along roadways, within parking lots and along developed site perimeters or transects. If properly designed they can be useful for improving water chemistry and hydrology by infiltration/percolation into underlying soils and the settling of PM. Swales were one of the earliest techniques studied as a method for reducing runoff pollution and are still an important method utilized for LID. Many swale studies were evaluated in the literature review. The reports did not always provide the percent removal or increase of nutrient concentrations or the amount of runoff infiltrated, but the studies listed show the poor performance of swales to reduce nutrient concentrations, although, when properly designed their ability to infiltrate storm runoff usually reduced pollutant loads. Most research showed that metals, hydrocarbons and PM were efficiently removed

Many studies provided useful suggestions about the parameters that improve the design and performance of swales. Early studies were concerned with the problem of estimating the infiltration rates of soils and determined that the rate was three to four times lower than predicted by the double-ring infiltrometer, but the infiltrometer was better than the lab permeameter or published values (Avellaneda 1985, Yousef et al. 1985, Wanielista et al. 1988). The most important parameters for improving swale performance included: grass cover and good maintenance (Anderson 1982); aerobic ditches in conjunction with road shoulders working better than road shoulders alone (Wanielista et al. 1978). Adequate infiltration rates along with shallow side slopes, and topography improved performance (Avellaneda 1985). Increased surface area, drying out between storm events, and thin slow growing vegetative cover for erosion control were important design parameters (Yousef et al. 1985, Cristina et al. 2002). Longer swales and shallower longitudinal slopes improved infiltration (Yu et al. 2001). A summary article which analyzed 16 of these studies determined: drainage channels alone provided negligible removal of most pollutants, water quality swales demonstrated a much greater and more consistent capability to remove pollutants, and most of the mass removal could be accounted for by infiltration (Schuler and Holland 2000). The authors also suggested key design elements for dry swales which included: the ability to retain the water quality volume over the entire length by temporary ponding, pre-treatment and gentle slopes, modification of the parent soils to improve infiltration, perforated pipes to keep swales dry after storms, and parabolic or trapezoidal shapes. Swale blocks were evaluated and important considerations were reported such as stable construction methods, vegetation cover, shallow slope, and swale elevations constructed in relation to the road so that ponded water does not degrade the road base (Wanielista et al. 1988, Yousef et al. 1985). Barrett et al. (1998) found that medians with slopes of less than 12% and length of at least 8m were effective in reducing stormwater loads from highway. A swale study in Alabama (Pitt et al. 2007) found a 1% slope much more efficient in trapping particulates than a 3% slope or a 5% slope and that swale length was a significant factor affecting particle size distribution, while grass type, slope and flow rate were insignificant. The median particle sizes were consistently decreased by swale length.

SAND FILTERS

Slow sand filtration has been used for decades to treat wastewater and purify drinking water and was employed as an attempt to improve storm runoff chemistry from already developed urban areas. Sand filters have many of the same characteristics as engineered bioretention (rain) used in LID designs. Sand filters are composed of a primary sedimentation chamber and a

filtration bed. The filter bed contains perforated PVC pipe wrapped in a porous textile liner and embedded at the top of the sand or other media. Sand filter systems operate by gravitational movement of water down through the sand bed. About 12 studies were reported in the literature review. Initial monitoring results by the City of Austin (1990) found TSS, lead, zinc, organic nitrogen removal rates in excess of 75%. Removal rates for coliform bacteria, ammonia and ortho-phosphorus, and copper were moderate and quite variable. Negative removal rates were frequently reported for TDS and nitrate-nitrogen. Results include the following: sand filters remove particulate pollutants such as suspended PM, PM-associated metals and biogenic PM-associated nutrients but removal rates for dissolved pollutants were quite low and sometimes negative. Much of the pollutant removal occurred by sedimentation as opposed to filtration. Cristina et al. (2002) reported that 90% of the particulate matter was separated by sedimentation in a transportation land use drainage facility within 120 min. Column experiments in the laboratory indicated that depending on size and gradation sand had good hydraulic conductivity under empty bed conditions and that concrete sand removed PM and some trace metals, likely as chemical precipitation by the concrete sand, but generated negative removals for nitrate, phosphorus and dissolved organic carbon. Compost filters removed about half of the incoming oil and grease and approached TPH removal rates reported for compost (Woodward Clyde 1998). A sand filter in St. Petersburg found mean removal efficiency for microbial indicators was greatest for fluorescent sphere (99%), followed by MS coliphage (88%), fecal coliforms (65%) and total coliforms (59%), but water quality standards were exceeded in the treated effluent during 1 of 3 sampling events for both total and fecal coliform (Kurz 1997). Bioretention with clayey soil appear to remove pollutants more than basic granular sand filters (Coffman et al. 1999).

Problems associated with sand filters include clogging by particles and bacteria and the periodic sand replacement necessary for systems to be effective (Urbonas and Ruzzo 1986). In addition, the filters can accumulate sediment and lose hydraulic conductivity. Other problems cited were the need for a sufficient capture detention volume upstream of the device and a properly sized filter for the regular maintenance cycle. Some techniques that may improve performance are: surface screens, careful selection of sod cover, limiting use of filter fabric, pre-treatment devices with suitable media addition to sand, and limiting sites to those that are entirely impervious (City of Austin 1990). Highlights of the design recommendations emphasized: positive drainage through the sand filter to prevent dead spots, a deep layer of flooded gravel below the sand filter to maintain aerobic conditions and emphasized that sand filters should be used for impervious areas only or they will become clogged. Generally sand is an very ineffective media for dissolved pollutants although sand is economical (Liu et al. 2005).

UNDERGROUND INFILTRATION/EXFILTRATION SYSTEMS

Infiltration systems are built underground to collect water and either route it through underdrains or other devices to a connected stormwater pond. Exfiltration systems are designed to store water completely underground and slowly release it into the surrounding soils. Computed infiltration rates were much higher than observed and the disparity was explained because the method assumed that the rate of exfiltration per unit area from both side and bottom of the trench were the same while the bottom accounted for much less infiltration (2%) than the sides (Branscome and Tomasello 1987). A study testing filter fabric (Evans 1990) found that silt was trapped in the fabric and the study recommended washing the rock aggregate before installation. In addition poor infiltration could be caused by the fabric interface, fabric material,

rock debris, or silty material in runoff. An experimental study in Brazil reported that after two years trenches were still able to control excessive runoff volumes by infiltration into soils that contained high clay content, but that recession becomes faster as soil saturation increases (de Souza et al. 2002).

Teng and Sansalone (2004) investigated the performance of an in-situ partial exfiltration system and 71 to 96 % of PM was removed. Also, a cementitious permeable pavement was found to remove from 60 to 100% of PM, depending on the particle sizes (Kuang et al., 2007; Sansalone et al., 2008).

EFFLUENT FILTRATION

Similar to underground infiltration systems is effluent filtration that relies on underground filters constructed in the side bank or beneath wet or dry stormwater ponds. Four studies were analyzed and in all cases the pond was much better at removing pollutants than the non-engineered filter media system (Table 2).

The primary mechanisms responsible for the removal process occurred in the water column of the pond rather than the filter media or by infiltration which removed pollutants when measured on a mass basis. The ability of the filter media to retain pollutants over a long period of time is compromised by the very low specific surface area and therefore low exchange sites and adsorption on the silica sand media (Harper and Miracle 1993). The filter underdrain system studied by Harper et al. (1999) exhibited highly variable hydraulic characteristics and was prone to clogging after only a few weeks of operation. Also in the absence of substantial losses of groundwater seepage from the pond, it appears that the filter underdrain system would be incapable of maintaining the dry pond in a near-dry condition. Sansalone and Ma (2009) demonstrated that the equilibrium capacity of Al-oxide modified clay soils was very high for phosphorus and that there was negligible desorption of phosphorus from this engineered soil media (Sansalone and Ma 2009).

The side bank filters studied by Teague and Rushton (2004) revealed that they were extremely effective for reducing suspended PM and total metals but exported nutrients probably caused by organics trapped by the filter and cross contamination with ground water. It should be emphasized that their data reported in Table 2 represents the effluent of the filters compared to the effluent of the pond after rain events and does not represent a percent removal by the pond as the other studies do. In addition, the filters flowed continuously even when the pond level was below the intake pipes and the high level of nutrients is probably the result of cross contamination with ground water.

In the study of volumetric clarification incorporating adsorptive filters (Sansalone et al., 2009), 52 to 98% of PM was removed and SSC in effluent was lower than 30 mg/L. In addition, Pathapati and Sansalone (2009) also employed computational fluid dynamics modeling (CFD) to predict the performance of a passive radial cartridge filter.

BIORETENTION

Bioretention areas are landscaping features adapted to treat stormwater runoff on the development site. Typical bioretention cells are somewhat similar to sand filters since they both filter runoff through 0.7 to 1.3 m (2.5 to 4 ft) of soil or occasionally engineered soil media. Such cells are commonly located in parking lot islands or within small pockets in residential land uses. Surface runoff is directed into shallow, landscaped depressions designed to incorporate many of the pollutant removal mechanisms in natural vegetated systems such as forests. Some runoff

from larger storms is generally diverted past the facility to the storm drain system. A summary review of bioretention systems presented by Clar et al. (2007) provided the following insight: 1) Suspended PM removal was over 90%, but the need for systems to meet local conditions was emphasized (Hsieh and Davis 2005). 2) Phosphorus data showed mixed results with 70 to 85% removal (Hsieh and Davis 2005), and it appears that the P-content of soils is critical (Hunt et al. 2006). 3) Nitrogen behavior is complex with removal likely related to cation exchange capacity of the media (Davis et al. 2001). 4) Nitrate is not held by soil media and is dependent on biological processes to convert the captured ammonia and organic nitrogen to nitrate during inter-event periods or by the redox potential. 5) Heavy metals appear to be efficiently removed and most removal occurs in the upper surface layer of the media, however dissolved metals need further study. 6) Oil and grease were readily removed in laboratory studies by a layer of composted leaf mulch and its associated bacteria (Hong et al. 2006, Dietz and Clausen 2006). 7) Chlorides rapidly move through bioretention cells with no significant reduction. 8) Pathogenic bacteria show significant reductions (70%) of indicator species (Hunt et al. 2007). 9) Mitigation of peak flow is dependent on soil infiltration rates (UNHSC 2006, Hunt 2007). The literature shows considerable variations in pollutant reductions/increases in the concentrations of nutrients (Table 3), but the ability of bioretention to infiltrate storm runoff indicates that on a mass basis pollutant loads are usually reduced. Of some concern is the migration of mobile pollutants into groundwater. Pollutants of concern are: nitrate-nitrogen, pesticides especially Lindane and Chlordane, organic compounds such as pyrene and fluoranthene, pathogens including enteroviruses, zinc, and chlorides (Pitt 2000).

The results of several research projects provide information important to bioretention designs. For example, high hydraulic loading rates may not result in a detention time long enough to mineralize phosphorus into easily assimilated inorganic compounds (Newman and Lynch 2001). The Green and Ampt infiltration equation can provide useful charts to determine the maximum water depth in an infiltration structure (Akan 1002). Results indicate that if an underdrain is not connected to the stormwater system, high flow and pollutant retention could be achieved with the 2.54 cm (1 inch) design method (Dietz and Clausen 2006). The SCS curve number does not have the flexibility or defensibility to give credit for the variety of LID components and the curve number accuracy has been brought into significant question, thus other models should be used (Dietz 2007). Bioretention mulch can be a temporary sink for metals, nitrogen and phosphorus, but garden soils are a source for these pollutants (Dietz and Clausen 2006). Removal rates for shallow bioretention depths were less than deeper depths (Davis et al. 2003). Retention of nutrients has been problematic caused by high concentrations in the planting media and fertilization (Dietz 2007). In a Danish study sands were evaluated to determine their P-sorption capacity and the results showed that some sands are used up after only a few months, whereas others would subsist for a much longer time and calcium was identified as the most important characteristic for P-removal (Brix et al. 2001). An anaerobic zone significantly ($p > 0.10$) reduced total phosphorus and iron concentrations in the bioretention effluent (Hunt and Jarrett 2004).

GRAVEL BED FILTERS

Closely related to bioretention gardens are subsurface flow systems which are unlined or lined trenches or basins filled with a permeable packing medium such as rock and planted with emergent vegetation. Water purification is by contact with the media surfaces and the vegetated

roots. Two research reports were found that evaluated gravel bed filters. A research project in Orlando studied ten packed bed filters to determine the pollutant removal rates from different rock media and vegetation type (Egan et al. 1995). Results showed that cadmium, total phosphorus, total suspended solids and volatile suspended solids were removed by a least 80%, nitrogen species, by 60%, ammonia 6% and orthophosphate by 14%. Another study of a rock-bed wetland with continuously saturated conditions for near-anaerobic water quality treatment measured similar results (Ballesterio et al. 2007). Seasonal performance was evaluated and the wetland routinely achieved close to 99% removal for total suspended solids, total petroleum hydrocarbons, and zinc and greater than 80% for nitrate.

FILTER STRIPS

Filter strips are designed for runoff that passes over the vegetation in a uniform sheet flow. They may appear in any vegetated form from grass to forest and are designed to intercept runoff, lower flow velocity and spread water out as sheet flow. They are ideal components of the “outer zone” of a bioretention system. Nine papers were found that evaluated vegetated filter strips. A study of the potential of vegetated highway shoulders indicated they can retain suspended PM, metals, total petroleum hydrocarbons, and total phosphorus (Yonge 2000). In an 18-month field experiment designed to evaluate filter strips, the Kruskal-Wallis test indicated that 8.5 m filter strips reduced median concentrations of TSS and all N species, but 4.3 m filter strips only reduced TSS, ammonia and TKN (Mendez et al. 1999). A level spreader filter strip in North Carolina reduced peak flow 10%, TSS 79%, total nitrogen 39%, and total phosphorus 48% (Lombardo and Line 2004). A compost-amended filter strip indicated the amended soils substantially reduced water pollutant concentrations and loads in highway runoff (Lenth and Batts 2007). A 2-year study in North Carolina found the nitrate concentration decrease between the field-well and ditch-edge-well averaged 29% (buffer only), 63% (buffer and controlled drainage) and 73% (controlled drainage only) which was attributed to local soil and landscape properties such as denitrification in deeper reduced zones of the soil profile (Dukes et al. 2003). A study of the soil profile in filter strips suggest that urban hydrologic factors can increase the production and reduce the consumption of nitrate in riparian zones, reducing their ability to function as sinks for nitrate in the landscape (Groffman et al. 2002).

LABORATORY AND FIELD SCALE EXPERIMENTS

Considerable research has been aimed at providing a bioretention adsorptive media that can improve pollution reduction of LID stormwater treatment. Most amendments are added to sand to maintain the hydraulic conductivity. Over 20 research papers were analyzed for this report, but many of them did not test for nutrients or did not report any nutrient data (Table 4). A good research summary on stormwater treatment filtration (Woelkers et al. 2006) emphasized that filter media depends on desired pollutant removal and that the best performance was measured for large particles and aged media. The authors further indicated the ranking for a wide range of pollutants were as follows: Me-oxide clayey soil or cementitious media > activated carbon > sand with peat > sand with zeolites > compost.

Some of the processes reported that affected performance of pollution removal in laboratory column experiments included: 1) The importance of a mulch layer to remove PM, oil and grease and prevent clogging (Davis et al. 2001, Hsieh et al. 2005, Hong et al. 2006). 2) After the

natural organic material in runoff and generated from biogenic material, followed by newspaper (but a source of cadmium from newsprint) was the best solid-phase electron-donor substrate for denitrification out of the set studied -- alfalfa, leaf mulch compost, newspaper, sawdust, wheat straw, wood chips and elemental sulfur (Kim et al. 2003). 3) Upflow columns proved more effective than down flow column to reduce clogging of the media by solids and associated head loss. Also the effects of anaerobiosis on metal retention indicated metals were not mobilized by low oxygen or extreme pH conditions, but nutrient retention may not occur (Clark et al. 2002, Clark et al. 2004). 4) Preferential flow patterns through the columns are a potential problem (Hsieh and Davis 2005). 5) Both the individual gravel layer and the overall multi-filter were highly efficient at removing suspended PM and particulate-associated pollutants even after the filters became clogged, but dissolved nutrients were more variable, with little overall reduction in concentrations (Hatt et al. 2006). Research indicated that a high hydraulic conductivity media overlaying one with low hydraulic conductivity resulted in higher infiltration rates and was also more efficient in P-removal (Hsieh et al. 2007). 7) The ionic strength of the synthetic stormwater runoff significantly affects the capture of pathogens in the media. For example an ionic strength from 3.8 mM to 50 mM enhances the attachment of bacteria to the surface of the porous media. 8) Some media additions such as tire chips, brick and glass perform well but copper leaching was a problem (Sickles et al. 2007). 9) Various combinations of sand, compost and other materials were found effective for removing metals, but compost had the best physiochemical properties for sorption of metal ions (Seelsaen et al. 2006); although Mn-oxides were not tested in this study. 9). Manganese oxide media, including manganese coated polymeric media (MOPM) and manganese oxide coated cementitious media (MOCM) were evaluated by Liu and Sansalone (2004a, 2004b, 2005a, 2005b) in sorptive filtration system as a rainfall-runoff or snowmelt unit operation and process media for treatment metal species. Birnessite-coated and cryptomelane-coated forms of manganese, as well as iron oxide coated media were tested by Liu et al. (2001a, 2001b), Sansalone (1999), Li et al. (1999). Results indicate a very significant capacity for metal species, with the surface chemistry favoring the adsorption of metal species with selected oxides of iron favorable to phosphorus. Also it was from these studies that specific form of oxide, specific surface area and surface charge were found to be critical relative to performance capability. An aluminum oxide coated media (AOCM) illustrated that this media had the capacity to remove phosphorus that were orders of magnitude greater than perlite and sand (Sansalone and Ma, 2009; Wu et al., 2008; Ma and Sansalone 2007). In a field study where the AOCM media was part of an exfiltration device, metals were reduced (24% to 93%) while total mass reduction (57% to 98%) was enhanced by exfiltration (Sansalone and Teng 2004). TSS and COD showed similar results. The device also reduced peak flow by 36% to 85% and storm volume by 55% to 70%. Other results indicated higher rainfall intensity resulted in higher dissolved fraction values for the inflow. Also copper and lead mainly complexed with organic matter in the influent while carbonate complexes in the effluent increased (Sansalone et al. 2006, Guo et al 2006).

ACKNOWLEDGEMENTS

This literature review was funded in part through the Florida Department of Environmental Protection (Contract No.WM910) and the Department of Environmental Engineering Sciences at the University of Florida.

REFERENCES

- Akan, A.O. (2002). Sizing stormwater infiltration structures. *Journal of Hydraulic Engineering*, 128(5), 534-537.
- Anderson, D.E. 1982. Evaluation of Swale Design. Masters Thesis, University of Central Florida. <http://www.stormwater.ucf.edu/FILES/Anderson>
- Avellaneda, Eduardo. 1985. Infiltration through Roadside Swales. Master's Thesis, University of Central Florida. <http://www.stormwater.ucf.edu/FILES/Avellaneda>
- Ballestero, T.P., R.M. Roseen, and J.P. Houle. 2007. Gravel Wetland Design and Performance for Stormwater Management. In *Proceedings of World Environmental and Water Resources Congress 2007: Restoring Our Natural Habitat*. ASCE.
- Barrett, M. E., Walsh, P. M., Malina, J. F., and Charbeneau, R. J. (1998). "Performance of Vegetative Controls for Treating Highway Runoff." *J. Environ. Eng.*, 124(11), 1121-1128.
- Birch, G.F, M. S. Fazeli, and C. Matthai. 2005. Efficiency of an Infiltration Basin in Removing Contaminants from Urban Stormwater. *Environmental Monitoring and Assessment* 101: 23–38 c_ Springer.
- Brown, R.A. and W.F.Hunt. 2008. Bioretention performance in the upper coastal plain of North Carolina. *ASCE/EWRI World Environmental and Water Resources Congress*. CD-ROM
- Branscome, J. and R.S. Tomasello. 1987. Field testing of Exfiltration Systems. South Florida Water Management District. Technical Publication 87-5.
- Brix, H., C.A.Arias, and M.del Bubba. 2001 Media selection for sustainable phosphorus removal in subsurface flows. *Water Science and Technology* :1 44:11-12.
- City of Austin (TX) 1990. Removal Efficiencies of stormwater control Structures. Final report. Environmental Resource Management Division. Austin, TX. 36 pp.
- Clar, M., A.P.Davis, W.F.Hunt, and R.G.Traver. 2007. Bioretention technology: An Overview of Current Practice and Future Needs. *Proceedings 2nd LID Conference*, March 12-14, Wilmington, NC. <http://www.soil.ncsu.edu/swetc/lid/home.htm>.
- Clark, Shirley and Robert Pitt. 1999. Stormwater Treatment at Critical Areas: Evaluation of Filtration Media. EPA/600/R-00/010. <http://unix.eng.ua.edu/~rpitt/Publications/StormwaterTreatability/filter>
- Clark, S.; Pitt, R. (2002). BMP filters: Upflow vs. Downflow. *Linking Stormwater BMP Designs and Performance to Receiving Water Impact Mitigation*, Proc. of an Engineering Foundation Conf., August 19 – 24, 2001, Snowmass, CO. 489-493.
- Clark, S.; Pitt, R.; Brown, P. 2002. Effect of anaerobiosis on filter media pollutant retention. *Linking Stormwater BMP. Designs and Performance to Receiving Water Impact Mitigation*, Proc. of an Engineering Foundation Conf., August 19

Coffman, L.S.; Goo, R.; and Frederick, R. (1999) Low-Impact Development an Innovative Alternative Approach to Stormwater Management. ASCE 26th Annual. Conf. Water Resour. Plann. Manage. 1999 Annual. Conf. Environ. Eng.,

Cristina C. and Sansalone J.J., “First Flush, Power Law And Particle Separation Diagrams For Urban Storm-Water Suspended Particulates”, *J. of Environmental Engineering*, 129 (4), 298-307, April 2003.

Cristina C., Tramonte J., and Sansalone J.J., “A Process Design Selection Methodology For Separation Of Traffic-Generated Sediments In Runoff”, *J. of Water, Air and Soil Pollution*, 136 (5), 33-53, May 2002.

Davis, A. P., M. Shokouhian, H. Sharma, and C. Minami. 2001. Laboratory Study of Biological Retention for Urban Stormwater Management. *Water Environ. Res.*, 73(1):5-14.

Davis, A. P., M. Shokouhian, H. Sharma, C. Minami, and D. Winogradoff. 2003. Water Quality Improvement through Bioretention: Lead, copper, and zinc removal. *Water Environ. Res.* 75(1):73-82.

Davis, A. P., Shodouhian, M., Sharma, H., and Minami, C. 2006. Water Quality Improvement through Bioretention Media: Nitrogen and Phosphorus Removal.. *Water Environment Research* 78(3):284-293.

Davis, A.P., M. Shokouhian, H.Sharma, and C. Minami. 2001. Laboratory Study of Biological Retention (Bioretention) for Urban Storm Water Management. *Water Environ. Res.*, 73(1):5-14.

Davis, A.P., M. Shokouhian, H.Sharma, and C. Minami. 2006. Water Quality Improvement through Bioretention Media: Nitrogen and Phosphorus Removal. *Water Environ. Res.* 78(3):284-293.

Davis, A.P. 2007. Field performance of bioretention: Water quality. *Environmental Engineering Science*. 24(8):1048-1063.

de Souza, V.C.B. Goldenfum, J.A.; Barraud, S. 2002. An Experimental and Numerical study of infiltration trenches .Proc. 9th Int. Conf. Urban Drainage –. CD-ROM.

Dean, C.M., Sansalone J.J., Cartledge, F.K., and Pardue, J.H., “Influence Of Hydrology On Rainfall-Runoff Metal Element Speciation”, *J. of Environmental Engineering*, 131 (4), 632-642, April 2005.

DeBusk, T.A. and M.A. Langston. 1997. An Evaluation of Filter Media for Treating Stormwater Runoff. Proceedings of the 5th Biennial Stormwater Research Conference, Southwest Florida Water Management District, Brooksville, FL 32604

Dietz, M.E. and John C. Clausen. 2006. Saturation to Improve Pollutant Retention in a Rain Garden. *Environ. Sci. Technol.*, 40 (4), 1335 -1340, 2006.

Dietz, M.E.; Clausen, J.C. 2005. A Field Evaluation of Rain Garden Flow and Pollutant Treatment. *Water, Air, Soil Pollution*. 167(1-4):123-138.

Dietz, Michael E. 2007. Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions. *Water Air Soil Pollution* July 2007.

Dorman, M., J. Hartigan, J. Steg and T. Quaserbarth. 1989. Retention/Detention and Overland Flow for Pollutant Removal from Highway Stormwater Runoff. Vol. I research Report. Federal Highway Administration. FJWA/RD-89/202.202pp.

Dukes, M.D., R. O. Evans, J. W. Gilliam, and S. H. Kunickis. 2003. Effects of Controlled Drainage and Riparian Buffers on Shallow Groundwater Quality *J. Irrig. and Drain. Engr.*, 129:82-92, Issue 2.

Egan, T. J., L. S. Burroughs and T. R. Attaway. 1995. Packed Bed Filter. In. 4th Biennial Stormwater Research Conference, SWFWD, Brooksville, FL 34604.

Emerson, C.; Traver, R.G. (2004). Villanova Bio-Infiltration Traffic Island: Proc. 2004 World Water and Environmental Resources Congress. ASCE Reston, VA. CD-ROM. 5pp

Erickson, A.J., J. S. Gulliver, and P. T. Weiss. 2007. Enhanced Sand Filtration for Storm Water Phosphorus Removal. In World Environmental and Water Resources Congress 2007: Restoring Our Natural Habitat. ASCE.

Evans, David L. 1990. Evaluation of Exfiltration Systems. University of Central Florida. http://www.stormwater.ucf.edu/research/FILES/exfiltration_designs09_1990.pdf

Goldberg, J. 1993. Dayton Avenue Swale Biofiltration Study. Seattle Engineering Department. Seattle WA. 67pp.

Gowan, T.D. and C.E. Watkins. 1997. Stormwater Quality Management Using a Combined Wet-Detention Sand-filter Stormwater Facility. 5th Biennial Stormwater Research Conference. SWFWMD Brooksville, FL

Groffman, P.M.; Boulware, N.J.; Zipperer, W.C.; Pouyat, R.V.; Band, L.E.; Colosimo, M.F. 2002. Soil nitrogen cycle processes in urban riparian zones. *Environmental Science and Technology*, 36(21), 4547-4552.

Guo T., Sansalone J., and Piro P., "The Role Of In-Situ Unit Operation/Process Infiltration Treatment On Partitioning And Speciation Of Rainfall-Runoff", *Water Science and Technology*, 54 (6-7): 255-261, 2006.

Harper, H.H. 1988. Effects of Stormwater Management Systems on Groundwater Quality. Final report, Florida Department of Environmental Regulation, Project WM190.

Harper, H.H. and D. Miracle. 1993. Treatment Efficiencies of Detention with Filtration Systems. 3rd Biennial Stormwater Conference, pp 186-198. SWFWMD, Brooksville, FL.

Harper, H.H., J.L. Herr, and D. Baker. 1999. Performance Evaluation of Dry Detention Stormwater Systems, 6th Biennial Stormwater Research Conference, SWFWMD, Brooksville, FL

Hatt, B.E., N. Siriwardene, A. Deletic and T.D. Fletcher. 2006. Filter media for stormwater treatment and recycling: the influence of hydraulic properties of flow on

Herrera Environmental Consultants (HEC). 1996. Sammamish Phase II Restoration Project. Technical Memo Pilot Scale Test Results. Lakemont Park Stormwater Treatment Facility. Submitted to City of Bellevue, WA.

Hunt, W.F., J.T. Smith, S.J. Jadlocki, J.M. Hathaway, and P.R. Eubanks. 2008. Pollutant removal and peak flow mitigation by a bioretention cell in urban Charlotte, N.C. *J. of Environmental Engineering* vol134(5):403-408.

Hong, E., Seagren, E.A., and Davis, A.P. 2006. Sustainable Oil and Grease Removal from Synthetic Storm Water Runoff Using Bench-Scale Bioretention Studies. *Water Environ. Res.*, 78(2):141-155.

Hsieh, C.-h and Davis, A.P. 2005. Evaluation and Optimization of Bioretention Media for Treatment of Urban Storm Water Runoff. *J. Environ. Eng. ASCE*, 131(11):1521-1531.

Hsieh, C.-h and Davis, A.P. 2005. Multiple-Event Study of Bioretention for Treatment of Urban Storm Water Runoff. *Water Sci. Technol* 51(3-4):177-181.

Hsieh, C.-h, Davis, A.P., and Needelman, B.A., 2007. Bioretention Column Studies of Phosphorus Removal from Urban Stormwater Runoff. *Water Environ. Res.*, 79(2), 177-184.

Hsieh, C.-h, Davis, A.P., and Needelman, B.A., 2007. Nitrogen Removal from Urban Stormwater Runoff through Layered Bioretention Columns. *Water Environ. Res.*, 79(12), 2404-2411.

Hunt, W. F., J.T. Smith and J.M. Hathaway. 2007. Nutrient, Metal and Bacteria Removal by an Urban Bioretention Area in Charlotte, NC. *J. of Environmental Engineering* .

Hunt, W.F., A.R. Jarrett, J.T. Smith and L.J. Sharkey. 2006. Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina. *Journal of Irrigation and Drainage Engineering*. 132(6):600-608.

Hunt, W.F. and A.R. Jarrett. 2004. Evaluating Bioretention Areas from Two Field Sites in North Carolina. *Critical Transitions in Water and Environmental Resources Management: Proc. 2004 World Water and Environmental Resources Congress*. American Society of Civil Engineers, Reston, VA. CD-ROM. 10 pages.

Kim J-Y., Ma J., Howerter K., Garofalo G., and Sansalone J.J., "Interactions Of Phosphorus With Anthropogenic And Engineered Particulate Matter As A Function Of Mass, Number And Surface Area", *Urban Water Systems, Monograph 11*, Edited by James W. CHI Publications, Guelph, Ontario, 20 pp., Dec., 2007.

Kim, H., E.A. Seagren, and A.P.Davis. 2003. Engineered Bioretention for Removal of Nitrate from Stormwater Runoff. *Water Environment Res.* 75(4):355-367.

King County Department of Natural Resource (KCDNR). 1998. Lake Sammamish Water Quality Management project. Final Report. Washington State Department of Ecology. Seattle, WA.

Kuang X., Kim J-Y., Gnecco I., Raju S., Garofalo G., Sansalone J., "Particle Separation And Hydrologic Control By Cementitious Permeable Pavement", *J. of Transportation Research Record*, Vol. 1992, 56-65. Dec. 2007.

Kurz, R.C. 1997. Removal of Bacteria, Viruses, and Florescent Spheres from Stormwater Using an Above-Ground Sand Filter System. 5th Biennial Stormwater Research Conference, SWFWMD Brooksville, FL 32604.

Leif, W. 1999. Compost Stormwater Filter Evaluation Final Report. Snohomish County Department of Public Works. Surface Water Management Division. Everett, WA. 62pp.

Lenth, J and D. Batts. 2007. Performance Monitoring Results from a Study of Compost-Amended Vegetated Filter Strips.

Li Y., Buchberger S.G., and Sansalone J.J., "Variably Saturated Flow in A Storm Water Partial Exfiltration Trench", *J. of Environmental Engineering*, 125 (6), 556-565, June 1999.

Liu B., Berretta C., Gnecco I., Ying G., and Sansalone J., "Control of Highway Stormwater During Event and Inter-Event Retention in BMPs", *J. of Transportation Research Record*, (November), 2009.

Liu D., Teng Z., Sansalone J.J., and Cartledge F.K., "Surface Characteristics of Sorptive-Filtration Storm Water Media: Low Specific Gravity ($\rho_s < 1.0$) Oxide Coated Floating Media", *J. of Environmental Engineering*, 127 (10), 868-878, October 2001.

Liu D., Teng Z., Sansalone J.J., and Cartledge F.K., "Surface Characteristics of Sorptive-Filtration Storm Water Media: Higher Specific Gravity ($\rho_s > 1.0$) Oxide Coated Fixed Media", *J. of Environmental Engineering*, 127 (10), 879-888, October 2001.

Liu D., Sansalone J.J., and Cartledge F.K., "Adsorption Characteristics Of Oxide Coated Polymeric Media ($\rho_s < 1.0$) For Stormwater Treatment: Batch Equilibria And Kinetics", *J. of Environmental Engineering*, 130 (4), 374-382, April 2004.

Liu D., Sansalone J.J., and Cartledge F.K., "Adsorption Characteristics Of Oxide Coated Polymeric Media ($\rho_s < 1.0$) For Storm Water Treatment: Equilibria And Kinetics Models", *J. of Environmental Engineering*, 130 (4), 383-391, April 2004.

Liu D., Sansalone J.J., and Cartledge F.K., "Adsorption Kinetics For Urban Rainfall-Runoff Metals By Composite Oxide-Coated Polymeric Media", *J. of Environmental Engineering*, 131 (8): 1168-1177, August 2005.

Liu D., Sansalone J.J., and Cartledge F.K., “Comparison Of Sorptive Filter Media For Treatment Of Metals In Runoff”, *J. of Environmental Engineering*, 131 (8): 1178-1186 August 2005.

Lloyd, S.D., Fletcher, T.D., Wong, T.H.F. and Wootton, R.M. (2001), Assessment of Pollutant Removal in a Newly Constructed Bio-retention System, 2nd South Pacific Stormwater Conference, Auckland, New Zealand, 27 – 29 June 2001, pp.20-30.

Lombardo, C. and D. Line. 2004. Evaluating the Effectiveness of Low Impact Development. NCSU Water Quality Group, NC State University. Conference proceedings: Putting the LID on SWM <http://lowimpactdevelopment.org/>

Lucas, W. C. and M. Greenway. 2007. A Study of Nutrient retention Dynamics in Vegetated and Non-vegetated Bioretention Mesocosms. 2nd National Low Impact Development <http://www.soil.ncsu.edu/swetc/lid/home.htm>

Ma, J., and John Sansalone. 2007. Mass Transfer Behavior of Media for Treatment of Stormwater Phosphorus. Proc. World Environmental and Water Resources Congress 2007: Restoring Our Natural Habitat. ASCE.

Mendez, A.; Dillaha, T.A.; and Mostaghimi, S. 276, (1999) Sediment and Nitrogen Transport in Grass Filter Strips. *J. Am. Water Resour. Assoc.* 35(4): 867.

Newman, J.M. and T. Lynch. 2001. The Everglades Nutrient Removal Project test cells: STA optimization – status of the research at the north site. *Water Science and Technology* 44(11–12):117–122 © IWA .

Osborn, S. and J. Packman. 2008. A comparison of conventional and low impact development stormwater best management practices. ASCE/EWRI World Environmental and Water Resources Congress. CD Rom.

Pathapati S. and Sansalone J., “Combining Particle Analyses with Computation Fluid Dynamics Modeling to Predict Hetero-disperse Particulate Matter Fate and Pressure Drop in a Passive Runoff Radial Filter”, *ASCE J. of Environmental Engineering*, 135(2), 77-85, 2009.

Pitt, R.; Clark, S.; and Field, R. (2000) Potential Groundwater Contamination Associated with Stormwater Infiltration. 2000 Annual Meeting and International Conference of the American Institute of Hydrology

Rushton, B. T. and R. Hastings. 2001. Florida Aquarium Parking Lot: A Treatment Train Approach to Stormwater Management. SWFWMD, Brooksville, Fl. <http://www.swfwmd.state.fl.us/ppr/reports/files/>

Sansalone J.J., “Adsorptive-Infiltration of Metals in Urban Drainage – Media Characteristics”, *Science of the Total Environment*, 235 (1-3) 179-188, September 1999.

Sansalone J.J., “In-Situ Performance of A Passive Treatment System for Metal Elements in Urban Surface Waters”, *Water Science and Technology*, 39 (2), pp. 193-200, February 1999.

Sansalone J., Liu B. and Kim J-Y, “Volumetric Clarifying Filtration of Urban Source Area Rainfall-Runoff”, *ASCE J. of Environmental Engineering*, 135, (8), 2009.

Sansalone J. and Ma J. “Parametric Evaluation of Batch Equilibria for Stormwater Phosphorus Adsorption on Aluminum Oxide Media”, *ASCE J. of Environmental Engineering*, 135 (9), 737-746, 2009.

Sansalone J., Kuang X., Ranieri, V., “Permeable Pavement as a Hydraulic and Filtration Interface for Urban Drainage” *ASCE J. of Irrigation and Drainage*, 134(5), 666-674, October 2008.

Sansalone, J, X. Kuang, and J. Ma. 2006 An In-Situ Permeable Pavement and Media System for Hydrologic, Particulate and Phosphorus Management. Proc. 2nd Biennial Stormwater Management Research Symposium,
<http://www.stormwater.ucf.edu/conferences/9thstormwaterCD/index.html>

Sansalone J. and Glenn D., “Metal Distributions In Soils Receiving Urban Pavement Runoff And Snowmelt”, *Water Environment Research*, 79 (7): 736-752, July 2007.

Sansalone J.J. and Teng Z., “Transient Rainfall-Runoff Loadings To A Partial Exfiltration System: Implications For Urban Water Quantity And Quality”, *J. of Environmental Engineering*, 131 (8): 1155-1167, August 2005.

Sansalone, J. and Z. Teng. 2004. In Situ Partial Exfiltration of Rainfall Runoff. 1: Quality and Quantity Attenuation. *Journal of Environmental Engineering*, Vol. 130(9): 990-1007.

Schuler, T. R. and K.Holland. 2000. Ditches or Biological Filters? Classifying Pollutant Removal in Open Channels. . Article 116. <http://www.cwp.org/>

Seattle Metro and Washington Ecology. 1992. Biofiltration Swale Performance: Recommendations and Design Considerations. Publication No 657. Washington Dept. of Ecology. 20pp.

Seelsaen, N, R. McLaughlan, S. Moore, J.E. Ball and R.M. Stuetz. 2006. Pollutant removal efficiency of alternative filtration media in stormwater treatment. *Water Science & Technology* Vol 54(6–7):299–305 Q IWA Publishing 2006.

Sharkey, L.J., and W.F.Hunt. 2005. Case Studies on the Performance of Bioretention Areas in North Carolina. In 8th Biennial Stormwater Research & Watershed Management Conference SWFWMD <http://www.swfwmd.state.fl.us/documents/>

Sickles, L., L., N. Parker, J. S. Wu, and H. Hilger. 2007. Evaluation of Regionally Appropriate and Cost Effective Bioretention Media Mixes. World Environmental and Water Resources Congress 2007: Restoring Our Natural Habitat. ASCE.

Smith, D.P. 2006. Hillsborough Filter Plot Demonstration Final Report. Florida Department of Environmental Protection (No SO113).

<http://www.dep.state.fl.us/water/nonpoint/docs/nonpoint/HillsboroFilterReport.pdf/>

Smith, R. A. and W. F. Hunt. 2007. Pollutant Removal in Bioretention Cells with Grass Cover. Proceedings 2nd National Low Impact Development Conference,

<http://www.soil.ncsu.edu/swetc/lid/home.htm>

Stanford, R.L. and S L. Yu. 2006. Field Evaluation of a Stormwater Bioretention pollutant removal. Water Science & Technology Vol 54 No 6–7 pp 263–271

Teague, K. and B. Rushton. 2004. Stormwater Runoff Treatment by a Filtration System and Wet Pond in Tampa, Florida. SWFWMD Brooksville, Fl.

<http://www.swfwmd.state.fl.us/ppr/reports/files/>

Teng, Z, and J. Sansalone. 2004. In Situ Partial Exfiltration of Rainfall Runoff II: Particle Separation. Journal of Environmental Engineering September: 1008

Teng Z., Smithson J., Ping Z., and Sansalone J.J., “Geospatial Distribution Of Heavy Metals In Transportation Land Use Soils”, *J. of Transportation Research Board*, 1797, 11-22, November 2002.

Traver, R.; Dean, E.; Emerson, C. (2005). Performance of a BMP infiltration trench. Proc. 2005 Watershed Management Conf.. Am. Society of Civil Engineers. 1027.

Turer D., Maynard B.J., and Sansalone J.J., “Heavy Metal Contamination In Soils Of Urban Highways: Comparison Between Runoff And Soil Concentrations”, *J. of Water, Air and Soil Pollution*, 132 (3), 214-230, December 2001.

UNHSC (University of New Hampshire Stormwater Center). 2006. 2005 Data Report, cICEET, Durham, NH.

Urbonas, B.R. and W.Ruzzo. 1986. Standardization of Detention Pond Design for Phosphorus Removal. Urban Runoff Pollution, NATO ASI Series Vol, G10, Springer-Verlag, Berlin.

Wanielista, M., Y. Yousef, and E. Avellaneda. 1988. Alternatives for the Treatment of Groundwater Contaminants-Infiltration Capacity of Roadside Swales. E-20-84.

http://www.stormwater.ucf.edu/FILES/publications/wanielista_04_1988_alternatives_ground_contaminants.pdf

Wanielista, M.P., R.N.Gennaro, J.H.Bell and J.W.Johnson. 1978. Shallow-Water Roadside Ditches for Stormwater Purification. <http://www.stormwater.ucf.edu/FILES/wan1978paper.pdf>

Woelkers, D., B.Pitt, and S. Clark. 2006. Stormwater treatment Filtration as a Stormwater Control. Stormcon 2006. Denver Co.

<http://unix.eng.ua.edu/~rpitt/Publications/StormwaterTreatability/Filtration%20Woelkers%20et%20al%20Stromcon%2006.pdf>

Woodward-Clyde, Inc. 1998. Santa Monica Bay Area Municipal Strmwater/Urban runoff Pilot Project-Evaluation of Potential Catch Basin Retrofits. Prepared for City of Sana Monica, CA.

Wu, T., Gnecco, I., Berretta, C., Ma, J. and Sansalone, J., “Stormwater Phosphorus Adsorption on Oxide-Coated Media”, Proceedings of WEFTEC2008, Water Environment Federation, Chicago, IL, October 2008, 16 pages.

Ying G. and Sansalone J., “Partitioning and granulometric distribution of metal leachate from urban traffic dry deposition particulate matter subject to acidic rainfall and runoff retention”, *Water Research*, 42 (15), 4146-4162, September 2008.

Yonge, D.R. 2000. Contaminant Detection in Highway Grass Filter Strips. - Final research rept. Washington Div. Report 3 WA-RD-474.1.

Yousef, Y.A., M.P.Wanielista, H.H.Harper, D.B.Pearce and R.D. Tolbert. 1985. Removal of Highway Contaminants by Roadside Swales. University of Central Florida.FLHPR E-11-81, http://www.stormwater.ucf.edu/FILES/publications/wanielista_03_1985_removal_highway_contaminants.pdf

Yousef, Y., M.Wanielista, H. Harper, D. Pearce and R. Tolbert. 1985. Best Management Practices-Removal of Highway Contaminants by Roadside Swales. Final Report. University of Central Florida Department of Trnsportation. 166pp.

Yu, S.L.; Kuo, J.T.; Fassman, E.A.; and Pan, H. 2001. Field Test of Grassed-Swale Performance in Removing Runoff Pollution. *J. Water Resour. Plan. Man.* 127:168.

Yu, S., Barnes and V.Gerde. 1993. Testing of Best Mangement Practices for Controlling Highway Runoff. Virginia Transportation Research Council. FHWA/VA-93-R16.60pp.

Zhang, L, E.A. Seagren, and A.P. Davis. 2007. Column Studies on transport and Capture of Pathogens from Urban Stormwater Runoff. 2nd National Low Impact Development Conference <http://www.soil.ncsu.edu/swetc/lid/home.htm>.

Table 1 Decrease or Increase of Nutrient Concentrations Measured in Swales

Volume Infiltrated %	Nitrogen			Phosphorus		Authors	Comments
	Total %	Nitrate %	Ammonia %	Total %	TDP %		
41-91	↘70	-	-	↘94	-	Wanielista et al. 1978	40 ft from road edge
-	↘30	-	-	↗	-	Seattle Metro 1992	200 ft long; 4% slope
0	↘40	↗	-	↘19	↗	Harper 1988	Wet swale, sandy
80	-	-	-	-	-	Harper 1988	Dry swale, sandy
-	↘48	-	-	↘18	-	Dorman et al. 1989	200 ft long; 1% slope
-	↘28	↘11	-	↘41	-	Yu 1993	200 ft long; 4.7% slope
30-80	-	↘31	-	↘5	↘30	Goldberg 1993	600 ft long; Dry swale
-	-	↘9	↘16	↘39	↗	Goldberg 1993	Wet swale
-	-	↘36 - 59	-	↘45 ~ 55	-	Barrett et al. 1998	Slope less than 12% Length of at least 8 m
69	↗20	↗2	↘40	↗109	↗355	Rushton et al. 2001*	Dry swale, small garden area
83	↗28	-	-	↗216	↗355	Rushton et al. 2001*	Dry swale, larger garden area
-	0	↘	-	↘ 24 ~ 55	-	Lloyd 2001	Dosing exp., Gravel and soil

[-] No data available

[↗] Increase in Concentration

[↘] Decrease in Concentration

Table 2 Decrease or Increase of Concentrations of Runoff Nutrients or PM in Filtration/Exfiltration Systems

Nitrogen			Phosphorus		PM*	Authors	Comments
Total %	Nitrate %	Ammonia %	Total %	TDP %			
-	↘30	↘2	↘80	↘37	-	Harper, 1993	Most of removal by sedimentation basin
↗	-	↗	↘67	-	-	Gowan & Watkins, 1997	Mass removal; Conc. variable
-	↘	↘	0	↗		Harper et al., 1999	Filter only; Dry pond
-	-	-	-	-	-	Li et al., 1999	Partial exfiltration trench 2D model
-	-	-	-	-	↘90	Cristina et al., 2002; Cristina & Sansalone, 2003	Sedimentation in a transportation land use drainage facility within a detention time of 120 min
↗13	↗62	↗62	↗50	↗222	-	Teague & Rushton, 2004	Conc. Compared to pond; probable groundwater pollution
-	-	-	-	-	↘71~96	Teng & Sansalone, 2004	In situ partial exfiltration system
-	-	-	-	-	-	Kim et al., 2007	Particle gradation in runoff and distribution of pollutants across particle gradation
-	-	-	-	-	↘60~100	Kuang et al., 2007	Cementitious permeable pavement
-	-	-	-	-	-	Sansalone et al. 2008	Cementitious permeable pavement
-	↘80	↗	↘80	↘60	↘52~98	Liu et al., 2009	Volumetric clarification incorporating adsorptive filters
-	-	-	-	-	↘	Sansalone et al., 2009	Effluent SSC < 30 mg/L with median head loss of 5 mm
-	-	-	-	-	↘72~88	Pathapati & Sansalone, 2009	Passive radial cartridge filter

*Particulate Matter (PM)

[-] No data available

[↗] Increase in Concentration

[↘] Decrease in Concentration

Table 3 Decrease or Increase of Concentrations of Nutrients in Bioretention

Volume Infiltrated %	Nitrogen			Phosphorus		Authors	Comments
	Total %	Nitrate %	Ammonia %	Total %	TDP %		
high	↘40	↘ 13~75	-	-	-	Hunt & Jarrett, 2004	Load reductions
high	-	0	-	↘38	-	Lombardo & Line, 2004	
69	-	-	-	-	-	Emerson & Traver, 2004	Designed to capture 1st inch
-	↗418	↘50	↗124	↗1294	-	Sharkey & Hunt, 2005	Conventional cell
-	↗379	↘77	↗1175	↗1552	-	Sharkey & Hunt, 2005	Induced anaerobic cell
69	↘27	↘26	↘77	↘39	↘54	Sharkey & Hunt, 2005	Unlined cell
58	↘60	↘73	↘84	↘53	-	Sharkey & Hunt, 2005	Lined cell
High	0	↗116	-	↘51	-	Birch et al., 2005	Weighted concentrations
92	↘18	↘	↘	↗	-	Dietz & Clausen, 2006	Designed to capture 1st inch
-	↘55~65 (TKN)	↘< 20	-	↘70~80	-	Davis et al., 2006	Bioretention facilities of 60~80 cm depth
-	-	↗16~56	↘13~59	-	-	Hsieh et al., 2007	Two bioretention columns with different media-layering
-	-	↘83	-	↘76	-	Davis, 2007	One standard design cell; one with an anoxic sump
-	↘61	-	↘79	-	↗127	Smith & Hunt 2007	N cell; anaerobic cell
high	-	-	-	-	-	Smith & Hunt 2007	S cell; well drained; no outflow
high	↘80	-	-	↘72	-	Brown & Hunt, 2008	Shallow grass cell
high	↘32	0	-	↘31	-	Hunt et al., 2008	Low P media; aerobic
-	-	-	-	↘74	-	Osborn & Packman, 2008	Seasons strongly influenced

[-] No data available

[↗] Increase in Concentration

[↘] Decrease in Concentration

Table 4 Decrease or Increase of Concentrations of Nutrients in Laboratory or Field Tests That Evaluated Soil Amendments Designed to Improve Performance

Nitrogen			Phosphorus		Media Tested*	Authors
Total %	Nitrate %	TKN %	Total %	TDP %		
-	-	-	↘38	-	Quartz sand	DeBusk &Langston, 1997
-	-	-	↘88	-	Wollastine	DeBusk & Langston, 1997
-	-	-	↘44	-	Peat	DeBusk &Langston, 1997
-	-	-	↘41	-	Limerock	DeBusk & Langston, 1997
-	-	-	↗	-	Compost	Leif, 1999
-	-	-	↘67	↘18	Calcite Limestone	KCDNR, 1998
-	-	-	↘68	↘50	Steel Fiber	KCDNR, 1998
-	-	-	↘80	-	Steel Wool	HEC, 1996
-	↘80	-	-	-	Newspaper	Kim et al., 2003
-	↗ 95	-	↘4	-	Compost	Leif, 1999
-	↗ 34	-	↘41	-	Compost	Stewart, 1992
-	↗ 281	↘56	↘88	-	Top Soil < 6% clay + sand	Sickles et al., 2007
-	↗ 45	↘76	↘88	-	Top Soil 23% clay; no sand	Sickles et al., 2008
-	↗174	↘63	↘72	-	Sand only	Sickles et al., 2009
-	↗148	↘70	↘88	-	Tires + top soil + sand	Sickles et al., 2010
-	↗ 281	↘65	↘ 60~ 80	-	Brick + top soil + sand	Sickles et al., 2011
-	↗212	↘63		-	Glass + top soil + sand	Sickles et al. 2012
-	0	↘ 60 ~ 80	↘ 60~ 80	-	Sand	Davis et al., 2001
-	↗ > 20	↘ 55 ~ 65	↘ 70 ~ 80	-	Sand	Davis et al., 2006
-	-	↘20	↘55	-	Filtera	Stanford & Yu, 2006
-	-	↘ 93**	-	-	Zeolite	Smith ,2006
-	-	-	↘ 34~ 81	-	Steel wool	Erickson et al., 2007
↘80	-	-	↘90	-	Vegetated loam	Lucas & Greenway, 2007
↘43	-	-	↘75	-	Non-vegetated loam	Lucas & Greenway, 2007
↘41	-	-	↘90	-	Sand only	Lucas & Greenway ,2007
-	-	-	-	↘11	Perlite @ 0.1 mg/L/TDP	Sansalone, 2008
-	-	-	-	↘90	AOCS*** @ 0.1 mg/L/TDP	Sansalone, 2008
-	-	-	-	↘4	Perlite @ 0.5 mg/L/TDP	Sansalone ,2008
-	-	-	-	↘98	AOCS*** @ 0.5 mg/L/TDP	Sansalone, 2008
-	-	-	-	↘90	AOCM****/Perlite	Wu et al., 2008
-	-	-	-	↘90	AOCM	Sansalone and Ma, 2009

[-] No data available

[↗] Increase in Concentration

[↘] Decrease in Concentration

*most media mixed with sand

**93% decrease in ammonia; 23% decrease in total inorganic nitrogen

***Aluminum Oxide Coated Soil

****Aluminum Oxide Coated Media

Table 5 Decrease or Increase of Concentrations of Metals in Laboratory or Field Tests

Metals (%)	System/ Media tested	Authors	Comments
Cu, Zn, Cd, Pb	Partial exfiltration trench with oxide-coated sand	Sansalone, 1999	Bench scale simulation
Cu, Zn, Cd, Pb ↘90	MOPM*	Liu et al., 2001a,b Liu et al., 2004a,b	Relative adsorption affinity of MOPM: Pb>Cu>Cd>Zn
Pb, Zn, Cu, Cr	-	Turer et al., 2001	Great majority of the metal content is immobile
Cu, Zn, Cd, Pb	-	Teng et al., 2002	Geospatial distribution of metal elements
Cu, Zn, Cd, Pb (↘24 ~ 93)	In-situ partial exfiltration with Fe- coated sand	Sansalone & Teng, 2004	Volume reductions ranged from 55 ~ 70%
Cu, Zn, Cd, Pb	MOPM; IOCS**; MOCM***	Liu et al., 2005	MOCM and MOPM have high capacity for metals
Cu, Zn, Cd, Pb	MOPM	Liu et al., 2005	A fast adsorption with 30min followed by a slower reaction from 5 to 15h
Cu (↘80 ~ 90)	Partial exfiltration system	Sansalone & Teng, 2005	15*20m paved drainage area
Cu, Zn, Cd, Pb	-	Dean et al., 2005	Metals partition between particulate and dissolved species
Cu (↘90.7), Zn(↘95.5), Cd(↘49.2), Pb(↘50.7); Organic forms: CuDOM (↘97.3), ZnDOM(↘98.5), CdDOM(↘82.2), PbDOM(↘84.9)	Engineered partial exfiltration reactor system	Guo et al., 2006	Rainfall intensity resulted in higher dissolved fraction for influent Cu, Zn and Cd
Cu, Zn, Cd, Pb	Soils receiving urban pavement runoff and snowmelt	Sansalone & Glenn III, 2007	Over 80 of the metal mass was associated with particles greater than 106µm
Cu(↘57), Zn(↘62), Pb(↘83)	Bioretention	Davis, 2007	Two bioretention facilities with different design
Cu, Zn, Cd, Pb, Cr, As	-	Ying & Sansalone, 2008	Granulometric distribution of metals from dry deposition particulate matter

[-] No data available

[↗] Increase in Concentration

[↘] Decrease in Concentration

*Manganese Oxide Coated Polymeric Media

**Iron Oxide Coated Sand

***Manganese Oxide Coated Media

CHAPTER 3: NUTRIENTS PARTITIONING AND TRANSPORT IN RAINFALL RUNOFF FROM AN INSTITUTIONAL SOURCE AREA

List of Tables	3-ii
List of Figures	3-iii
ABSTRACT	3-1
INTRODUCTION	3-1
OBJECTIVES	3-2
BACKGROUND	3-2
SJRWMD	3-2
Nutrient Concentrations from Paved Surfaces.....	3-3
Mass-limited (first-order) vs. Flow-limited (zero-order) Delivery	3-3
SITE DESCRIPTIONS	3-3
METHODOLOGY	3-4
Stormwater Sample Collection	3-4
Traffic Count.....	3-4
Nutrient Partitioning	3-5
EMC Calculations.....	3-5
Mass-Limited vs. Flow-Limited Behavior.....	3-6
Particle Size Distribution (PSD)	3-6
RESULTS	3-7
Hydrology	3-7
Traffic Count.....	3-7
M(V) Curves: Particulate Fractions and Particulate N and P	3-7
M(V) Curves: TDS and Dissolved N and P.....	3-7
Fractions of PM.....	3-8
Nutrient Partitioning	3-8
Total Watershed Nutrient Loads	3-8
EMC of Water Chemistry Parameters	3-8
IMPLICATIONS/DISCUSSION.....	3-9
CONCLUSIONS.....	3-9
REFERENCES	3-10

List of Tables

Table 1 Summary of Hydrology	3-14
Table 2 Cumulative Total of Phosphorous, Nitrogen, and Particulate Matter.....	3-15
Table 3 Values of k_0 and k_1 for particulate-bound N and P, and PM	3-16
Table 4 Values of k_0 and k_1 for PO_4^{3-} , NO_3^- , and TDS	3-17
Table 5 EMC of Particulate and dissolved Phosphorus, Nitrogen, and Particulate Matter	3-18

List of Figures

Figure 1 Plan view of catchment	3-19
Figure 2 Event-based Hydrology	3-20
Figure 3 Event-based rainfall-runoff coefficient	3-21
Figure 4 Traffic count for catchment basin during a typical weekday and weekend	3-22
Figure 5 Mass-Limited behavior of particulate fractions, and particulate N and P	3-23
Figure 6 Mass-limited and flow-limited behavior of dissolved Nitrogen, Phosphorus, and Total Dissolved Solids	3-24
Figure 7 Fraction of suspended, settleable, and sediment vs. the maximum SSC concentration throughout the hydrograph	3-25
Figure 8 Event-based particle size distribution of PM.....	3-26
Figure 9 Dissolved fraction and equilibrium partitioning coefficient for Phosphorus and Nitrogen	3-27
Figure 10 Comparison of dissolved fraction and partitioning coefficient for other similar sites that represent parking of pavement of an institutional land use	3-28
Figure 11 Total annual nutrient loads of catchment basin for total Phosphorus, Nitrogen, and PM based on the high and low runoff coefficients	3-29
Figure 12 Comparison of particulate and dissolved Nitrogen and Phosphorus to other similar sites that represent parking of pavement of an institutional land use	3-30

ABSTRACT

Paved urban interfaces subject to rainfall-runoff processes, as well as biogenic, anthropogenic and wastewater reuse loads can be effective conveyors of metals, nutrients, xenobiotics, and particulate matter (PM). Therefore, examining the coupled relationships between rainfall and runoff, hydrologic transport of load and nutrient partitioning, are important to design effective source area controls. The focus of this study is an asphalt-paved institutional source area parking of approximately 450 m² in Gainesville, Florida subject to biogenic and anthropogenic loads. Event-based hydrologic, nutrient and PM data were collected. From these data, transport and partitioning were determined and concentrations of nutrients and PM were compared to similar source areas. Abstractions were significant for this sloped paved surface, with volumetric runoff coefficients below 0.5 on an event basis and the mean initial pavement residence time was 26 minutes with a standard deviation of 5 minutes. On an event basis the median dissolved fraction of nitrogen (N) was 0.21 (21%) and 0.36 (36%) for phosphorus (P). When classified as suspended, settleable and sediment fractions, transported PM was dominated by suspended and sediment. Transported PM had a hetero-disperse particle size distribution (PSD) ranging from colloidal-size to coarse sand approaching 1000 μ m. PM and PM-bound transport was mass-limited with a mean k_1 value of 5.67, 5.97, and 4.58 for P, N and SSC respectively. Median values of K_d for N and P were 41,870 and 21,753 L/kg respectively. Compared to similar source areas the N, P and PM loads were higher, while f_d and K_d were similar. With proper treatment, rainfall-runoff could be used in a reuse irrigation application.

INTRODUCTION

The generation, transport and fate of urban source areas nutrients are temporal processes. Nutrient sources include both anthropogenic and biogenic sources. In cases where there is high imperviousness, anthropogenic sources can include vehicles from transportation activities and urban practices such as wastewater reuse and fertilizer application (Sansalone and Ying, 2008, Novotny and Olem 1994). For example, estimates of particulate matter (PM) fluxes ranged from 26.87 to 94.37 g/m²-day for paved urban areas impacted by vehicular transportation (Sansalone and Ying, 2008). Studies have demonstrated that anthropogenic PM results from the abrasive interactions of tires, pavement, engine and brake as well as settleable exhaust and maintenance activities (Sansalone, 2001). The biogenic PM results from vegetation sources such as leaf fall, vegetative die-off and landscape maintenance (Mytyk and Delfino, 2004; Sansalone, 2001) intercepted by impervious pavement. As this biogenic material that is of lower specific gravity and in many cases of higher specific surface area, such as for leaves or grass clippings, such vegetation can be readily transported across hydraulically-efficient paved surfaces during a rainfall-runoff event. In many existing urban land uses, these biogenic material sources are of anthropogenic design, such as in a parking lot where there are minimal pervious areas except for vegetated or landscaped islands. In such urban designs the relative elevation and profile of such islands with respect to the surrounding pavement play a significant role in the transport and fate of biogenic material and reuse loads to the impervious pavement. For instance, in cases where an island is lower than the immediate surrounding parking lot elevations, effective drainage of pollutants into the islands, instead of transport onto the pavement, is possible. On the other hand,

if the profile of the median is designed to be significantly higher than the elevation of the parking lot, biogenic debris is transported to and across the impervious pavement during a storm event.

Hydrology coupled with water chemistry has a significant effect on pollutants present in rainfall-runoff. Factors such as the previous dry days (pdd) for a storm event can influence the potential quantity of pollutants for transport during a storm event (Sheng et al, 2008). Additionally, the intensity of a storm event, as well as the duration has a more significant influence the transport of runoff constituents than pdd (Gnecco et al, 2005). The geometric characteristics of the catchment or watershed plays an integral role in pollutant transport where source area watershed have been shown to generate a more defined and consistent first-flush (mass-limited behavior) as compared to larger and more complex watersheds (Sansalone and Cristina 2004).

OBJECTIVES

Commensurate with the transport and fate of nutrients and PM at the urban interface there are several objectives of the characterization portion of this study. The first objective is to quantify the concentration of nutrients and PM using non-parametric analysis on a sample basis for the Gainesville, Florida site to other urban land uses. This objective is evaluated for dissolved and particulate-bound phases of nitrogen (N) and phosphorus (P). Additionally, the transport behavior (mass-limited or flow-limited) of the N and P fractions, as well as the sediment, settleable, and suspended PM fractions, were evaluated. A third objective further differentiated PM into particle size distributions (PSD), modeling PSDs on an event basis. Indices of equilibrium partitioning, specifically the dissolved fraction (f_d) and partitioning coefficient (k_d) were examined. This characterization was required for design of the in-situ treatment system.

BACKGROUND

SJRWMD

Gainesville, Florida is a part of Alachua County, which is in large part the major contributor of the Orange Creek Basin. This greater basin is approximately 600 square miles in size, and the three major waterbodies in the Orange Creek Basin is Newnan's Lake, Lake Lochloosa, and Orange Lake. The institutional site of interest in this case drains initially to Lake Alice, a lake on- campus at the University of Florida, and eventually outfalls into Orange Lake. The annual rainfall influences the resulting overall runoff that ultimately contributes to the larger Orange Creek Basin. During the year of 2007, approximately 1200 mm of rainfall was recorded at the institutional site in interest for this study (Wunderground, 2007). From the beginning of 1999 to the end of 2003 the Saint John's River Water Management District (SJRWMD) monitored these three waterbodies comprising the Orange Creek Basin. Particularly, the median total suspended solids (TSS), total phosphorous, and total nitrogen concentrations were 19 mg/L, 0.078 mg/L, and 2.03 mg/L respectively (SJRWMD). When comparing these water chemistry parameters to the concentrations listed by FDEP as being the maximum allowable freshwater body concentrations, the results are higher (FDEP, 2008). Particularly, the total Phosphorous Concentration is of concern in Orange Lake, which is why the Florida Department of Environmental Protection (FDEP) adopted in 2004 a water quality target of 45% reduction of its

Total Maximum Daily Load (TMDL) (FDEP, 2004). According to FDEP, Orange Lake, which is approximately 21 square miles, showed a general increase in nutrients from 1989 to 1998, indicating that that Dissolved Oxygen (DO) may be related to the problem (FDEP, 2001). Similarly, in the Orange Creek Basin, FDEP estimates in the 385,270 acre watershed, and of the 68 miles of assessed water bodies, that 50 miles are impaired by nutrients and DO (FDEP, 2001).

Nutrient Concentrations from Paved Surfaces

Previous studies have investigated nutrient partitioning in rainfall-runoff and have shown variable results. For example, an asphalt parking lot surface in Phoenix, Arizona generated nitrate (NO_3^-) and orthophosphate mean concentrations of 26.6 and 0.18 mg/L respectively (Hope et al, 2004). A Connecticut study illustrated total Nitrogen (TN) and total Phosphorous (TP) concentrations to be 8.0 and 0.244 mg/L respectively (Gilbert and Clausen, 2006). Mytyk and Delfino reported in 2004 that over a 50 year period at 5 of 14 monitored stations there was an increase in the median nitrate concentration in the Ocklawaha River (Mytyk and Delfino, 2004). More specifically the median nitrate concentration at one of the sites increased from 0.07 mg/L to 0.78 mg/L (Mytyk and Delfino, 2004). Dean et al. (2005) reported nitrate and orthophosphate event mean concentrations of 4.6 and 0.9 mg/L, respectively for a paved urban source area in Baton Rouge, LA. A study of rainfall-runoff in Temple Terrace, FL, indicated a mean TN concentration of 1.14 mg/L, which is significantly lower than the previous studies mentioned (Rushton, 2000). Finally, a study done in Ruskin, FL at an agricultural land use found the mean concentrations of organic nitrogen, NO_3^- , orthophosphate, and particulate P to be 1.325, 0.385, 0.937, and 0.572 mg/L respectively (Rushton, 2002).

Mass-limited (first-order) vs. Flow-limited (zero-order) Delivery

Over the last century there has been much debate on how pollutants are transported in rainfall-runoff. Early reference to such transport described a first-flush of equine fecal matter from urban surfaces (Metcalf and Eddy, 1916). While most researchers assume a mass-limited (zero-order) delivery, actual delivery represents one limit of a two limiting classifications of transport from urban surfaces (mass or flow limited) (Sheng et al. 2008). While there are many studies of first flush phenomena for PM and metals (Cristina and Sansalone 2004, Sansalone and Buchberger 1997) there are relatively few studies that have illustrated a first-flush of nutrients. Although a previous study that has analyzed nutrient transport in China, revealed that both TN and TP experience mass-limited behavior. (Li et al, 2007). Similarly, a study done in an urban watershed in South Korea determined that TN and TP delivery experienced a first flush phenomenon (Lee et al, 2002). Finally, a German research study has shown that TN experienced a mass-limited delivery, while TP experienced a flow-limited delivery (Geiger, 1987).

SITE DESCRIPTIONS

The institutional site in Gainesville, Florida, has characteristics in its existing watershed area that result in it being classified as an urban land use. The catchment used in this research, is approximately 450 m² in size and consists of a pavement parking lot that serves the respective

institution. The catchment is only one of a number of watershed catchments with catch basins intercepting flow for each parking lot catchment. Figure 1 delineates the basin of interest into one major throughway that vehicles pass on any given day, as well as two parking lanes that are frequently traveled. This catchment has two islands in between traffic lanes that function to provide partial runoff drainage because they are vegetated. In addition, these islands contain trees and vegetation that shed biogenic material to the impervious parking lot, material that is eventually transported during a rainfall-runoff event.

The geometric design of these islands in the parking lot transport most of the pollutants generated from organic sources, because of the elevation differences in its profile, compared to the remainder of the parking lot. Since the islands are significantly higher than the elevations of the rest of the parking lot, during a storm event where there are stronger crosswinds, inevitably pollutants off of these islands are transported to the sampling collection point in the catchment.

Additionally, in Figure 1, it is important to note that while flow travels down the parking lanes to the sampling point at the catch basin located at the downstream end of the catchment, that only the rainfall-runoff from the centerline, along the high-point elevation, are transported through the catchment. The rest of rainfall-runoff either being generated directly above or below the centerline are drained to separate catchments. The integrity of the pavement in the watershed varies, because there are numerous cracks that exist in the pavement, resulting in generated stormwater during an event to be infiltrated through cracks and openings in the pavement. Additionally, the pavement tends to be extremely rough in some regions, which provides depressional storage for some of the rainfall-runoff. Not only is the pavement surface rough, but tends to have uneven leveling, causing temporary depressional storage during a storm event. The asphalt pavement was placed approximately 10 years ago.

METHODOLOGY

Stormwater Sample Collection

The sample collection point during rainfall-runoff events was set up to collect the stormwater in such a manner to manually retrieve full cross-sectional flow samples. This method ensured accurate representation of the constituents including all biogenic and anthropogenic PM fractions. Historically, one of the very significant errors associated with autosampling has been the inability of the automatic sampler to represent pollutants; in particular pollutant loads, particulate matter and pollutants associated with the sediment and biogenic fractions. Therefore sampling followed methods published by Sansalone and Kim (2008). The rainfall-runoff that was transported to the outlet of the catchment was passed through a Parshall flume and drop box, enabling full-cross sectional samples to be obtained. To further compound the misrepresentation of automated sampling, samples are generally held in the sampler or lab for 24 hours before analysis. Whether refrigerated or otherwise; a 24 hour holding time can result in a significant change in partitioning for a solute (Sansalone and Buchberger 1997). Therefore sample holding times before fractionation and preservation were less than eight hours.

Traffic Count

Besides ensuring proper collection of stormwater samples, a determination of the amount of traffic that passes through the catchment on a daily basis was necessary. If accurate estimations of the daily traffic were made, an accurate estimate could be made on the total pollutants that were contributing to the watershed, because of travelling vehicles. The important assumption made in this process, in order to achieve the total contributing PM amounts, was that each vehicle contributed approximately 0.09 mg/m²-vehicle of PM (Sansalone and Ying 2008).

Because the catchment that was being examined for pollutants in rainfall-runoff was from an institutional source, typical peak hour traffic counts were not representative of the total pollutant loads to the watershed. Additionally, the vehicles that travelled through the catchment basin were significantly different on a typical weekday, compared to a typical weekend day.

Therefore, traffic counts were performed both on 10 September 2008 and 13 September 2008, to determine daily traffic through the catchment basin. The traffic count on both dates, were done between the hours of 6:00 am to 6:00 pm. Vehicles through the watershed were constantly monitored through this time, to be used in future analysis in combination with the amount of previous dry days before a rainfall event to determine total pollutant loads.

Nutrient Partitioning

Once samples were collected, laboratory analysis was necessary to determine water chemistry parameter concentrations, such as Total Nitrogen (TN), Total Phosphorous (TP), and PM. These parameters in turn were used in non-parametric analysis for resulting partitioning and transport during rainfall-runoff events. When examining TN and TP for partitioning in the resulting rainfall-runoff, (NH₃+NH₄) and NO₃²⁻ were the primary dissolved portion of TN; nitrite was a small fraction of the dissolved, while PO₄³⁻ species comprised the dissolved portion of TP. The relationships used to describe the nutrient partitioning of the rainfall-runoff is described below.

$$K_d = \left(\frac{P}{m} \right) / D \quad (1)$$

$$f_d = \frac{D}{D + P} \quad (2)$$

K_d is the partitioning coefficient (L/kg), P is the particulate-bound mass of a constituent, m is the TSS concentration of the adsorbing PM in the aqueous system, D is the dissolved mass of a constituent, and f_d is the dissolved fraction (Glenn and Sansalone, 2002).

EMC Calculations

Not only was the partitioning of the nutrients determined for each respective storm event, but the Event Mean Concentration (EMC) were determined.

$$EMC = \frac{M}{V} = \frac{\int_0^{t_r} c(t)q(t)dt}{\int_0^{t_r} q(t)dt} \quad (3)$$

In this equation the EMC is the flow weighted average concentration for the entire event, M is the total mass of constituent over entire event duration, V is the total volume of flow over entire event duration, $c(t)$ is the time variable dissolved or particulate bound concentration, $q(t)$ is the time variable flow, and t is time (Sansalone and Buchberger 1997).

Mass-Limited vs. Flow-Limited Behavior

After the EMC analysis, $M(V)$ curves were formulated, and mass-limited vs. flow-limited behavior could be determined for each of the storm events through the utilization of the appropriate equations. The first set of equations relate a first-order, mass-limited behavior.

$$\frac{dM}{dt} = -K \quad (4)$$

$$K = k_1 \quad (5)$$

$$\Delta M_t = M_0(1 - e^{-k_1 V_t}) \quad (6)$$

ΔM_t is the cumulative mass delivered, V_t is the cumulative volume, M_0 is the constituent mass on the surface at the beginning of the rainfall-runoff event, k_1 is the first order coefficient, K is the transport rate coefficient, and M is the instantaneous mass remaining on the watershed surface (Sheng et al. 2008, Sansalone and Buchberger 1997).

The equations below describe flow-limited events with a zero-order behavior.

$$\frac{dM}{dt} = -K \quad (7)$$

$$K = k_0 Q \quad (8)$$

$$\Delta M_t = k_0 V_t \quad (9)$$

k_0 is the zero-order coefficient, and all other parameters are defined as above (Sheng et al. 2008).

Particle Size Distribution (PSD)

The PSD of PM is of interest in the rainfall-runoff from each storm event, because it reveals how effective treatment should be designed to remove all or a majority of PM; in particular the suspended fraction of PM. Once PSD was determined in the laboratory for each sample using laser diffraction the PSD was modeled using a cumulative gamma distribution (Sansalone and Ying 2008). The median particle diameter, d_{50} based on mass was determined with other PSD indices for each storm event. The cumulative gamma distribution, a two-parameter model generated physically-based parameters; α , shape, and λ , scaling parameters. Laboratory methods are detailed in the SOPs and QAPP and not re-iterated herein.

RESULTS

Hydrology

The resulting hydrologic characteristics of the four respective storm events are displayed in Figure 2 and Table 1. It is important to note that of the four respective events, that the 05 May 2007 and 02 June 2007 events had lower intensity in rainfall, as well as lower total rainfall volume, while the 15 April 2007 and 29 June 2007 events had higher rainfall intensity, with greater runoff volume. The runoff coefficient at the site ranged from 0.19-0.47, which under initial examination is a relatively low runoff coefficient, considering that the catchment almost entirely consists of impervious surfaces. But when additionally considering the conditions of the pavement, as described above as having numerous cracks, as well as a rough pavement surface, these results are not surprising. The runoff coefficient differs with respect to time throughout any given storm event. Figure 3 illustrates for the four respective storm events the rainfall-runoff coefficient for the catchment, ranging from 0.13-0.32.

Traffic Count

Traffic counts were performed on both 10 September 2008 and 13 September 2008. The results of these traffic counts are displayed in Figure 4, where it is clear, as hypothesized that this institutional source area watershed has traffic constantly throughout a typical weekday. Additionally, not only is this daily traffic constant, but this traffic has atypical peaks as compared to municipal roadways because the catchment has its highest volume during the middle of the day, as well as during the evening traffic rush.

M(V) Curves: Particulate Fractions and Particulate N and P

Based on the hydrology of the rainfall-runoff event, the transport of PM can be further analyzed for mass-limited and flow limited behavior. The particulate fraction, as well as particulate N and P, demonstrated mass-limited behavior for all storm events. The particulate fraction consisting of suspended ($< 25 \mu\text{m}$), settleable (25 to $75 \mu\text{m}$), and sediment ($> 75 \mu\text{m}$) PM all demonstrate strong mass-limited behavior in Figure 5. Supplementing Figure 5 is Table 2 and Table 3, where Table 2 contains the cumulative totals of mass for each particulate fraction, and the latter reveals the k_1 values for these mass-limited events, as well as their respective R^2 (coefficient of determination). The particulate N and P, similar to the particulate fractions demonstrate mass-limited behavior, but results are variable for storm events, such as the 15 April 2007 and 05 May 2007 events.

M(V) Curves: TDS and Dissolved N and P

A majority of the storm events additionally have mass-limited behavior for TDS and the dissolved fraction of N and P. These results can be more carefully examined in Figure 6, in coordination with Table 2 and Table 4, which have the cumulative mass totals for the storm events, as well as the k_0 and k_1 values, with their respective R^2 values. Although a majority of the storm events for the dissolved fraction of N and P, and TDS display mass-limited behavior,

some flow-limited behavior exists particularly for nitrate during the 15 April 2007 and 02 June 2007 storm events.

Fractions of PM

PM is comprised of three major fractions including suspended, settleable, and sediment. The percent that these fractions comprise each sample in a given storm event are summarized in Figure 7. Sediment comprises most of the PM, comprising over 90 percent in some cases. The suspended sediment concentration (SSC) contains all three fractions, of suspended, settleable, and sediment. The SSC transport is illustrated with respect to time, in combination with the hydrograph during a given storm to examine PM concentration. All results are normalized to the maximum event concentration. The PSD for each respective storm event is given in Figure 8. The modeled curves fit the measured data with an R^2 of at least 0.98, and have relatively similar α and λ factors despite the variable hydrology.

Nutrient Partitioning

The resulting nutrient partitioning for both TP and TN is shown in Figure 9. The f_d range for both TP and TN is relatively low, typically between 0.1-0.4. This result is expected considering that most of the pollutants contributing towards the rainfall-runoff can be attributed to biogenic material from the raised vegetated islands that is dispersed to the pavement either by wind, leaf fall or maintenance practices. Similarly, the high k_d values demonstrate the tendency of TN and TP being particulate-bound. When comparing these f_d and k_d results to other urban sites, results are similar for other urban land uses. The sites used in comparison, in Figure 10, represent other urban land uses in Florida, as well as one other institutional site in Milwaukee, WI.

Total Watershed Nutrient Loads

The load impact of this institutional site on the environment is examined based on total annual constituent loads discharged. Based on the annual frequency distribution of wet weather events, and translation of rainfall to runoff for this catchment and watershed, the expected PM loads are summarized in Figure 11. Historically the precipitation to this site during the year 2007 can be seen in Figure 11. The site had an annual cumulative rainfall of approximately 1200 mm. Translating this precipitation into runoff for this site is most simply carried out using the range of volumetric rainfall-runoff coefficients, which are 0.13- 0.32 respectively. Using the median value of particulate P, dissolved P, particulate N, and dissolved N for the catchment, a median and high and low range of these nutrients load can be estimated. Figure 11 displays these estimated loads throughout 2007 for the nutrients fractions, as well as PM and TDS.

EMC of Water Chemistry Parameters

The EMC of relevant water chemistry parameters is summarized in Table 5. However, it is important to compare these EMCs to those of other urban sites that are similar urban land use. Figure 12 provides a comparison of the site in Gainesville, FL to other similar land uses in Florida, as well as another institutional site in Milwaukee, WI. Generally the concentration of TP, TN, and PM are higher for this catchment than for other catchments. There are likely two

primary reasons for this result: (1) the common use of automated sampling or non-representative sampling does not accurately represent water chemistry parameters, even as an EMC; and (2) the combination of a raised vegetated island design draining to impervious pavement results in a very efficient drainage conveyance that transports biogenic and anthropogenic loads for this institutional land use.

IMPLICATIONS/DISCUSSION

While it is recognized that automatic sampling is non-representative; it is also recognized that a paradigm shift in practice is unlikely. Ultimately, calibrated and validated in-situ sensors will supplant automated sampling but this is decades away from widespread adoption. Furthermore, while in-situ sensors such as laser diffraction offer a significant step forward, without calibration and validation such sensors can be just as non-representative as the current automated sampling. The finer and more mono-disperse the PSD (typical of filter effluent) the more robustly automated sampling can be defended. However for influent samples there is a significant mis-representation and this is a particular problem with respect to assessing TMDLs and assessing maintenance/clean-out requirements of unit operations and processes (commonly identified as BMPs in stormwater control). For example, the mis-representation of influent load to common small-footprint BMPs such as screened hydrodynamic separators designed to capture coarse debris and biogenic material in the screening process results in significant scour as the sump volume that is exhausted is significantly underestimated and the sludge in the sump generates deleterious water chemistry conditions. Results from this characterization indicate that on both a volumetric and gravimetric basis; the significant load of pollutants is associated with the sediment and gross solids fractions; those fractions effectively trapped during a runoff event BMPs such as hydrodynamic separators or even drainage appurtenances such as catch basins. Regular, if not frequent maintenance of these systems is required not only for recovery of mass that fills up such systems, but also for to mitigate potentially deleterious water chemistry conditions such as anoxic and anaerobic conditions in BMP sumps or tanks. Compounding the problem is that such small footprint BMP capture the gross solid and sediment fractions primarily, the fractions that are the most labile compared to the finer, hard to separate and more mobile fractions that such BMPs do not capture. As a result, later chapters examine adsorptive-filtration and media selection for fine PM separation and fine PM filtration.

CONCLUSIONS

Urban watersheds with impervious pavement can contribute significant amounts of nutrient pollutant loads and PM to MS4s and receiving waters. While the pavement itself can generate PM, it is the effective conveyance capability of the pavement combined with landscape design features of raised landscape beds and islands that result in the significant transport of nutrient and PM loads. A viable alternative is inverted or swaled islands such as a vegetated biofiltration area reactor (BAR) combined with cementitious permeable pavement (CPP) as will be illustrated in a later chapter. Florida-friendly landscape offers significant ecological benefit when applied in the context-appropriate design scenario. Redesign of this particular watershed in Gainesville, Florida could result in significant reductions of pollutants transported in rainfall-runoff, reduced thermal pollution and significant indirect reuse.

With the current design, nutrients, both TN and TP, partition in rainfall-runoff predominantly to the particulate-bound state, with a mean f_d value of 0.21 and 0.45 for N and P respectively. These results are accounted for in later chapters with media and treatment design and watershed re-design.

Additionally, a majority of the PM present in the rainfall-runoff exists in the sediment fraction as compared to settleable and suspended fractions, over 90 percent in some cases. This constitutive result has a significant impact on treatment design and BMP maintenance requirements. Although sediment exists as the majority of PM, suspended and settleable PM require control from a receiving water point of view.

Because a majority of PM and nutrients (except dissolved fractions) exhibit a first-flush phenomena, particulate P, particulate N, and SSC, with mean k_1 values of 5.67, 5.97, and 4.58 respectively, can be treated with a water quality volume concept. However, dissolved constituents which can illustrate a weak mass-limited or even flow-limited transport will require capture of the entire event. For P and N, as well as TDS, with a weak mass-limited behavior have median k_1 values of 3.84, 3.26, and 7.57 respectively. Therefore, attention must be given to the individual elution of all pollutants and phases to optimize control. Finally, these results demonstrate that the PSD of rainfall-runoff produced from storm events vary in particle diameter from less than 1 μm to over 1000 μm . For this reason, when designing treatment for PM, it is important to recognize the hetero-dispersivity of PM in runoff in order to design sustainable treatment and BMP maintenance strategies.

REFERENCES

- Brezonik, P.L., E.C. Blancher, V.B. Myers, C.L.Hilty, M.K. Leslie, C.R. Kratzer, G.D. Marbury, B.R. Snyder, T. L. Crisman & J. J. Messer, 1979. Factors affecting primary production in Lake Okeechobee, Florida. Rept. No. 077901, Dept. Env. Eng. Sci., Univ. Florida, Gainesville, FL: 294 pp.
- Christensen, E. R. and Soonthornnonda, P. (2005). Milwaukee Metropolitan Sewerage District (MMSD) stormwater monitoring program final report 2000-2004. University of Wisconsin – Milwaukee. pp. 99, 107, 115, 147, 151.
- Dean, C. M., Sansalone, J. J., Cartledge, F. K., and Pardue, J. H. (2005). Influence of hydrology on rainfall-runoff metal element speciation. *Journal of Environmental Engineering*, 131(4), pp. 632-642.
- Florida Department of Environmental Protection (FDEP) Division of Water Resource Management. (2001). Central District, Group 1 Basin, Basin Status Report Ocklawaha.
- Florida Department of Environmental Protection (FDEP). (2008). 62-302.530: Criteria for Surface Water Quality Classifications
- Geiger, W.F. Flushing effects in combined sewer systems. (1987). Proceedings of the 4th International Conference on Urban Storm Drainage, Lausanne, Switzerland. pp. 40-46.

- Gilbert, J.K., and Clausen, J.C. Stormwater runoff quality and quantity from asphalt, paver, and crushed stone driveways in Connecticut (2006). *Water Research* (40) pp. 826-832.
- Gnecco, I., Berretta, C., Lanza, L.G., and La Barbera, P. (2005). Storm water pollution in the urban environment in Genoa, Italy. *Atmospheric Research*, 77, pp. 60-73.
- Heaney, J.P. and Huber, W.C. (1984). Nationwide assessment of urban runoff impact on receiving water quality. *Water Resources Bulletin* 20 (1), pp. 35-42.
- Hope, D., Naegeli, M.W., Chan, A.H., and Grimm, N.B. Nutrients on asphalt parking surfaces in an urban environment. (2004). *Water, Air, and Soil Pollution*. (4). pp. 371-390.
- Lee, J.H., Bang, K.W., Ketchum, L.H., Choe, J.S., and Yu, M.J. First flush analysis of urban storm runoff. (2002). *The Science of the Total Environment* (293). pp. 163-175.
- Li, L., Yin, C., He, Q., and Kong, L., First flush of storm runoff pollution for an urban catchment in China. (2007). *Journal of Environment Sciences* (19). pp. 295-299.
- Metcalf, L and Eddy, H. (1916) *American Sewerage Practice Volume III: Disposal of Sewage*, McGraw-Hill Inc. New York, NY 877
- Mytyk, N. R. and J.J. Delfino. (2004). Evaluation of nitrate data in the Ocklawaha River Basin, Florida (1953 – 2002). *Journal of the American Water Resources Association*, 40 (4), pp. 913-924.
- Novotny, V., and Olem. (1994). *Water Quality: prevention, identification, and management of diffuse pollution*. Van Nostrand Reinhold, New York, New York, USA.
- Rushton, B.T. *Broadway Outfall Stormwater Retrofit Project, Phase II Monitoring CDS Unit and Constructed Pond Final Report*. (2000).
- Ruston, B.T. *Treatment of Stormwater Runoff From an Agricultural Basin by a Wet-Detention Pond in Ruskin, Florida Final Report* (2002).
- Rushton, B. T. and Hastings, R. *Florida Aquarium Parking Lot, A Treatment Train Approach to Stormwater Management, Final Report*. (2001).
- Sansalone, J.J. (2001). *Physical and Chemical Nature of Urban Storm Water Runoff Pollutants. Wet Weather Flow in the Urban Watershed. Technology and Management. Chapter 3*
- Sansalone, J. J. and Buchberger, S.G. (1997). Partitioning and first flush of metals in urban roadway storm water. *Journal of Environmental Engineering*, 123 (2), pp. 134-143.
- Sansalone, J.J., and Cristina, C.M. (2004) First Flush Concepts for Suspended and Dissolved Solids in Small Impervious Watersheds. *Journal of Environmental Engineering, ASCE*, Vol. 130, No. 11 pp. 1301-1314.

- Sansalone J. J., and Ying, G. (2008). Granulometric relationships for urban source area runoff as a function of hydrologic event classification and sedimentation. *Water, Air, and Soil Pollution*, 193 (1-4).
- Sheng, Y., Ying, G., and Sansalone J. (2008). Differentiation of transport for particulate and dissolved water chemistry load indices in rainfall-runoff from urban source area watersheds. *Journal of Hydrology*, 361 (1-2), pp. 144-158.

APPENDIX I: NOTATION

α : Shape Factor

λ : Scale Factor

BMP: Best Management Practices

DO: Dissolved Oxygen

EMC: Event Mean Concentration

FDEP: Florida Department of Environmental Protection

HS: Hydrodynamic Separator

N: Nitrogen

NO_3^- : Nitrate

P: Phosphorous

PM: Particulate Matter

PSD: Particle Size Distribution

TMDL: Total Maximum Daily Load

TN: Total Nitrogen

TP: Total Phosphorous

SJRWMD: Saint John's River Water Management District

SSC: Suspended Solids Concentration

TSS: Total Suspended Solids (mg/L)

Table 1 Summary of Hydrology

Event Measured	Previous Dry Time (days)	Rainfall Duration (min)	Runoff Duration (min)	Rain Depth (mm)	Runoff Volume (L)	C (-)	t _c (min)	t _{mean} (min)	Q ₅₀ (L/min)	Q _{max} (L/min)
15 April 2007	4.02	30	57	22.9	816.2	0.19	27.0	27.0	12.4	109.1
5 May 2007	11.81	40	55	2.0	751.1	0.33	25.0	7.0	2.2	84.2
2 June 2007	8.00	75	96	2.3	474.5	0.21	32.0	16.1	3.0	21.9
29 June 2007	3.95	101	116	1.4	5264.7	0.47	19.0	6.9	0.2	960.0
All events mean	6.95	62	81	9.7	1826.6	0.30	25.8	14.2	4.4	293.8
All events median	6.01	58	77	6.9	783.6	0.27	26.0	11.5	2.6	96.7
All events SD	3.76	33	30	9.8	2296.9	0.13	5.4	9.6	5.4	445.7
All events RSD (%)	54.07	53	37	101.9	125.7	42.0	20.9	67.2	122.6	151.7

C: Runoff Coefficient

t_c: Initial lag time (min)

t_{mean}: Mean lag time (min)

Q₅₀: Median flow rate during storm event (L/min)

Q_{max}: Maximum flow rate during storm event (L/min)

Table 2 Cumulative Total of Phosphorous, Nitrogen, and Particulate Matter

Storm Event	P: Particulate [mg/L]	PO ₄ ³⁻ [mg/L]	N: Particulate [mg/L]	NO ₃ ⁻ [mg/L]	Suspended PM [mg/L]	Settleable PM [mg/L]	Sediment PM [mg/L]	SSC [mg/L]
15 April 2007	15.8	7.7	12.1	23.2	149.2	129.4	177.9	456.5
5 May 2007	52.7	25.3	18.0	26.5	852.5	714.8	12267.2	13834.5
2 June 2007	2.0	5.6	12.8	1.6	26.7	14.0	108.1	148.7
29 June 2007	23.8	6.7	17.3	4.2	609.2	530.9	2905.3	4045.4

Table 3 Values of k_0 and k_1 for particulate-bound N and P, and PM

Storm Event	k_0 or k_1	R^2
Particulate P		
15 April 2007	$k_1 = 3.26$	0.99
5 May 2007	$k_1 = 1.80$	0.97
2 June 2007	$k_1 = 7.82$	0.98
29 June 2007	$k_1 = 9.78$	0.96
Particulate N		
15 April 2007	$k_1 = 1.86$	0.95
5 May 2007	$k_1 = 2.93$	0.98
2 June 2007	$k_1 = 4.63$	0.99
29 June 2007	$k_1 = 14.48$	0.75
Suspended PM		
15 April 2007	$k_1 = 2.65$	0.87
5 May 2007	$k_1 = 1.95$	0.97
2 June 2007	$k_1 = 2.32$	0.99
29 June 2007	$k_1 = 7.26$	0.92
Settleable PM		
15 April 2007	$k_1 = 8.79$	0.96
5 May 2007	$k_1 = 1.61$	0.94
2 June 2007	$k_1 = 3.56$	0.99
29 June 2007	$k_1 = 4.01$	0.99
Sediment PM		
15 April 2007	$k_1 = 9.30$	0.94
5 May 2007	$k_1 = 2.85$	0.91
2 June 2007	$k_1 = 5.23$	0.77
29 June 2007	$k_1 = 5.15$	0.98
SSC		
15 April 2007	$k_1 = 5.73$	0.97
5 May 2007	$k_1 = 2.74$	0.92
2 June 2007	$k_1 = 4.65$	0.85
29 June 2007	$k_1 = 5.19$	0.99

Table 4 Values of k_0 and k_1 for PO_4^{3-} , NO_3^- , and TDS

Storm Event	k_0 or k_1	R^2
PO_4^{3-}		
15 April 2007	$k_1 = 2.59$	0.96
5 May 2007	$k_1 = 2.84$	0.97
2 June 2007	$k_1 = 3.84$	0.99
29 June 2007	$k_1 = 20.55$	0.60
NO_3^-		
15 April 2007	$k_0 = 0.92$	0.99
5 May 2007	$k_1 = 3.26$	0.97
2 June 2007	$k_1 = 2.12$	0.90
29 June 2007	$k_1 = 23.87$	0.75
TDS		
15 April 2007	$k_0 = 0.89$	0.98
5 May 2007	$k_1 = 3.40$	0.91
2 June 2007	$k_1 = 7.57$	0.98
29 June 2007	$k_1 = 16.63$	0.74

Table 5 EMC of Particulate and dissolved Phosphorus, Nitrogen, and Particulate Matter

Storm Event	P: Particulate [mg/L]	PO ₄ ³⁻ [mg/L]	N: Particulate [mg/L]	NO ₃ ⁻ [mg/L]	Suspended PM [mg/L]	Settleable PM [mg/L]	Sediment PM [mg/L]	SSC [mg/L]
15 April 2007	3.5	1.6	11.5	4.7	149.2	129.4	177.9	79.5
5 May 2007	8.4	3.4	2.5	3.5	115.0	124.3	2045.0	2284.4
2 June 2007	0.6	0.8	1.7	0.2	4.3	2.0	9.2	15.4
29 June 2007	2.0	0.3	1.1	0.2	51.7	71.7	385.6	86.4
All events mean	3.6	1.5	4.2	2.1	80.1	81.8	654.4	616.4
All events median	2.7	1.2	2.1	1.9	83.4	98.0	281.7	82.9
All events SD	3.4	1.3	4.9	2.3	64.7	59.3	939.8	1112.4
All events RSD	93.8	86.8	116.9	107.4	80.8	72.4	143.6	180.5

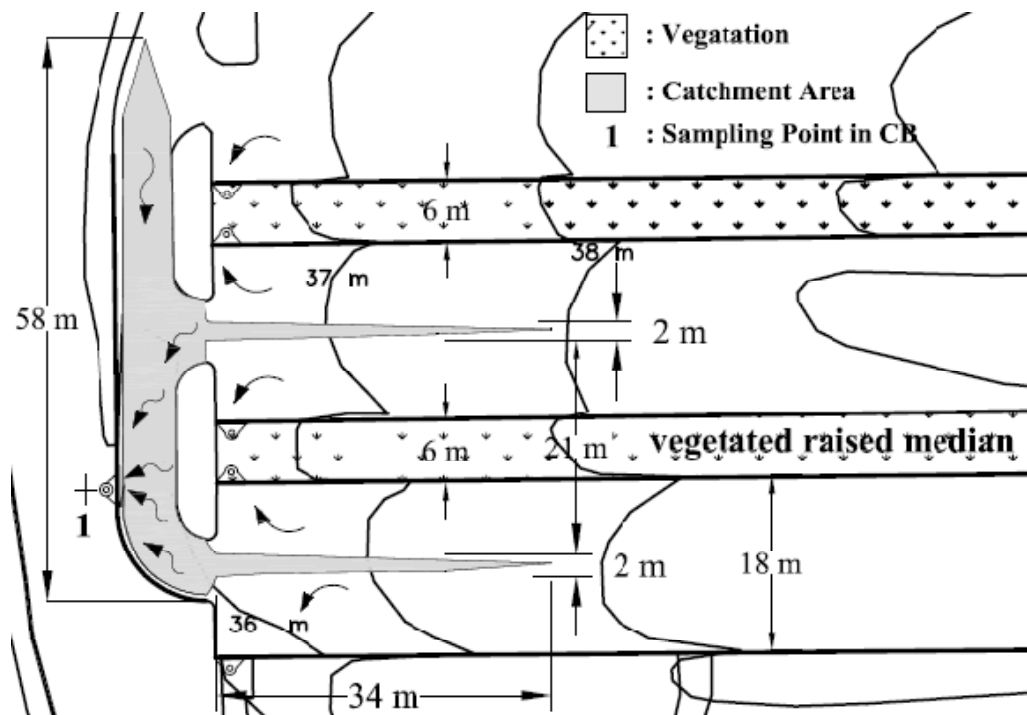


Figure 1 Plan view of catchment

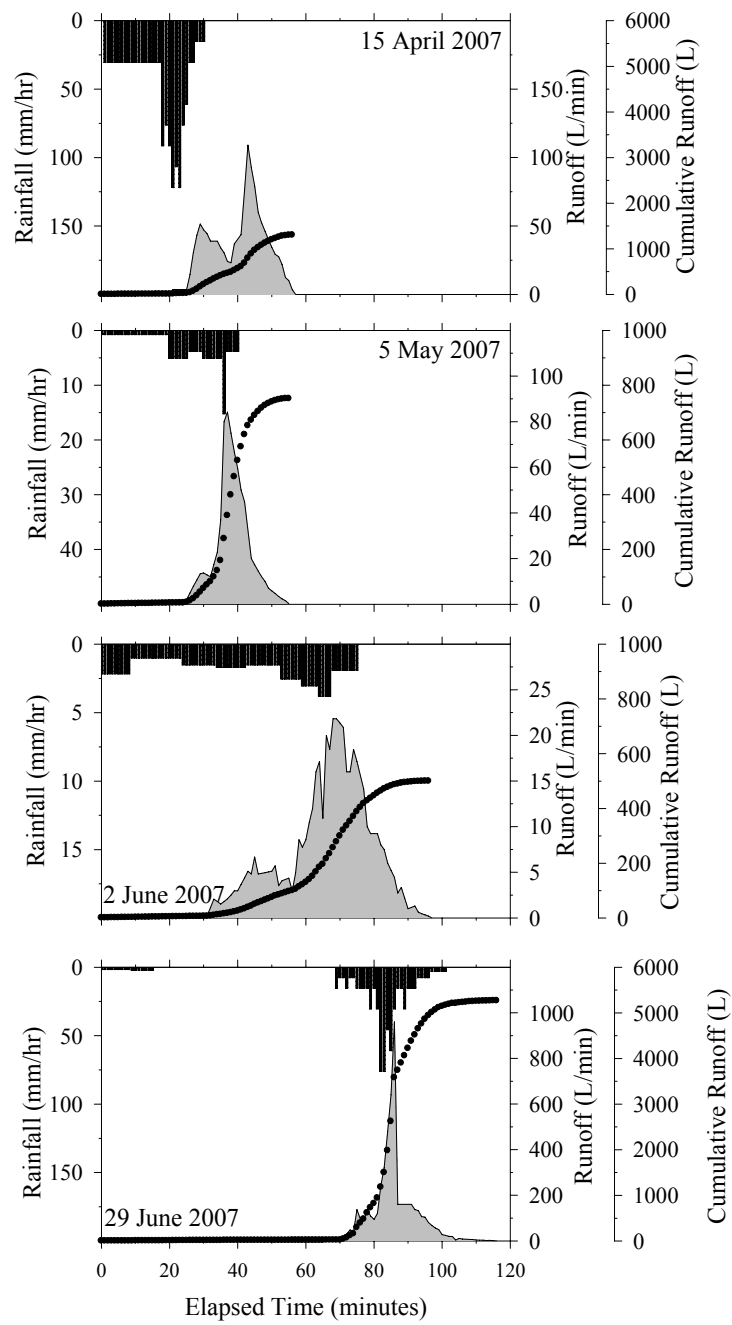


Figure 2 Event-based Hydrology

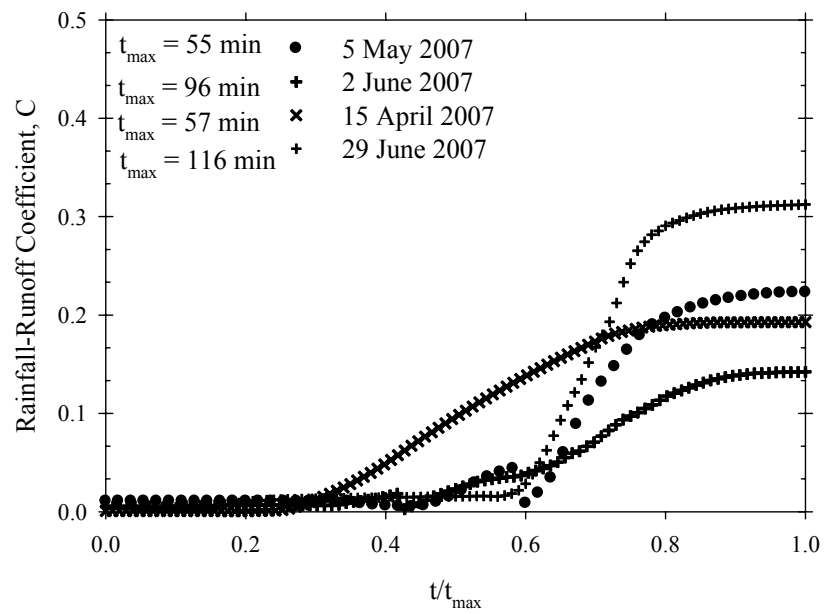


Figure 3 Event-based rainfall-runoff coefficient

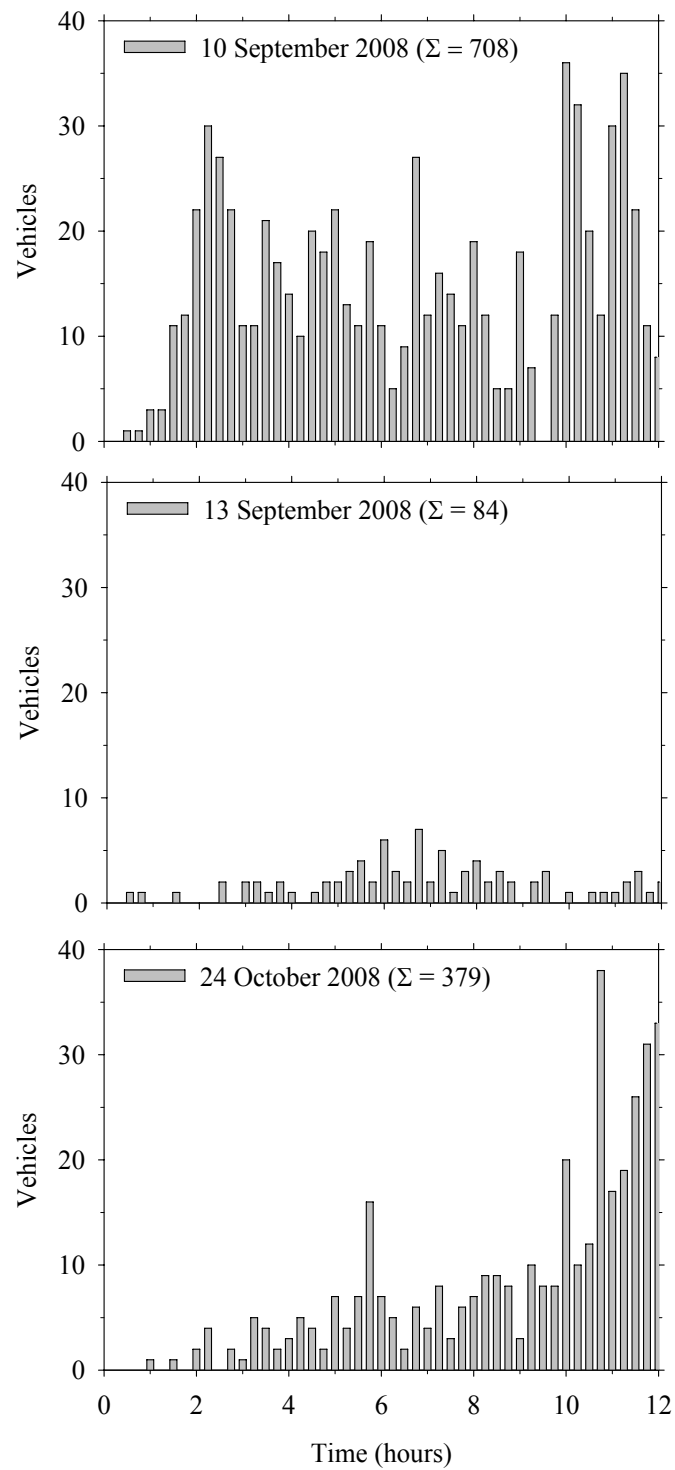


Figure 4 Traffic count for catchment basin during a typical weekday and weekend

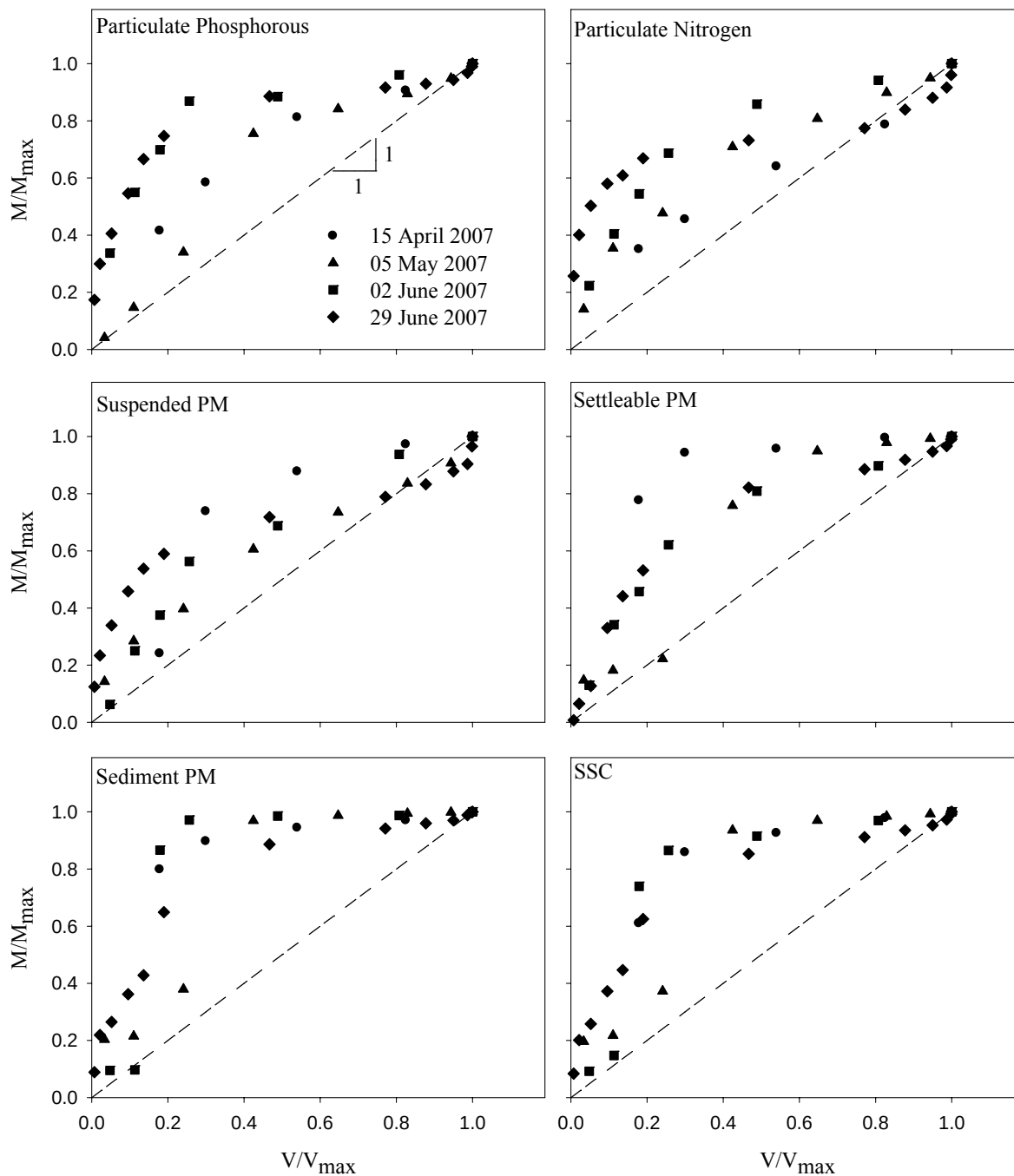


Figure 5 Mass-Limited behavior of particulate fractions, and particulate N and P

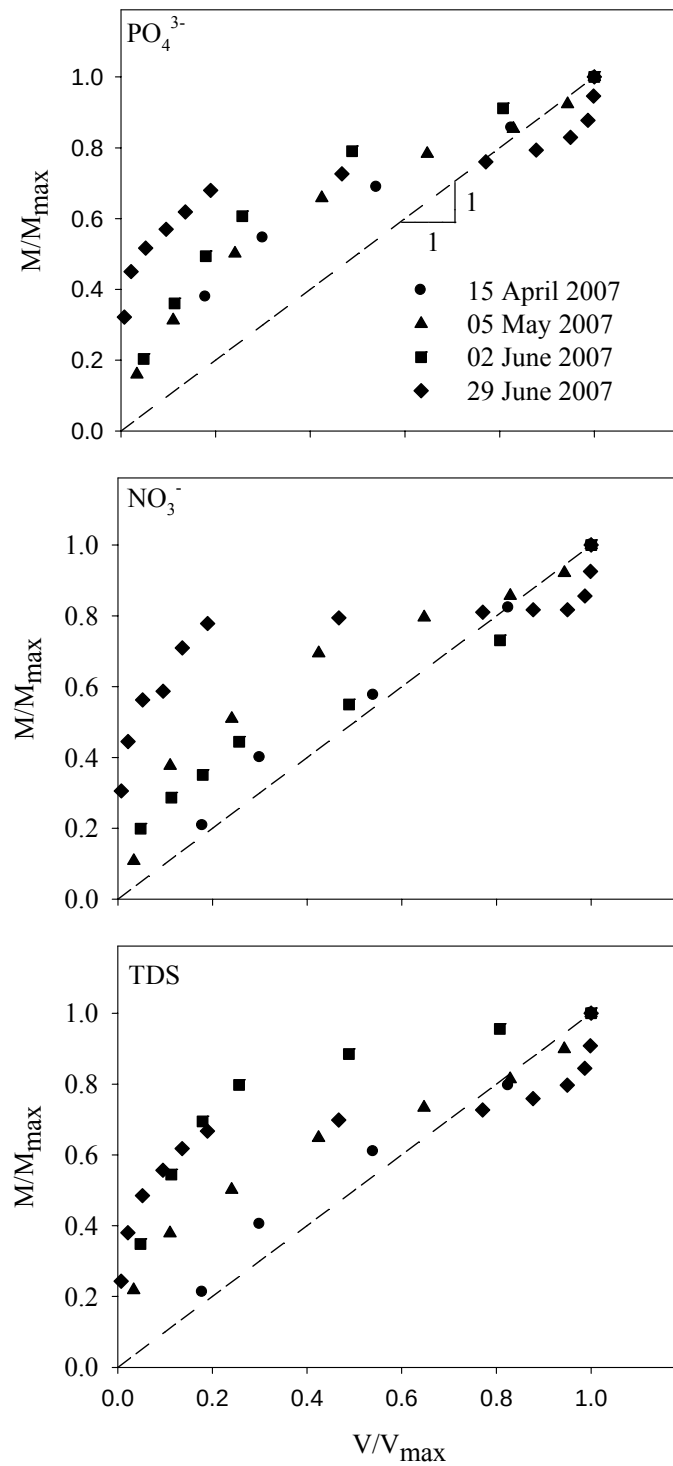


Figure 6 Mass-limited and flow-limited behavior of dissolved Nitrogen, Phosphorus, and Total Dissolved Solids

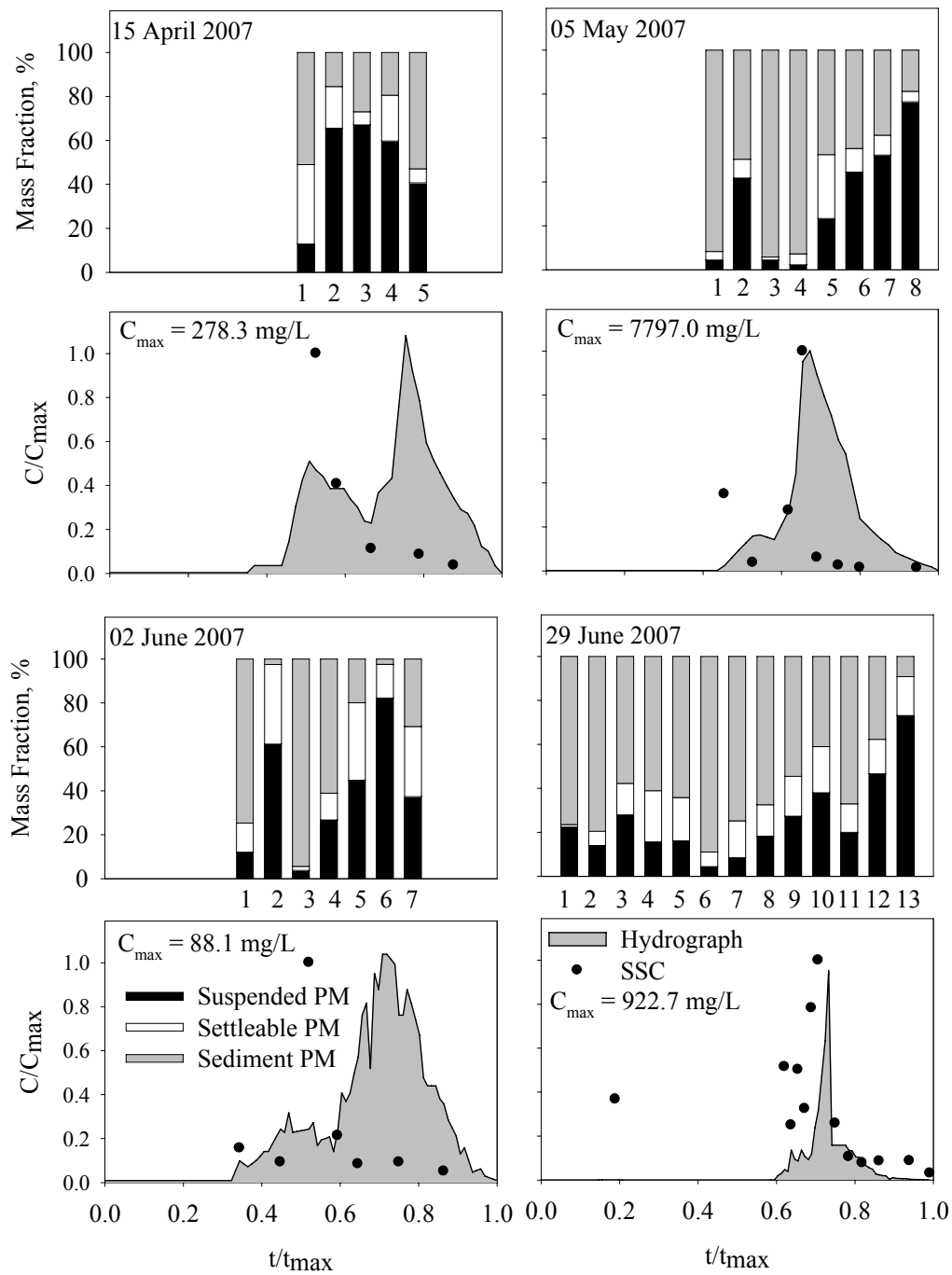


Figure 7 Fraction of suspended, settleable, and sediment vs. the maximum SSC concentration throughout the hydrograph

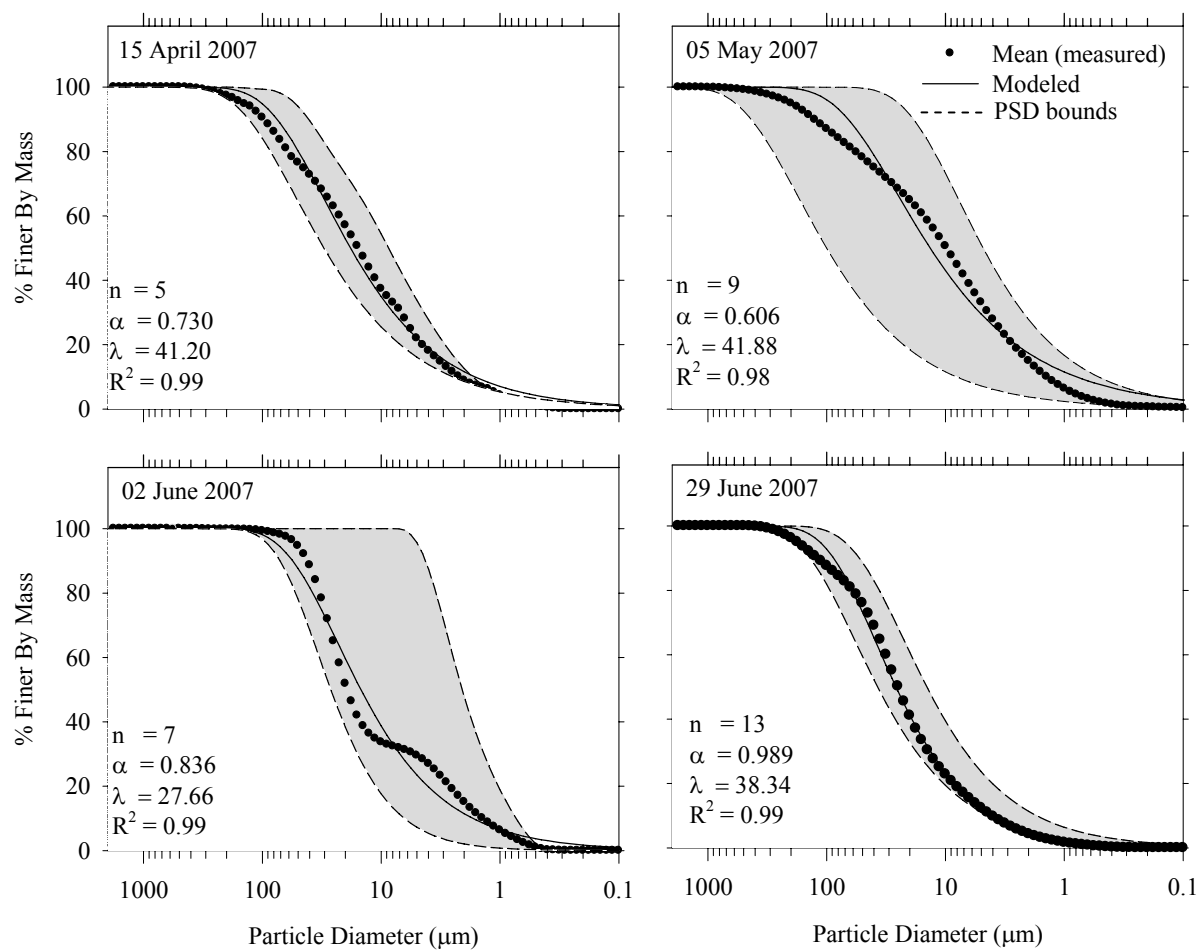


Figure 8 Event-based particle size distribution of PM

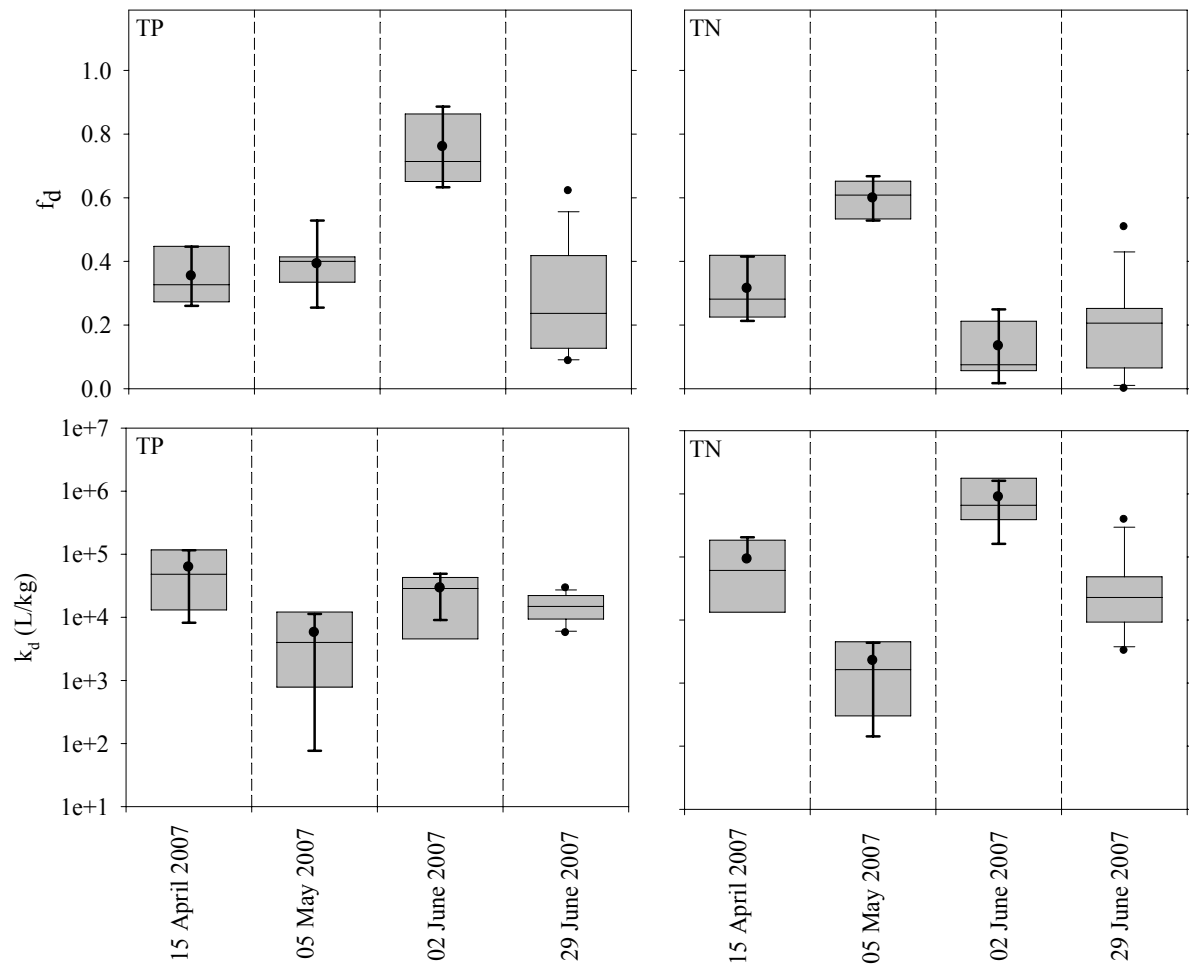


Figure 9 Dissolved fraction and equilibrium partitioning coefficient for Phosphorus and Nitrogen

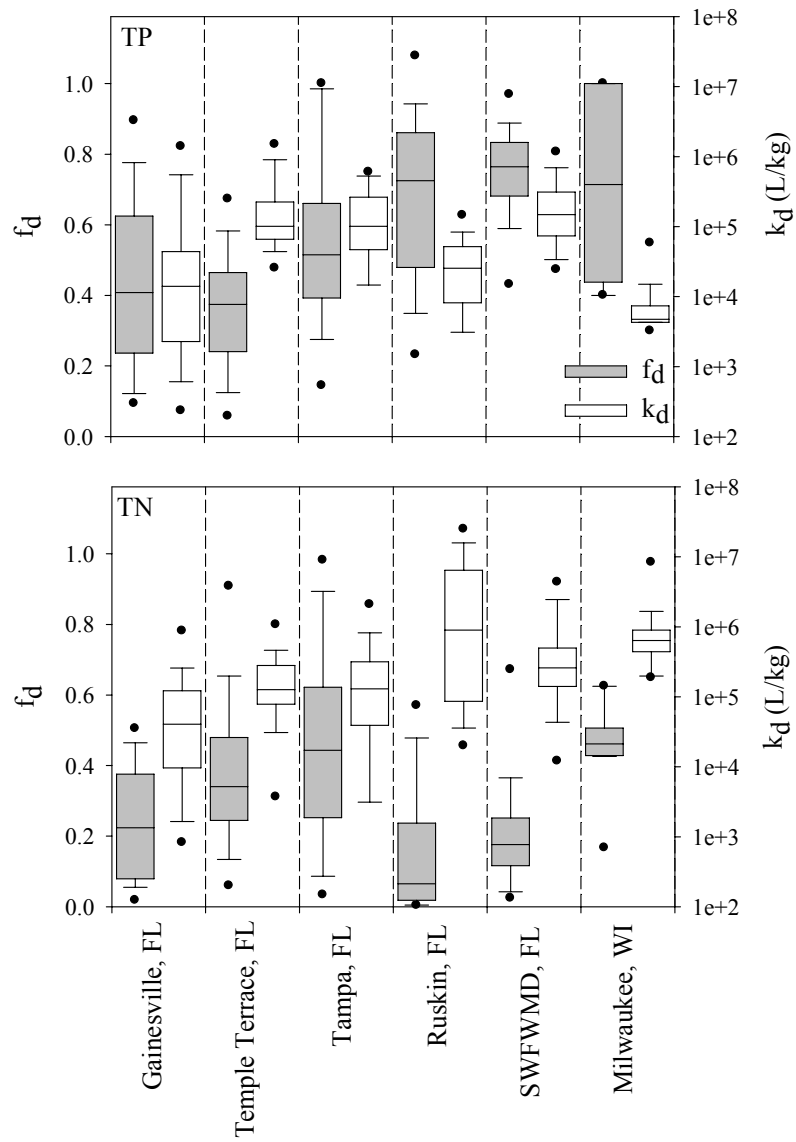


Figure 10 Comparison of dissolved fraction and partitioning coefficient for other similar sites that represent parking of pavement of an institutional land use

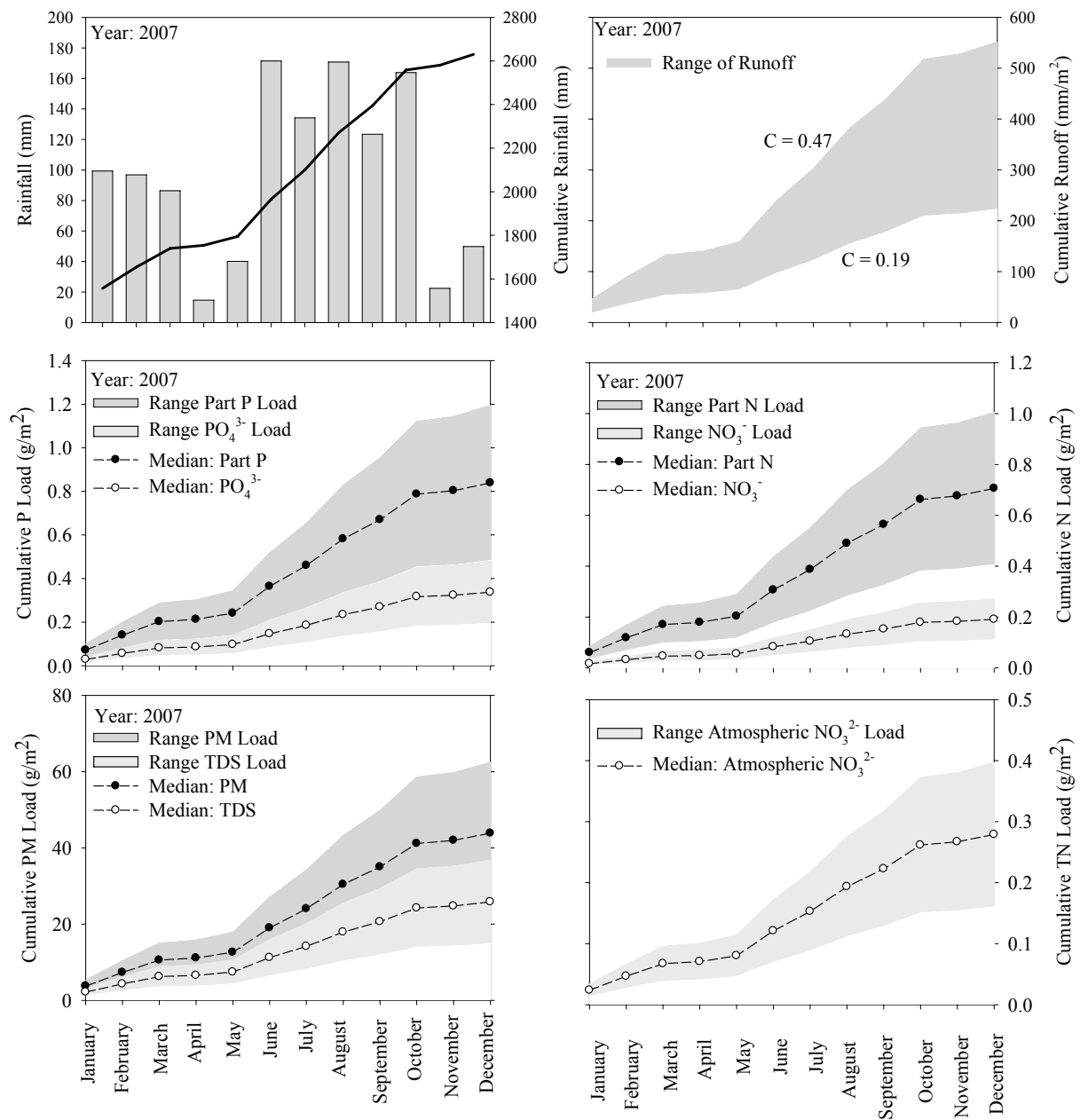


Figure 11 Total annual nutrient loads of catchment basin for total Phosphorus, Nitrogen, and PM based on the high and low runoff coefficients

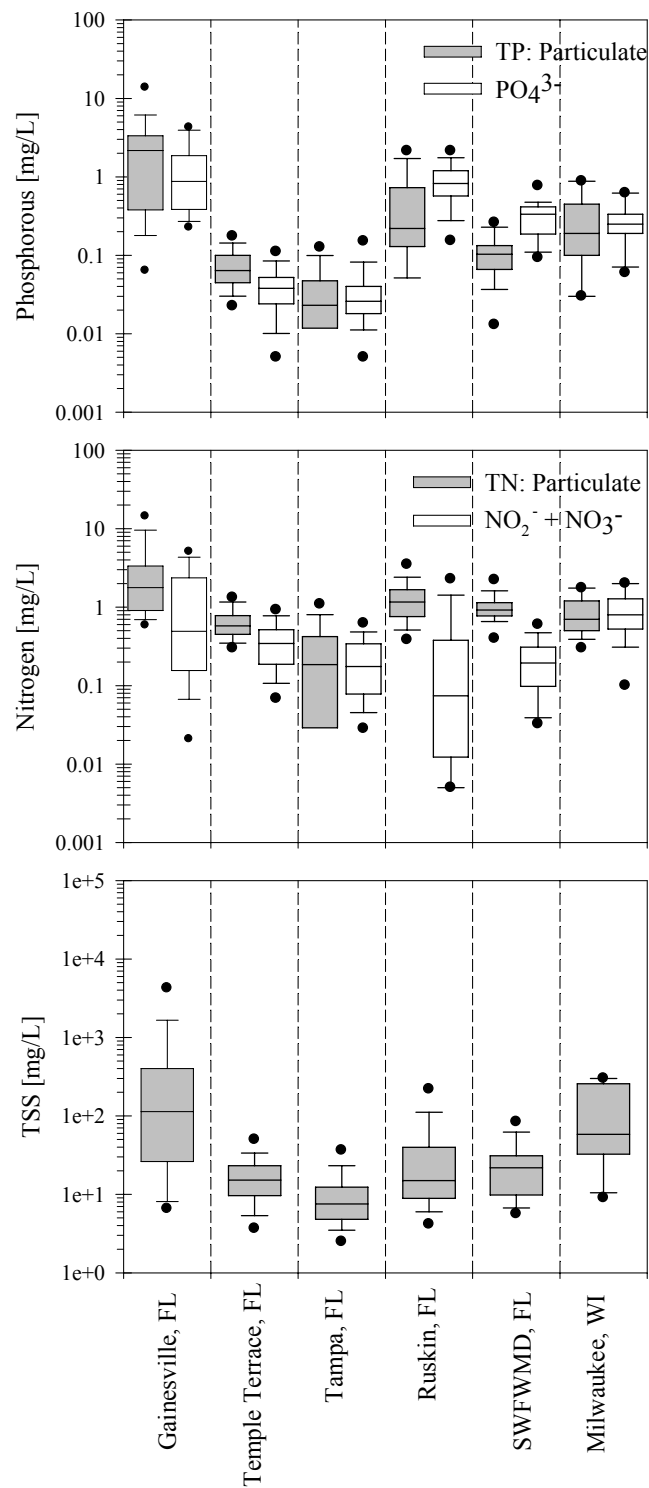


Figure 12 Comparison of particulate and dissolved Nitrogen and Phosphorus to other similar sites that represent parking of pavement of an institutional land use

CHAPTER 4: TESTING OF ENGINEERED SOIL MEDIA FOR PHOSPHORUS ADSORPTION OR DESORPTION

List of Tables	4-ii
List of Figures	4-iii
INTRODUCTION	4-1
MATERIALS AND METHODOLOGY	4-4
Engineered Soil Media Preparation	4-4
Engineered Soil Media Tests	4-4
Modeling	4-7
RESULTS AND DISCUSSION	4-9
Adsorption Equilibrium Isotherm Study	4-9
Adsorption Equilibrium Kinetic Study	4-9
Breakthrough Study	4-10
Desorption Study	4-10
REFERENCES	4-11

List of Tables

Table 1 Freundlich Isotherm Model Constants.....	4-15
Table 2 Second Order Potential Driving Kinetic Model Constants.....	4-16
Table 3 Thomas Model Constants	4-17
Table 4 Breakthrough and Exhaustion Capacity for Phosphorus Adsorption	4-18
Table 5 Summary of Media Capacity	4-19

List of Figures

Figure 1 Schematic experimental configuration of TDP adsorption kinetics on adsorbent media	4-20
Figure 2 Schematic experimental configuration of TDP adsorption breakthrough on adsorbent media	4-20
Figure 3 Phosphorus equilibrium isotherm for AO _{CMc} (0.85 - 2 mm).....	4-21
Figure 4 Phosphorus equilibrium isotherm for AO _{CMc} (2 – 4.75 mm).....	4-21
Figure 5 Phosphorus equilibrium isotherm for AO _{CMp} (2 – 4.75 mm).....	4-22
Figure 6 Phosphorus equilibrium isotherm for Expanded clay substrate (0.85 – 2 mm)	4-22
Figure 7 Phosphorus equilibrium isotherm for Expanded clay substrate (2 – 4.75 mm)	4-23
Figure 8 Phosphorus equilibrium isotherm for Pumice substrate (2 – 4.75 mm)	4-23
Figure 9 Phosphorus equilibrium isotherm for Bioretention soil media (0.001 – 10 mm).....	4-24
Figure 10 Phosphorus equilibrium isotherm for UCF-1 (0.5 – 4.75 mm)	4-24
Figure 11 Phosphorus equilibrium isotherm for UCF-2 (0.85 – 10 mm)	4-25
Figure 12 Phosphorus equilibrium isotherm for Expanded Shale-1 (2 – 10 mm)	4-25
Figure 13 Phosphorus equilibrium isotherm for Expanded Shale-2 (0.45 – 4.5 mm)	4-26
Figure 14 Phosphorus equilibrium isotherm for AO _{CMpcc} and CM _{pcc} (0.85 – 2 mm).....	4-26
Figure 15 Phosphorus adsorption kinetics for AO _{CMc} (0.85 - 2 mm).....	4-27
Figure 16 Phosphorus adsorption kinetics for AO _{CMc} (2 – 4.75 mm)	4-27
Figure 17 Phosphorus adsorption kinetics for AO _{CMp} (2 – 4.75 mm)	4-28
Figure 18 Phosphorus adsorption kinetics for Expanded clay substrate (0.85 – 2 mm).....	4-28
Figure 19 Phosphorus adsorption kinetics for Expanded clay substrate (2 – 4.75 mm).....	4-29
Figure 20 Phosphorus adsorption kinetics for Pumice substrate (2 – 4.75 mm)	4-29
Figure 21 Phosphorus adsorption kinetics for Bioretention soil media (0.001 – 10 mm)	4-30
Figure 22 Phosphorus adsorption kinetics for UCF-1 (0.5 – 4.75 mm)	4-30
Figure 23 Phosphorus adsorption kinetics for UCF-2 (0.85 – 10 mm)	4-31
Figure 24 Phosphorus adsorption kinetics for Expanded Shale -1 (2 - 10 mm)	4-31
Figure 25 Phosphorus adsorption kinetics for Expanded Shale - 2 (0.45 – 4.5 mm)	4-32
Figure 26 Phosphorus adsorption kinetics for AO _{CMpcc} and CM _{pcc} (0.85 – 2 mm)	4-32
Figure 27 Phosphorus breakthrough test for AO _{CMc} (0.85 – 2 mm)	4-33
Figure 28 Phosphorus breakthrough test for AO _{CMc} (2 – 4.75 mm)	4-33
Figure 29 Phosphorus breakthrough test for AO _{CMp} (2 – 4.75 mm)	4-34
Figure 30 Phosphorus breakthrough test for Pumice substrate (2 – 4.75 mm).....	4-34
Figure 31 Phosphorus breakthrough test for Bioretention soil media(0.001 – 10 mm)	4-35

Figure 32 Phosphorus breakthrough test for UCF-1 (0.5 – 4.75 mm).....	4-35
Figure 33 Phosphorus breakthrough test for UCF-2 (0.85 – 10 mm).....	4-36
Figure 34 Phosphorus breakthrough test for Expanded Shale-1 (2 – 10 mm).....	4-36
Figure 35 Phosphorus breakthrough test for Expanded Shale - 2 (0.45 – 4.5 mm).....	4-37
Figure 36 Phosphorus breakthrough test for AOCM _{pcc} and CM _{pcc} (0.85 – 2 mm).....	4-37
Figure 37 Phosphorus Adsorption-Desorption test for UCF-1 media (0.5 – 4.75 mm). The distance and area between the data and the C/C_0 line = 1.0 represents phosphorus desorption in terms of concentration and mass, respectively.	4-38
Figure 38 Phosphorus Adsorption-Desorption test for UCF-2 (0.85 – 10 mm). The distance and area between the data and the C/C_0 line = 1.0 represents phosphorus desorption in terms of concentration and mass, respectively.	4-38
Figure 39 Phosphorus Adsorption-Desorption test for Expanded Shale -1 (2 - 10 mm). The distance and area between the data and the C/C_0 line = 1.0 represents phosphorus desorption in terms of concentration and mass, respectively.	4-39
Figure 40 Phosphorus Adsorption-Desorption test for Expanded Shale -2 (0.45 – 4.5 mm). The distance and area between the data and the C/C_0 line = 1.0 represents phosphorus desorption in terms of concentration and mass, respectively.	4-39
Figure 41 Phosphorus Adsorption test for AOCM _C (2 – 4.75 mm). This media did not exhibit any desorption and all data are below the C/C_0 line = 1.0; therefore the distance and area between the data and the C/C_0 line = 1.0 represents phosphorus adsorption in terms of concentration and mass, respectively.	4-40

INTRODUCTION

Phosphorus is recognized as a primary nutrient discharged in excess to surface waters and ground water; and such enrichment by phosphorus is regarded as a main reason for eutrophication. The aesthetic, chemical and ecological degradation of receiving waters as a result of rainfall-runoff discharges enriched with phosphorus (nitrogen notwithstanding) has led to significant public stakeholder concerns and regulation intended to mitigate the significant environmental and ecological impacts (Bowes et al. 2005). Nutrients are generated from nonpoint (diffuse) biogenic and anthropogenic sources such as vegetation, fertilizers, detergents, animal waste, infrastructure, and traffic; as well as point sources such as domestic and industrial sewage waters, and transferred into natural and built environs through many different pathways (Ray 1997; Waschbusch et al. 1999). The built environs as the impervious interface that transforms rainfall to runoff, is a major nonpoint source and pathway of nutrients. Runoff can contain high phosphorus concentrations that can accelerate eutrophication for many receiving waters (USEPA 1993; Dean et al. 2005; Kim et al. 2008). There has been much work in Europe and North America to reduce nutrient point sources from industrial and municipal sewage, but nonpoint source control of urban rainfall-runoff, is still of major concern and nonpoint sources are more difficult to manage than wastewater (Duda, 1993; Sansalone 2005).

As a stormwater pollutant load, many methods of controlling phosphorus have been investigated, such as constructed wetland system (Gervin and Brix 2001; Seo et al. 2005), filtration, infiltration and detention/retention basins (Bartone and Uchirin 1999; Dechesne et al. 2005; Hsieh et al. 2007), in-situ filtration (Sansalone and Teng 2004, Teng and Sansalone 2004), storm-treat systems (sedimentation tank) (Sonstrom et al. 2002), urban wet detention ponds (Wu et al. 1996; Comings et al. 2000; Wang et al. 2004), and vegetative controls (Barrett et al. 1998). Whether identified, explicitly or not, the basic mechanisms in these studies are sedimentation and filtration of particulate matter (PM) with the potential of adsorption either during or prior to sedimentation or filtration. Other studies explicitly demonstrated the role of adsorption during the filtration process onto oxide-coated media (Sansalone and Teng 2004). While sedimentation occurs in all unit operations, whether by design or otherwise, designs based strictly on sedimentation such as with detention/retention basins, tanks or even hydrodynamic separators, designed based on surface overflow rate concepts are challenged in populated urban area since there is generally a requirement of large operational area and volume, if suspended PM and the associated phosphorus requires separation. Additionally, sedimentation is a physical mechanism intended to separate PM, not soluble phosphorus, unless there is partitioning from solution to PM during sedimentation. However, while partitioning does occur in the sedimentation process, there is also the potential for re-partitioning back to the water column due to changing water chemistry conditions during runoff storage. While shallow basins with large surface areas can have significant gas transfer with the atmosphere, thereby remaining oxic, below-grade systems such as tanks, tunnels, and storage pipelines do not allow such exchange, with anoxic/anaerobic conditions that can occur within 48 hours. Another very real challenge for these basins is the potential of contaminating underlying soil and groundwater, whether with phosphorus species, metals more mobile nitrogen species such as nitrate. The potential for groundwater and natural spring contamination in karst areas such as central and north Florida is well-recognized and significant (Arias et al. 2006). Furthermore, beyond Florida, the direct or proximate communication between runoff stored in an unlined basin and groundwater or in karst conditions,

is common in nearly 25% of the United States. Despite these challenges, if such basins or tanks are properly designed, operated, and frequently maintained (a rare occurrence) such systems can be effective for the temporary separation of phosphorus as well as the long-term management of runoff PM sludge containing phosphorus and other constituents that partition during the sedimentation and storage phase. Ignoring the potential for phosphorus separation, uptake and burial, the importance of above-ground basins, when properly designed, operated and maintained, is the ability to provide some degree of hydrologic restoration through infiltration, evaporation and storage. However, given the difficulty of such basins to capture high levels of soluble phosphorus, the potential of phosphorus leaching as vegetation dies, the potential of phosphorus migration to karst areas, and generally large basin surface area requirements for separation of suspended PM exist; requires adsorptive-filtration as secondary treatment.

More recently manufactured filtration-type unit operations are becoming more widely used in urban conditions because of their smaller footprint and their ability to separate suspended PM albeit at lower surface loading rate. For a filter the surface loading rate is based on the “representative” filter surface area, depending on the direction of flow. For example for an axial prismatic filter, the surface area is the cross-sectional area which is orthogonal to flow. For a radial cartridge filter with inward radial flow the two-dimensional flow is radial (ignoring the parabolic curvature in the third dimension) and therefore the surface area is the representative radial surface (at the geometric mean radius). A major consideration for filtration systems, even stormwater media systems intended to function with adsorption as a primary mechanism is clogging (excessive head loss with filter ripening). This is of particular concern for passive filters, driven primarily by head differences and gravity. While mechanisms such as filter ripening can be beneficial for adsorptive-filtration performance; progressive filter ripening results in increasingly non-linear head loss and eventual clogging for the filter.

Filtration systems (engineered filters, bioretention, infiltration trenches) that are not properly designed or maintained commonly result in premature clogging. Much of this premature failure can be tied to a lack of understanding of filtration mechanisms for urban rainfall-runoff or snowmelt loadings, the lack of upstream primary treatment that lowers primary effluent PM levels to the range of 20 to 50 mg/L (Cristina and Sansalone 2003) with sustainable filters loaded by an influent less than 20 to 30 mg/L without regular on-line backwashing; or simply improper filter and upstream unit operation design. An adsorptive-filter will fail (clogging, or poor adsorption and/or filtration) without proper stormwater conditioning by a primary unit operation or the wrong media selection, such as sand or perlite. Five decades of unit operation and process knowledge gained from the wastewater and drinking water industries should be kept in mind when designing and maintaining stormwater filters; including the benefits of flow equalization. It is noted that adsorptive-filtration is a secondary-tertiary unit operation and as such requires upstream conditioning. Additionally, there are a plethora of media that are promoted in the marketplace may be well-intentioned from either a business point of view or from an intuitive point of view, but simply cannot achieve effective phosphorus or metals removal efficiency (Bubba et al. 2003; Liu et al. 2005; Kim et al. 2008). To meet current and expected stormwater chemistry treatment requirement, advanced in-situ phosphorus treatment technologies and amendment materials have to be developed for urban rainfall-runoff. These technologies represent a combination of engineered media, an engineered system, and quantitative operation and maintenance (O&M) practices that synthesizes influent chemistry and loadings, effluent

requirements and the quantitative behavior of the engineered media and system. This chapter focuses on the engineered media component of such unit operations/processes.

Many filtration media types were developed with certain purposes. For example, manganese oxide media, including manganese coated polymeric media (MOPM) and manganese oxide coated cementitious media (MOCM) were evaluated by Liu and Sansalone (2004a, 2004b, 2005a, 2005b) in sorptive filtration system as a rainfall-runoff or snowmelt unit operation and process media for treatment metal species. Birnessite-coated and cryptomelane-coated forms of manganese, as well as iron oxide coated media were tested by Liu et al. (2001a, 2001b), Sansalone (1999a, 1999b), Li et al. (1999). Sansalone and Buchberger (1995) utilized filtration and exfiltration systems for treatment of metals in runoff that included iron oxide coated media under aerobic conditions. Results indicate a significant capacity for metal species by such media, with the surface chemistry favoring the adsorption of metal species with selected oxides of iron favorable to phosphorus. Also it was from these studies that specific form of oxide, specific surface area and surface charge were found to be critical relative to performance capability.

In order to remove phosphorus in rainfall-runoff, as well as receiving water bodies, aluminum oxide, iron oxide, or a combination of these oxides are utilized (Kim et al. 2008; Liu et al. 2005). In particular, aluminum oxide can be used in combination with porous, high surface area substrate or calcium-containing substrate such as concrete to produce an effective adsorptive media. While plain concrete media is temporarily effective, the mass transfer is that of precipitation resulting in an unstable build up of phosphorus on the media surface with such physical precipitate build-up being sloughed off periodically into the effluent. This result was also observed for metal precipitates on concrete media (Liu et al. 2005).

To date very few quantitative tools evaluating adsorptive-filter media for phosphorus adsorption have been implemented. Additionally continues to be limited information available and divergent performance claims for phosphorus removal for both manufactured and natural filtration systems using un-quantified media. Media applications that do exist with reported information tend to experience high performance variability (Davis et al. 2006, Heieh et al. 2007) or result in exporting phosphorus, or leaching of other indices such as metals or pH. Again, these challenges are due to the limited quantitative information of the behavior of the filter material. Moreover, availability and rapid replacement costs are concerns when media of lower capacity or longevity is employed for commercial use. Some materials have abundant sources and relative low cost, such as sand, peat, perlite or organic based materials made from different types of waste, but their performance for phosphorus removal does not satisfy the requirements imposed by regulatory agencies or public communities or meet TMDLs under many conditions.

The purpose of this study is to quantitatively examine the phosphorus removal performance of filter media. These filter media were examined based on standard engineering methods of adsorption phenomena and requirements of adsorption behavior for media. These requirements include a quantitative description of:

- (1) equilibrium isotherms (how much phosphorus can media uptake),
- (2) kinetics (how rapidly can phosphorus be taken up by the media), and
- (3) breakthrough (under flow-through hydraulic loading rates, what is the removal level and how long does the media lasts before performance diminishes, i.e. maintenance frequency).

Successful deployment of any media system requires the comparison of media behavior on a rigorous and equal basis through these three quantitative descriptions; in addition to desorption or leaching quantification. With such a methodology, media comparisons are clearly illustrated as a series of equilibria, kinetics and breakthrough results; providing a much-needed rigorous and defensible basis for to predict media performance.

MATERIALS AND METHODOLOGY

Engineered Soil Media Preparation

Materials:

Clay, a blowing agent and water are necessary materials that were used for raw substrate preparation. Aluminum nitrate was used for media coating.

Methodology:

Raw clay substrate

Dry clay was measured in appropriate quantities and well mixed with water using a drill mixer. The mixture is allowed to stand for a short while to generate enough pores. The well developed mixture with pores due to the effect of blowing agent was then transferred to an electric kiln. The mixture is fired in the kiln at a predetermined heating procedure.

By firing the mixture in the kiln, all the moisture is evaporated and a dry raw substrate with a large number of pores is obtained. This raw substrate is crushed to finer particles using an crusher (400 lb/hour). The soil media so obtained after crushing is passed through a series of sieves. Four particle size gradations namely particles > 4.75 mm, 2 ~ 4.75 mm, 0.85 ~ 2 mm, and < 0.85 mm were obtained using the appropriate size sieves. The soil media size selection was based on the filtration parameters such as adsorption capability, hydraulic conductivity and head loss (2 ~ 4.75 mm and 0.85 ~ 2 mm).

Coating

$\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ was used to prepare the coating solution. 1 M Al salt solution was mixed with washed dry media substrate in batch, until the substrate was just submerged and heated to dryness at 105°C or higher. After cooling the media is rinsed to a pH range of 5. The final media (AOCM_c) is ready to use.

Engineered Soil Media Tests

Materials:

Phosphorus solution

A phosphorus stock solution was prepared by dissolving anhydrous potassium dihydrogen orthophosphate (KH_2PO_4) powder (Analytical reagent grade, Fisher Scientific) into de-ionized (D.I.) water. The stock solutions were calibrated to 100.00 mg/L and 1000.00 mg/L concentrations and then utilized for standard solutions with DI water as necessary.

Media as Adsorbents

A wide range of candidate media were selected and tested in this study. The major composition and size of the adsorbents were summarized in Table 1. Three different aluminum oxide-coated media (AOCM) were prepared and examined, with soil-based clay media (AOCM_c), pumice (AOCM_p) and concrete (AOCM_{pcc}) as the raw substrate materials, respectively. The corresponding uncoated substrates of these media were also tested as controls.

The adsorbents include:

- | | |
|--|---|
| 1. AOCM _c (0.85 – 2 mm) | (aluminum oxide coated clay media) |
| 2. AOCM _c (2 – 4.75 mm) | (aluminum oxide coated clay media) |
| 3. Expanded clay substrate (0.85 – 2 mm) | (clay substrate only of AOCM) |
| 4. Expanded clay substrate (2 – 4.75 mm) | (clay substrate only of AOCM) |
| 5. AOCM _p (2 – 4.75 mm) | (aluminum oxide coated pumice media) |
| 6. Pumice substrate (2 – 4.75 mm) | (pumice substrate only) |
| 7. AOCM _{pcc} (0.85-2 mm) | (aluminum oxide coated concrete media) |
| 8. Concrete substrate (0.85 – 2 mm) | (concrete substrate only) |
| 9. Bioretention soil media (1m – 10 mm) | (commercial mixture for Prince George's County, Maryland P-index = 25) |
| 10. UCF - 1 (0.5 – 4.75 mm crumbs) | (proprietary mix including tire crumbs) |
| 11. UCF -2 (0.85 – 10 mm crumbs) | (supplied by UCF through FDEP request)
(proprietary mix including tire crumbs) |
| 12. Expanded shale - 1 (2 – 10 mm) | (supplied by UCF through FDEP request)
(commercial expanded shale) |
| 13. Expnded shale -2 (0.45 – 4.5 mm) | (commercial expanded shale) |

Methodology:

The total dissolved phosphate (TDP) adsorption characterization experiments consist of an adsorption equilibrium study, an adsorption kinetic study, a one-dimensional column breakthrough study and a desorption study. Phosphorus was measured by a HACH DR/5000 Spectrophotometer using PhosVer 3 Ascorbic Acid Method (Standard Method 1998). The ascorbic acid method was used to detect orthophosphate and a persulfate digestion was used to convert any other forms of phosphorus to orthophosphate. The amount of adsorbate that was adsorbed on the adsorbent was then calculated from the difference between the initial and equilibrium solute concentrations. A multi-meter (Orion 290A combination electrode) was

calibrated using a 3-point calibration curve with reference units at a pH of 4, 7, and 10. All measurements were duplicated and repeatability was assured with experimental error at $\pm 5\%$.

Adsorption Equilibrium (Isotherm) Study

In order to estimate static or dynamic adsorption capacity, it is essential to have information on adsorption equilibrium to begin to quantify how much phosphorous can be adsorbed (equilibrium capacity). A common way to represent the adsorption equilibrium is the isotherm from which the amount of phosphorus species adsorbed under a given set of chemistry conditions can be determined for a given media. In the present study, the specific working phosphorus concentration utilized to obtain isotherm data are: 0, 0.05, 0.5, 1.0, 2.5, 10, 25 and 50 mg/L. It is noted that a single point measurement is not an isotherm. Just as a single sample cannot represent the characteristics of a runoff event; a single point measurement cannot represent the equilibrium capacity except at that specific point. Ionic strength was fixed at 0.01 M using KCl. Solution pH was adjusted and maintained at 7.0 throughout experiments by dropwise addition of HCl or NaOH. 0.5 g adsorbent and 40 ml of phosphate solution were added in a 50 ml polyethylene centrifuge tube. The mixture was mixed on a horizontal bench shaker at a rate of 100 rpm allowing adsorption to take place at 20°C until equilibrium reached, usually 24 hr. The content in the centrifuge tube was then filtered through 0.45 μm syringe filter and the total dissolved phosphate concentration in the filtrate was measured using a spectrophotometer (HACH, DR5000). The amount of adsorbate that was adsorbed on the adsorbent was then calculated from the difference between the initial and equilibrium solute concentrations.

Adsorption Kinetic Study

To determine how rapidly a media will adsorb phosphorous, the kinetics of adsorption were investigated in the recirculating flow-through reactor. The sorbent solution ratio was 2 L to 20 g of media. The ionic strength was set at 0.01 M as KCl. The pH was maintained at 7. The surface loading rate was kept as 40 L/min-m² throughout the experiment. The surface loading rate was chosen based on real-time range of rainfall-runoff surface loading. For example, in Sansalone and Buchberger (1997)'s study, a surface loading rate of 50 L/min-m² is utilized for the peak of 1-year return event at an experimental site treating overland flow. Usually, the surface loading rate should range within 20 to 60 L/min-m². While the return event is a dated concept, it has heuristic value as a design yardstick. In this study, a representative value of 40 L/min-m² was maintained. Duplicate samples of 10 mL were collected at predetermined time intervals from the sampling port. The sample solution was then filtered through 0.45 μm filter and total dissolved phosphate concentration was determined using a spectrophotometer (HACH, DR5000). The experimental set-up of kinetic study is shown in Fig. 1.

Column Breakthrough Study

The column breakthrough study is a performance indicator (i.e. media bed service life), which is based on a predetermined level of performance (effluent concentration). Breakthrough is critical for prediction of how the media will perform and how frequently it needs to be replaced or maintained to ensure the desired performance is achieved. Breakthrough occurs when the predetermined removal performance is no longer achievable as a result of diminished

adsorption capacity (or effluent concentration). Breakthrough is quantified either on the number of pore volumes (PV) (volume of fluid equivalent to the hydraulically-available pore space of the media system); or the number of bed volumes (media plus pore volume). A Bed Volume (BV) of solution is equal to the volume of absorbent media and macroscopic pore volume contained in the media that are utilized, hence the media performance is measured based on the number of Bed Volumes (N_{BV}) that flow through the media system, in these tests a prismatic axial column.

Phosphorus adsorption for different adsorbents under continuous flow-through loading was investigated using a Teflon PFA column. A known mass of dry media was packed inside the column to absorb the phosphorus from the flow-through solution. Influent P concentration (C_0) was set up as 0.5 mg/L. The constant influent feed to the column is supplied by a peristaltic pump. The influent pH was adjusted to 7.0 and controlled throughout the experiment. Samples were collected at regular time intervals and effluent TDP (total dissolved phosphate) concentration (C_e) was then determined. The column studies were terminated when the media reached exhaustion (V_{exh}) i.e. C_e/C_0 equal to 0.9 (10% removal rate). The experimental set-up of column breakthrough study is shown in Fig. 2.

Modeling

In order to quantitatively evaluate the media performance, optimize the design of sorption systems, and explain the physical-chemical phenomena it is necessary to establish an appropriate mathematical model to describe the experimental data. Often mechanistic or statistical explanations are ignored in media evaluations.

The amount of adsorption at equilibrium, q_e [mg/g], was computed as follows:

$$q_e = \frac{(C_0 - C_e)V}{W} \quad (1)$$

C_0 and C_e are the initial and equilibrium solution concentrations [mg/L], respectively; V the volume of the solution [L] and W the weight of adsorbent used [g].

Adsorption Isotherm Modeling

Isotherm equations can represent the experimental data (equilibrium capacity) in a concise manner and such equations can also be used to predict behavior under conditions that have not been investigated. An isotherm model that has been commonly utilized to model clays and other heterogeneous media surfaces is the Freundlich isotherm. The Freundlich isotherm is often used for media with heterogeneous surfaces and surface affinities.

$$q = K_F C^{\frac{1}{n}} \quad (2)$$

K_F is the Freundlich constant and n the Freundlich exponent and the reciprocal is indicative of adsorption intensity and C_e the concentration of adsorbate in solution at equilibrium [mg/L]. The experimental data were fit to the Freundlich model using non-linear regression analysis.

The Freundlich expression has the form of a power law expression and was initially regarded as a completely empirical isotherm. However, for a mono-component system, the Freundlich isotherm can be obtained theoretically when an exponential distribution of adsorption energy is assumed. Alternatively, isotherm equations could also be developed from theory, based on kinetics for the interactions with the media surface, dissolved species and surface-complexed species.

Adsorption Kinetic Modeling

The study of adsorption kinetics describes the solute uptake rate, which evidently controls the residence time of adsorbate uptake at the solid-solution interface. Here, the kinetics of phosphorus adsorption on the media was analyzed using a transformation of second-order potential driving kinetic model developed by Liu et al (2005). The conformity between experimental data and model predicted values was evaluated by coefficients of determination (R^2), although a variety of statistical test results can be examined.

The differential equation:

$$\frac{dq_t}{dt} = k(q_e - q_t)^2 \quad (3)$$

Integrating Eq. (3) and applying the boundary conditions, gives:

$$\frac{1}{(q_e - q_t)} = \frac{1}{q_e} + kt \quad (4)$$

Eq. (4) can be rearranged to obtain the expression for q_t :

$$q_t = \frac{q_e t}{\frac{1}{q_e k} + t} \quad (5)$$

k is the equilibrium rate constant of pseudo second-order adsorption [g/mg-min].

Breakthrough Studies Modeling

The adsorption data from column studies was analyzed using the Thomas model as follows:

$$\frac{C_e}{C_0} = \frac{1}{1 + \exp\left[\frac{K_T(q_0 m - C_0 V)}{Q}\right]} \quad (6)$$

C_e is the effluent adsorbate concentration [mg/L], C_0 the influent adsorbate concentration [mg/L], K_T the Thomas rate constant [L/min-mg], q_0 the maximum solid phase concentration of

the solute [mg/g], m the mass of the adsorbent [g], V the throughput volume [L], and Q is the volumetric flow rate [L/min].

RESULTS AND DISCUSSION

Adsorption Equilibrium Isotherm Study

These results detail the summary provided in a quarterly report on media. Adsorption isotherms express the variation of specific adsorption with equilibrium concentrations of adsorbate in bulk solutions at constant temperature (Liu et al 2005). Several relationships can be used to describe the experimental data. Freundlich isotherm has a theoretical assumption of heterogeneous surface properties and was utilized to simulate the data obtained from the isotherm experiments, given the heterogeneous surface properties of the different adsorbents. Table 1 summarizes the Freundlich model constants and correlation determination R^2 of the fitness. Fig. 3 through Fig. 12 depict the adsorption isotherm for phosphorus on the media respectively, as well as the theoretical Freundlich equations. In all the cases, R^2 is no less than 0.94. In the Freundlich isotherm equation, the coefficient K_F is an indication of adsorption capacity and n reflects the steepness of the curve. From Table 1, it can be found that AO CM_c (0.85 – 2 mm) had an adsorption capacity of 3.63 mg/g, followed by AO CM_{pcc} (1.32 [mg/g]) and AO CM_c (2 – 4.75 mm, 1.05 [mg/g]), respectively. Generally, oxide coated media had significantly higher adsorption capacities than all the other media or media substrates. It was observed that the phosphate adsorption capacity of the clays be related to both the alumina – silica molecular ratio of the clay minerals and the alumina content of clay media. For example, a basic adsorption reaction of phosphorus with AO CM_c is the chemical adsorption reactions between phosphorus ions in solution and alumina surface groups on the clay. The significance of such reaction was also verified by the free energy calculations for the adsorption of phosphate on Al_2O_3 .

In addition, it can be found that adsorption capacity of different adsorbents can vary from 3.63 mg/g (AO CM_c) to a very low value of 0.0009 mg/g (UCF – 2). The more than 4000 times difference further demonstrates the diverse performance of the media being deployed and the necessity of quantitatively examination and comparison of different adsorbents. Results illustrate that the aluminum-coated clay media significantly outperformed all other media with respect to the highest equilibrium capacity.

Adsorption Equilibrium Kinetic Study

Fig. 13 through Fig. 22 illustrates the results obtained by kinetics experiments for the adsorption kinetics of phosphorus onto different adsorbents. A second order potential driving kinetic model was used to simulate the behavior (Liu et al 2005). As with the isotherm results, the time profiles of phosphorus uptake for the aluminum oxide and iron oxide media are similar: a single, smooth and continuous curve leading to saturation, with significantly higher rates of adsorption than all other media. The smooth and continuous curvatures may be an indication of the possible monolayer coverage of phosphorus on the surface of the adsorbents. A lumped analysis of kinetic data is sufficient for adsorption system design purpose and the simplicity of

the mathematical equation makes it convenient for practical use. The fit of the model is examined using a coefficient of determination.

The kinetic study results in the figures and in Table 2 are consistent with results of adsorption isotherm. The coated media illustrates much shorter equilibrium time and higher removal efficiency. For instance, q_e is 0.096 mg/g and 0.013 mg/g for AOCM_c (0.85 – 2 mm) and AOCM_c substrate (0.85 – 2 mm), respectively. The only difference between the two adsorbents is the aluminum oxide coating, while the q_e of the coated one is more than 7 times higher than that of the corresponding raw substrate. This result clearly reinforces the effectiveness of aluminum oxide coating for the improvement of media substrate adsorption capacity.

In addition, the data of UCF – 1 and UCF – 2 media cannot be fit with a potential driving kinetics model since negative q_e was obtained from the experiments, resulting from the phosphorus actually being desorbed from the UCF adsorbents.

Breakthrough Study

For one-dimensional column studies, the total dissolved phosphorus (TDP) concentration tested was 0.5 mg/L and the pH of the feed solution was 7.0. The mass of media used in the tests were determined by a comprehensive consideration of media capacity, L/D ratio of the reactor, time scale of experiments and experimental set-up configuration as well. Fig. 23 through Fig. 32 plots the ratio of effluent to influent phosphate concentration versus the flow through the column (expressed as number of bed volume, N_{BV})., the breakthrough curve cannot be obtained for all of the media tested due to poor behavior of the low capacity media. For bioretention soil media, the experiment run were difficult due to erosion of the clayey and fine silty fraction of the media. Breakthrough results are summarized in Table 3 and 4.

Again, uncoated media exhibit poor adsorption capacity and the performance of the UCF and expanded shale had even lower capacity. C_e/C_0 ratio is larger than 1, indicating that on the contrary of removing phosphorus from solution, these media release, or export phosphorus themselves. For the media showing good phosphorus removal capacity, the breakthrough was reached ($C_e/C_0 = 0.1$) from almost immediately to about 600 N_{BV} (AOCM_c (0.85 – 2 mm)). However, several media exhibited very high exhaustion capacity: 1000 N_{BV} for AOCM_{pcc} and CM_{pcc} and 2500 N_{BV} for AOCM_p, respectively. Moreover, a small break on the breakthrough curve may be observed for some media, which could be resulted from the instability when the media capacity was reached or slight desorption of phosphorus.

As a result of the isotherm, kinetics and breakthrough results, field deployment of clay-based AOCM was chosen. Field testing is described in later chapters. An equally viable choice would be concrete-based AOCM once the recycled or crushed concrete was carbonated.

Desorption Study

Breakthrough curves as well as desorption experimental data for the tested media are shown in Figures 33 to 37. It can be observed that for UCF and ESF media breakthrough is reached within 20 bed volumes. Moreover, all the four media exhibit certain degree of P leaching during

the breakthrough experiment which was exemplified as a higher effluent concentration compared with the initial P concentration. In such conditions, new adsorbent with the same mass was loaded into the reactor after BTC tests to evaluate desorption or leaching behavior of the media. Both UCF and ESF media release P. By comparison, AOCM showed much better performance without any desorption. With respect to all categories of media behavior, the clay-based soil media outperformed all other media tested and was chosen for field testing.

REFERENCES

- Arias M., Da Silva-Carballal J., Garcia-Rio L., Mejuto J., Nuñez A. (2006). "Retention of phosphorus by iron and aluminum-oxide-coated quartz particles." *J. of Colloid and Interface Sci.*, 295, 65-70.
- Barrett, M. E., Walsh, P. M., Malina, J. F., and Charbeneau, R. J. (1998). "Performance of Vegetative Controls for Treating Highway Runoff." *J. Environ. Eng.*, 124(11), 1121-1128.
- Bartone, D. M., and Uchirin, C. G. (1999). "Comparison of Pollutant Removal Efficiency for Two Residential Storm Water Basins." *J. Environ. Eng.*, 125(7), 674-677.
- Braja M. D. (2001) "Principles of Geotechnical Engineering" 5th edition, Thomson Learning
- Bowes, M.J., House, W.A., Hadgkinson, R.A. and Leach, D.V., 2005. Phosphorus-Discharge Hysteresis During Storm Events Along a Rivers Catchment: the River Swale, UK. *Water Res.*, 29, 751-762.
- Bubba, M. D., Arias, C. A., and Brix, H. (2003). "Phosphorus Adsorption Maximum of Sands for Use as Media in Subsurface Flow Constructed Reed Beds as Measured by the Langmuir Isotherm." *Water Res.*, 37, 3390-3400.
- Comings, K. J., Booth, D. B., and Horner, R. R. (2000). "Storm Water Pollutant Removal by Two Wet Ponds in Bellevue, Washington." *J. Environ. Eng.*, 126(4), 321-330.
- Cristina C. and Sansalone J.J., (2003). "First Flush, Power Law and Particle Separation Diagrams For Urban Storm-Water Suspended Particulates", *J. of Environmental Engineering*, 129 (4), 298-307.
- Davis A. P., Shokouhian M., Sharma H. and Minami C. (2006). "Water Quality Improvement through Bioretention Media: Nitrogen and Phosphorus Removal", *Water Environ. Res.*, 78 (3), 284 - 293
- Dean, C.M., Sansalone, J.J., Cartledge, F.K., Pardue, J.H., 2005. Influence of hydrology on rainfall-runoff metal element speciation. *Journal of Environmental Engineering-ASCE* 131(4), 632-642.
- Dechesne, M., Barraud, S., and Bardin, J. P. (2005). "Experimental Assessment of

Stormwater Infiltration Basin Evolution.” *J. Environ. Eng.*, 131 (7), 1090-1098.

Duda A.M., 1993. Addressing nonpoint sources of water pollution must become an international priority. *Water Sci. Technol.*, 28, 1-11.

Hsieh C. H., Davis A. P. and Needelman B. A. (2007). “Bioretention Column Studies of Phosphorus Removal from Urban Stormwater runoff” *Water Environ. Res.*, 79 (2), 177 - 184

Gervin, L., and Brix, H. (2001). “Removal of Nutrients from Combined Sewer Overflows and Lake Water in a Vertical-Flow Constructed Wetland System.” *Water Sci. Technol.*, 44(11-12), 171-176.

Kim J-Y., Ma J., Howerter K., Garofalo G., and Sansalone J.J., “Interactions Of Phosphorus With Anthropogenic And Engineered Particulate Matter As A Function Of Mass, Number And Surface Area”, *Urban Water Systems, Monograph 11*, Edited by James W. CHI Publications, Guelph, Ontario, 20 pp. Feb. 2008

Li Y, Buchberger S. G., and Sansalone J. J. (1999). “ Variable Saturated Flow in A Storm Water Partial Exfiltration Trench.” *J. Environ. Eng.*, 125 (6), 556-565

Liu D., Sansalone J. J. and Cartledge F. K. (2005). “Adsorption Kinetics for Urban Rainfall-Runoff Metals by Composite Oxide-Coated Polymeric Media.” *J. Environ. Eng.*, 131 (8), 1168-1177

Liu D., Sansalone J. J. and Cartledge F. K. (2005). “Comparison of Sorptive Filter Media for Treatment of Metals in Runoff.” *J. Environ. Eng.*, 131 (8), 1155-1167

Liu D., Sansalone J. J. and Cartledge F. K. (2004). “Adsorption Characteristics of Oxide Coated Polymeric Media ($\rho_s < 1.0$) for Stormwater Treatment: Batch Equilibria and Kinetics.” *J. Environ. Eng.*, 130 (4), 374-382

Liu D., Sansalone J. J. and Cartledge F. K. (2004). “Adsorption Characteristics of Oxide Coated Polymeric Media ($\rho_s < 1.0$) for Storm Water Treatment: Equilibria and Kinetics Models.” *J. Environ. Eng.*, 130 (4), 383-391

Liu D., Teng Z. Sansalone J. J. and Cartledge F. K. (2001). “Surface Characteristics of Sorptive-Filtration Storm Water Media: Low Specific Gravity ($\rho_s < 1.0$) Oxide Coated Floating Media.” *J. Environ. Eng.*, 127 (10), 868-878

Liu D., Teng Z., Sansalone J. J. and Cartledge F. K. (2001). “Surface Characteristics of Sorptive-Filtration Storm Water Media: Higher Specific Gravity ($\rho_s > 1.0$) Oxide Coated Fixed Media.” *J. Environ. Eng.*, 127 (10), 879-888

Ray, H. (1997). “Street dirt as a phosphorus source in urban stormwater.” *Ph.D. dissertation*, University of Alabama at Birmingham, 125.

- Sansalone J. J. (1999). "Adsorptive-Infiltration of Metals in Urban Drainage-Media Characteristics." *Sci, Tot. Environ.*, 235 (1-3), 179-188
- Sansalone J. J. (1999). "In-situ Performance of a Passive Treatment System for Metal Elements in Urban Surface Waters." *Wat. Sci. Tech.*, 39 (2), 193-200
- Sansalone J. J. and Buchberger S. G. (1995). "An Infiltration Device as a Best Management Practice for Pollutants in Highway Runoff." *Wat. Sci. Tech.*, 32 (1), 119-125
- Sansaone J. J., Koran J., Buchberger S. G. and Smithson J. (1998). "Physical Characteristics of Highway Solids Transported During Rainfall." *J. Environ. Eng.*, 124 (5), 427-440
- Sansalone, J.J., and Teng, Z. (2005). "Transient Rainfall-Runoff Loadings to a Partial Exfiltration System: Implications for Urban Water Quantity and Quality." *J. Environ. Eng.*, 130(9), 990-1007.
- Sansalone J.J. (2005), "Perspective On The Synthesis Of Unit Operations And Process (UOP) Concepts With Hydrologic Controls For Rainfall-Runoff", *J. of Environmental Engineering*, 131 (7): 995-997.
- Seo, D. C., Cho, J. S., Lee, H. J., and Heo, J. S. (2005). "Phosphorus Retention Capacity of Filter Media for Estimating the Longevity of Constructed Wetland." *Water Res.*, 39(11), 2445-2457.
- Sonstrom, R. S., Clausen, J. C., and Askew, D. R. (2002). "Treatment of Parking Lot Stormwater Using a StormTreat System." *Environ. Sci. Technol.*, 36(20), 4441-4446.
- Teng, Z., and Sansalone, J.J. (2004). "In situ partial exfiltration of rainfall runoff. II: particle separation." *J. Environ. Eng.*, 130(9), 1008-1020.
- U.S. Environmental Protection Agency (1993). "Handbook: Urban Runoff Pollution Prevention and Control Planning." *EPA 1625/R-93/004*, Office of Research and Development, Washington, DC.
- Visvanathan, C., Werellagama, D. R. I. B., and Aim, R. B. (1996). "Surface Water Pretreatment Using Floating Media Filter." *J. Environ. Eng.*, 122(1), 25-33.
- Wang, G. T., Chen, S., Barber, M. E., and Yonge, D. R. (2004). "Modeling Flow and Pollutant Removal of Wet Detention Pond Treating Stormwater Runoff." *J. Environ. Eng.*, 130(11), 1315-1321.
- Waschbusch, R. J., Selbig, W. R., and Bannerman, R. T. (1999). "Sources of Phosphorus in Stormwater and Street Dirt from Two Urban Residential Basins In Madison, Wisconsin, 1994–95." *Water-Resources Investigations Report 99-4021*, U.S. Geological Survey, Middleton, Wisconsin.

Wu, J. S., Holman, R. E., and Dorney, J. R. (1996). "Systematic Evaluation of Pollution Removal by Urban Wet Detention Ponds." *J. Environ. Eng.*, 122(11), 983-988.

Table 1 Freundlich Isotherm Model Constants

Media		Freundlich Model		
Adsorbents	Diameter (mm)	K_F	n	R^2
AOCM _c (clay)	0.85 - 2	3.63	1.54	0.94
AOCM _c (clay)	2 – 4.75	1.05	2.74	0.96
Expanded clay substrate	0.85 - 2	0.018	1.27	0.95
Expanded clay substrate	2 – 4.75	0.0077	1.57	0.98
AOCM _p	2 – 4.75	0.39	3.8	0.96
Pumice substrate	2 – 4.75	0.012	1.2	0.96
AOCM _{pcc}	0.85 - 2	1.32	1.72	0.99
CM _{pcc} , Concrete substrate	0.85 - 2	0.52	1.87	0.96
Bioretention soil media	0.001 - 10	0.18	2.58	0.99
UCF - 1	0.5 – 4.75	0.0027	0.85	0.98
UCF -2	0.85 - 10	0.0009	0.66	0.98
Expanded shale-1	2 - 10	0.06	1.9	0.95
Expanded shale-2	0.45 – 4.5	0.14	1.82	0.98

Table 2 Second Order Potential Driving Kinetic Model Constants

Media		Second Order Potential Driving Kinetic Model		
Media	Diameter (mm)	q_e [mg/g]	K [g/mg-min]	R^2
AOCM _c (clay)	0.85 - 2	0.096	6.09	0.98
AOCM _c (clay)	2 – 4.75	0.093	7.83	0.99
Expanded clay substrate	0.85 - 2	0.013	4.57	0.96
Expanded clay substrate	2 – 4.75	0.03	4.8	0.96
AOCM _p	2 – 4.75	0.11	1.19	0.95
Pumice substrate	2 – 4.75	0.03	0.87	0.97
AOCM _{pcc}	0.85 - 2	0.13	0.51	0.97
CM _{pcc} , Concrete substrate	0.85 - 2	0.13	0.29	0.94
Bioretention soil media	0.001 - 10	0.02	4.67	0.95
UCF - 1	0.5 – 4.75	Not available*		
UCF -2	0.85 - 10	Not available*		
Expanded shale-1	2 - 10	0.03	0.98	0.91
Expanded shale-2	0.45 – 4.5	0.086	0.58	0.95

*The media does not show any adsorption capacity but release certain amount of P.

Table 3 Thomas Model Constants

Media		Thomas Model		
Adsorbents	Diameter (mm)	K_T [L/min-mg]	q_0 [mg/g]	R^2
AOCM _c (clay)	0.85-2	0.0029	1.26	0.94
AOCM _c (clay)	2-4.75	0.0024	0.11	0.85
AOCM _p	2-4.75	0.0014	0.4	0.92
Pumice substrate	2-4.75	5.29	0.00077	0.77
AOCM _{pcc}	0.85-2	0.0021	0.25	0.94
CM _{pcc} , Concrete substrate	0.85-2	0.0022	0.24	0.98
Biofilter Media	0.001 - 10	13.09	0.0024	0.55
UCF -1	0.5 – 4.75	23.62	0.0018	0.48
UCF -2	0.85 - 10	11.23	0.0024	0.81
Shale-1	2 - 10	23.02	0.0021	0.6
Shale-2	0.45 – 4.5	20	0.0018	0.83

Table 4 Breakthrough and Exhaustion Capacity for Phosphorus Adsorption

Adsorbents	Diameter (mm)	X /M _b [mg/g]	X /M _{exh} [mg/g]	V _b [BV]	V _{exh} [BV]
AOCM _c (clay)	0.85-2	0.70	1.36	680	2000
AOCM _p	2-4.75	0.0002	0.25	<1	1600
Pumice Substrate	2-4.75	< 0.0001	0.0046	<1	36
AOCM _{pcc}	0.85 - 2	0.076	0.26	200	955
CM _{pcc}	0.85 - 2	0.056	0.25	120	1075
Bioretention Soil Media	0.001 - 10	< 0.0001	0.012	<1	220
UCF -1	0.5 – 4.75	Phosphorus leaching from media			
UCF -2	0.85 - 10	Phosphorus leaching from media			
Expanded Shale - 1	2 - 10	Phosphorus leaching from media			
Expanded Shale - 2	0.45 – 4.5	< 0.0001	0.0014	<1	12

Note: X / M_b = breakthrough capacity as C / C₀ = 0.1; X / M_{exh} = exhaustion capacity as C / C₀ = 0.9; V_b = number of bed volumes (BV) treated at an effluent breakthrough level of C / C₀ = 0.1; V_{exh} = number of bed volumes (BV) treated at an effluent exhaustion level of C / C₀ = 0.9.

Table 5 Summary of Media Capacity

Media	Adsorption	Kinetics	Breakthrough Capacity	Exhaustion Capacity
AOCM _c (clay) (0.85 - 2 mm)	●	●	●	●
AOCM _c (clay) (2 – 4.75 mm)	●	●	○	◇
Expanded clay substrate (0.85 - 2 mm)	○	○	○	○
Expanded clay substrate (2 – 4.75 mm)	○	○	○	○
AOCM _p	◇	●	○	●
Pumice substrate	○	○	○	○
AOCM _{pcc}	●	●	◇	●
CM _{pcc} , Concrete substrate	●	●	◇	●
Bioretention soil media	○	●	○	○
UCF - 1	○	○	○	○
UCF -2	○	○	○	○
Expanded shale-1	○	○	○	○
Expanded shale-2	○	○	○	○

- High capacity
- ◇ Medium capacity
- Low capacity

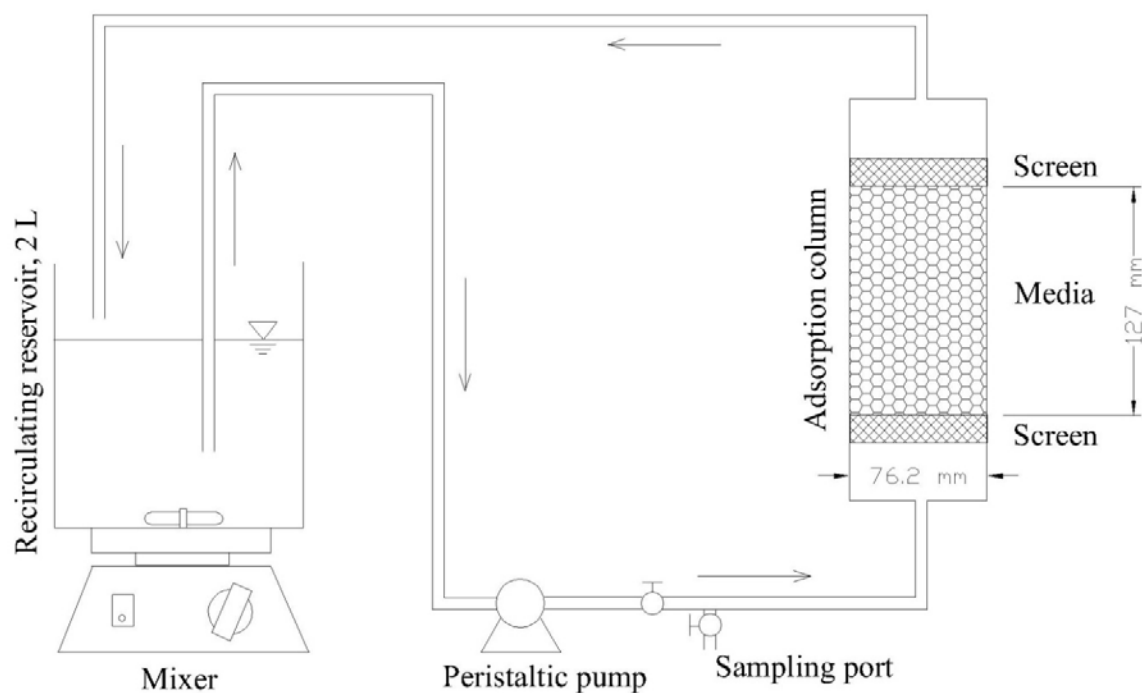


Figure 1 Schematic experimental configuration of TDP adsorption kinetics on adsorbent media

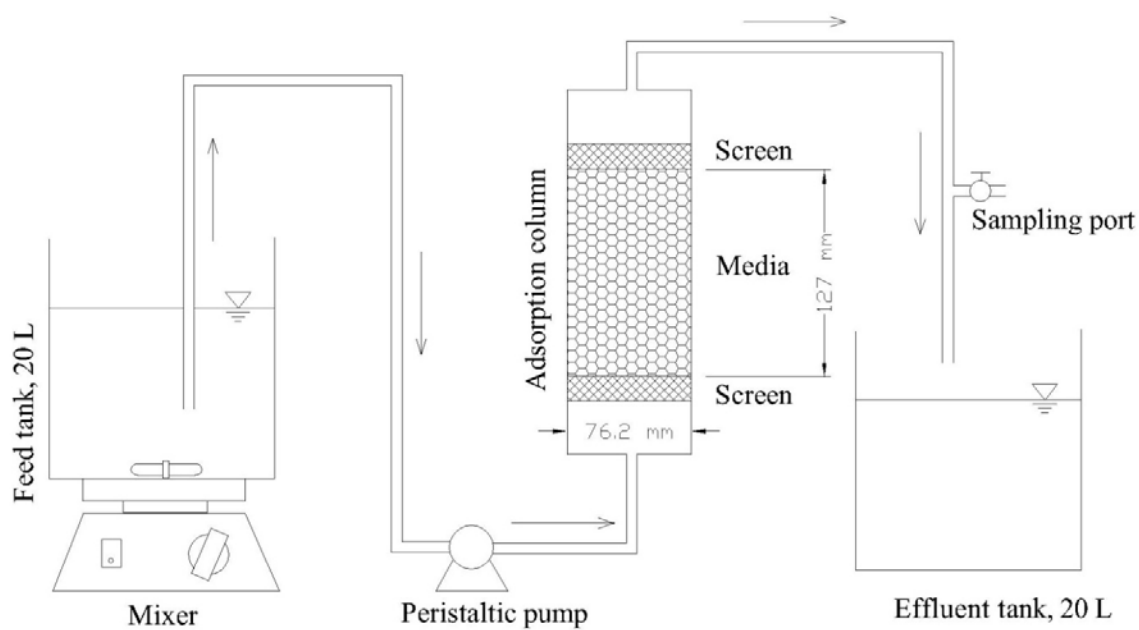


Figure 2 Schematic experimental configuration of TDP adsorption breakthrough on adsorbent media

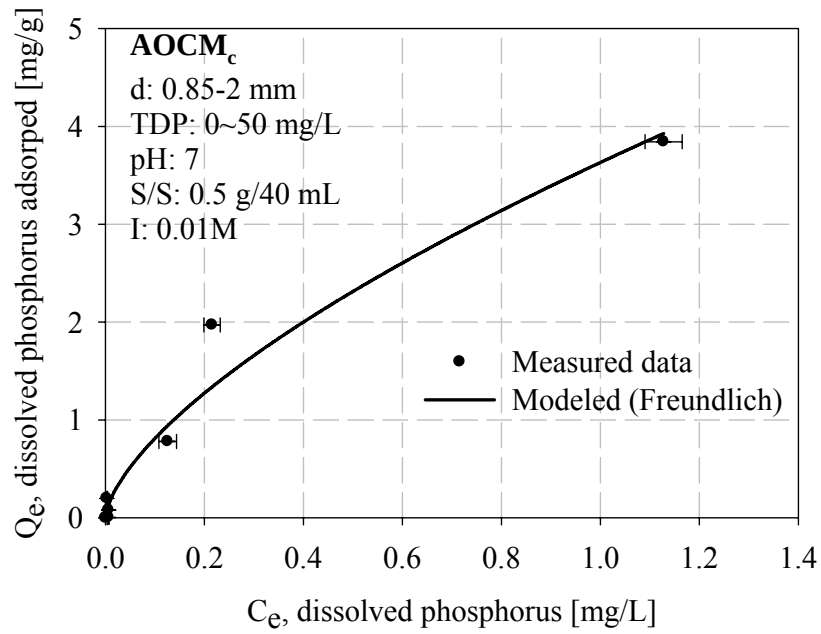


Figure 3 Phosphorus equilibrium isotherm for AOCM_c (0.85 - 2 mm)

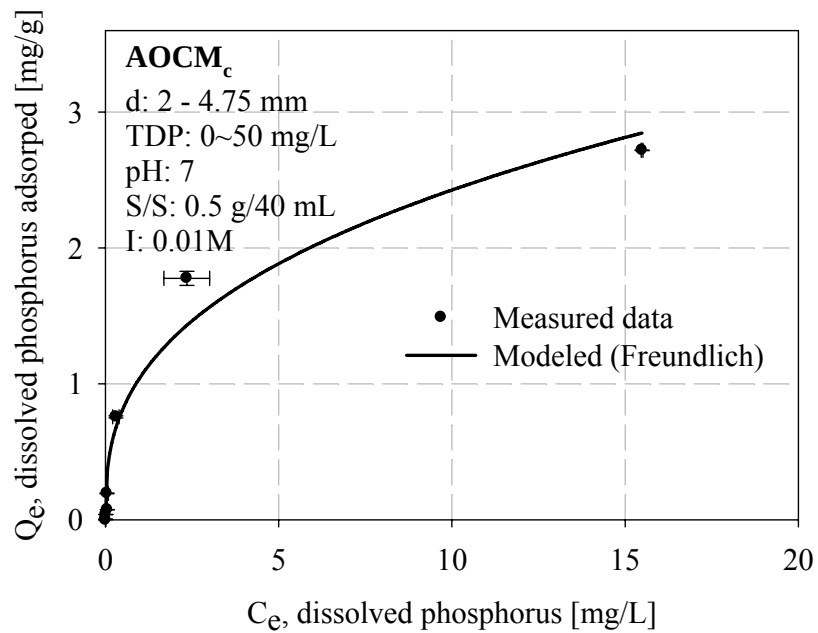


Figure 4 Phosphorus equilibrium isotherm for AOCM_c (2 – 4.75 mm)

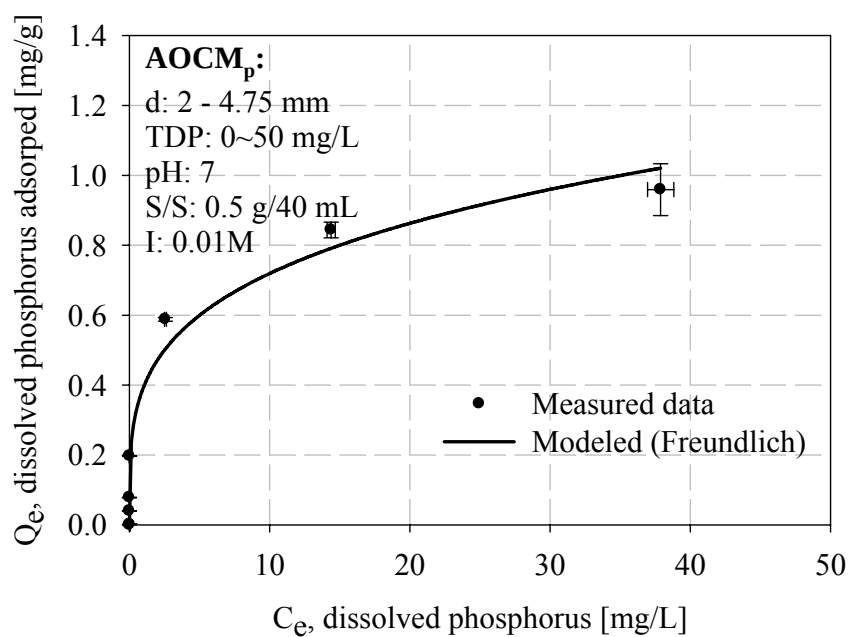


Figure 5 Phosphorus equilibrium isotherm for AOCP_p (2 – 4.75 mm)

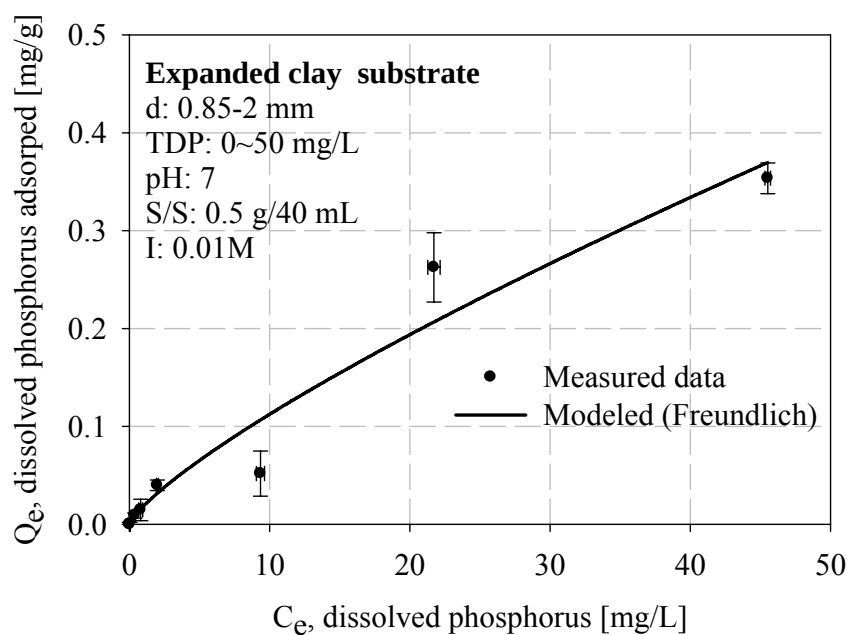


Figure 6 Phosphorus equilibrium isotherm for Expanded clay substrate (0.85 – 2 mm)

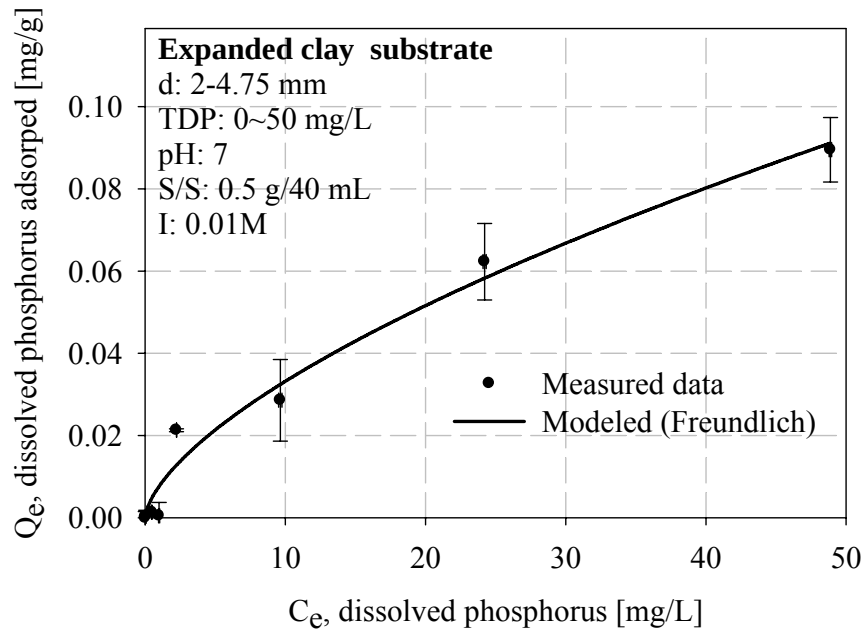


Figure 7 Phosphorus equilibrium isotherm for Expanded clay substrate (2 – 4.75 mm)

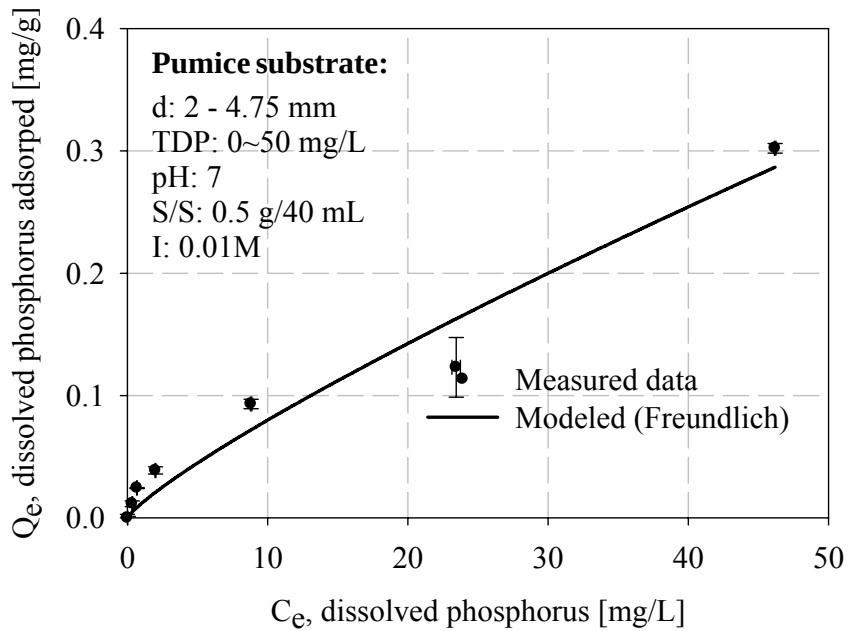


Figure 8 Phosphorus equilibrium isotherm for Pumice substrate (2 – 4.75 mm)

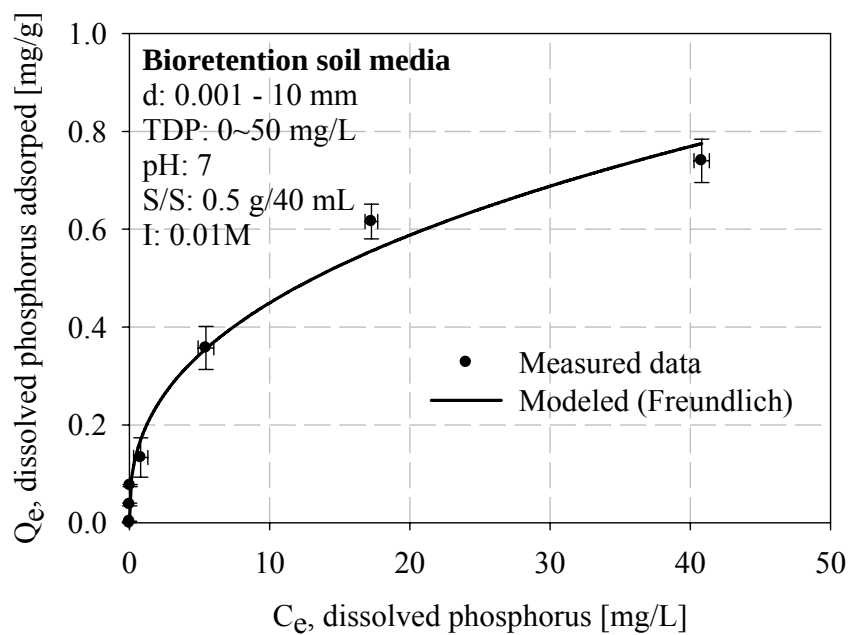


Figure 9 Phosphorus equilibrium isotherm for Bioretention soil media (0.001 – 10 mm)

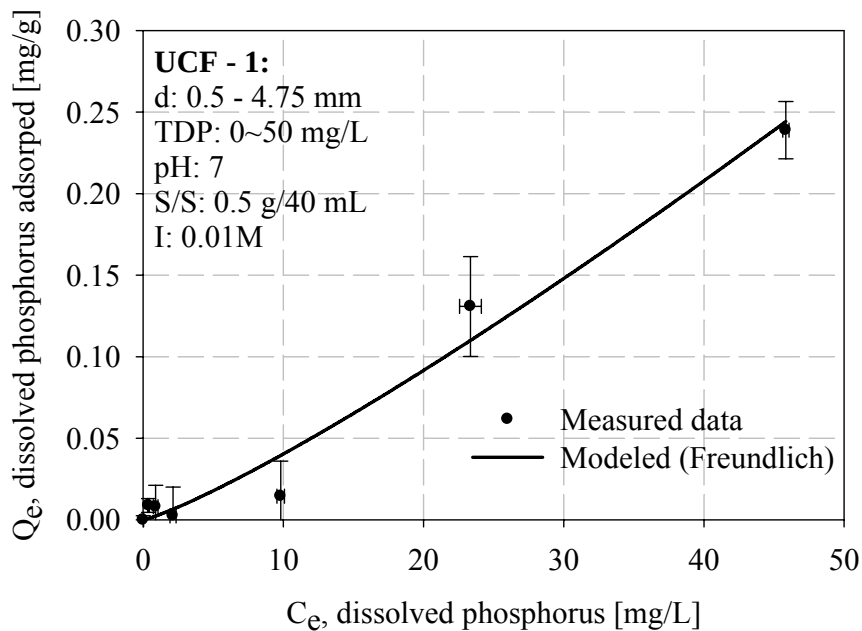


Figure 10 Phosphorus equilibrium isotherm for UCF-1 (0.5 – 4.75 mm)

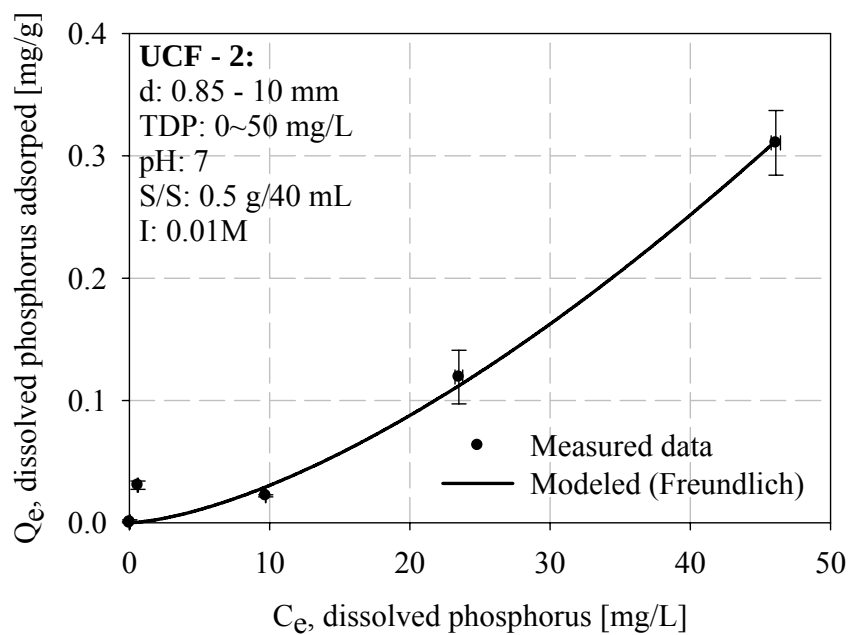


Figure 11 Phosphorus equilibrium isotherm for UCF-2 (0.85 – 10 mm)

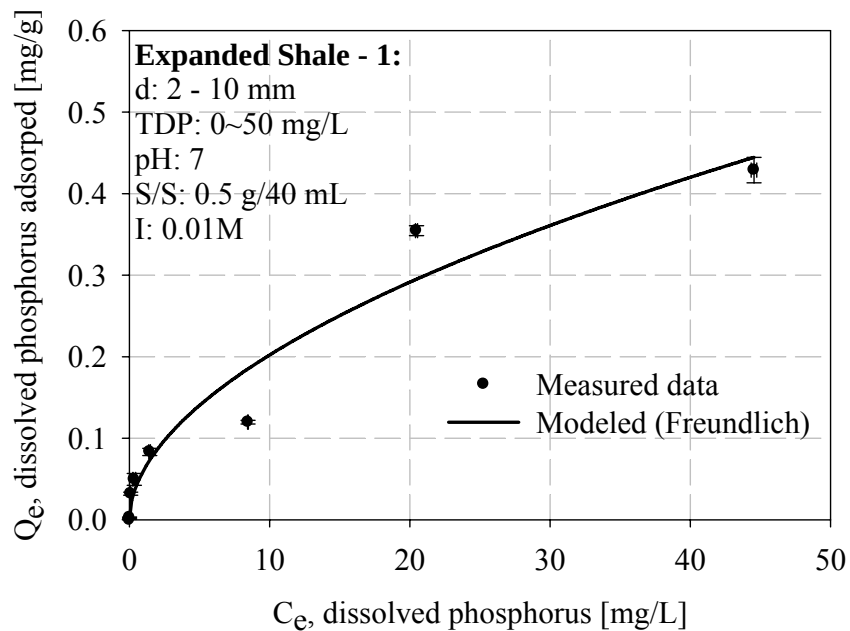


Figure 12 Phosphorus equilibrium isotherm for Expanded Shale-1 (2 – 10 mm)

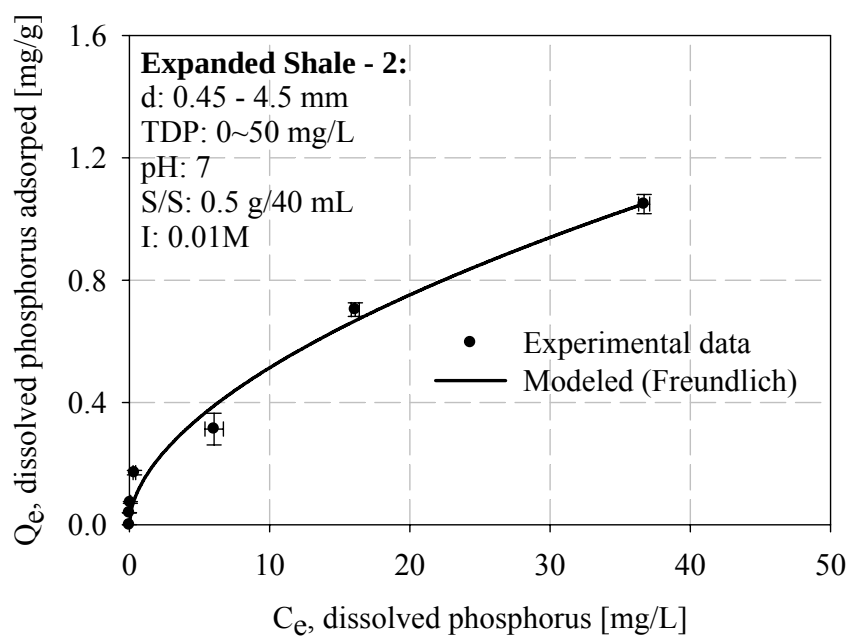


Figure 13 Phosphorus equilibrium isotherm for Expanded Shale-2 (0.45 – 4.5 mm)

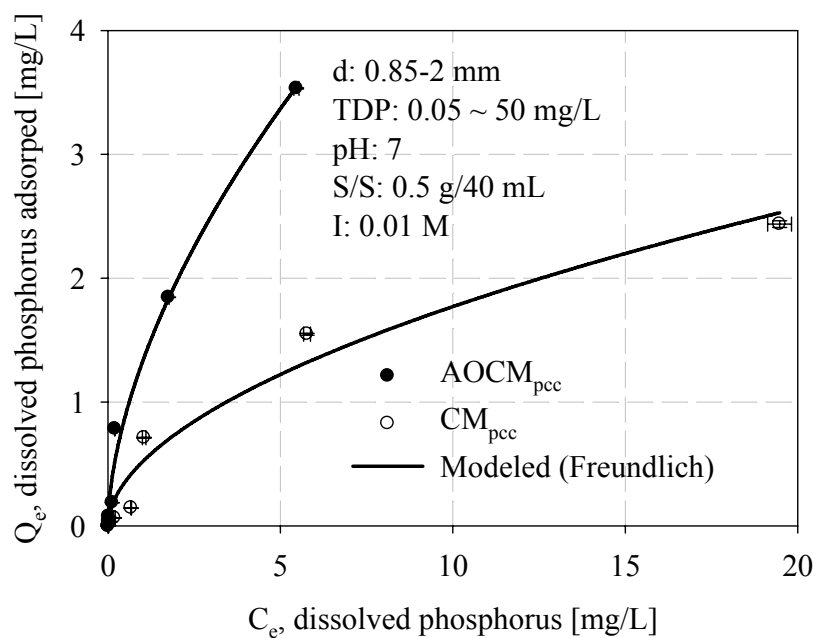


Figure 14 Phosphorus equilibrium isotherm for AOCP_{pcc} and CM_{pcc} (0.85 – 2 mm)

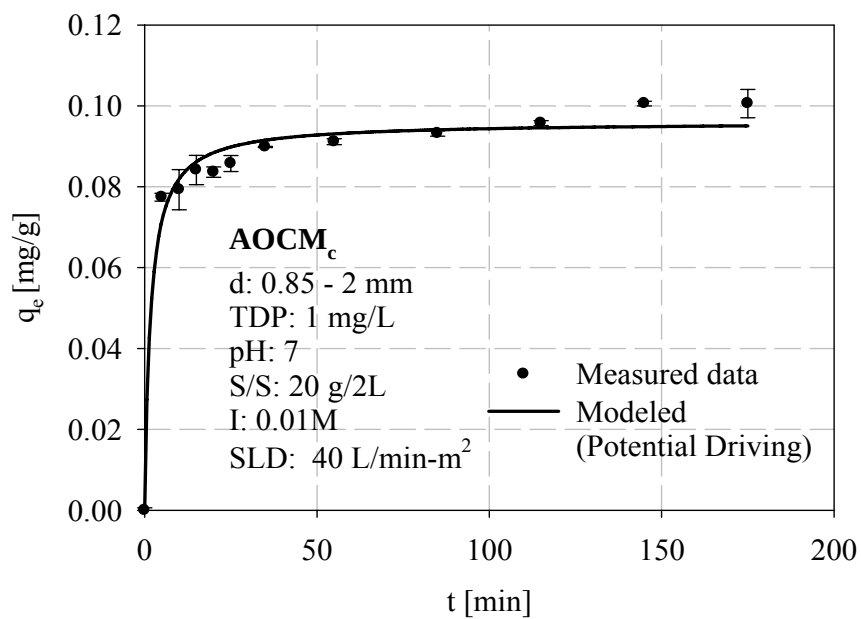


Figure 15 Phosphorus adsorption kinetics for AOCCM_c (0.85 - 2 mm)

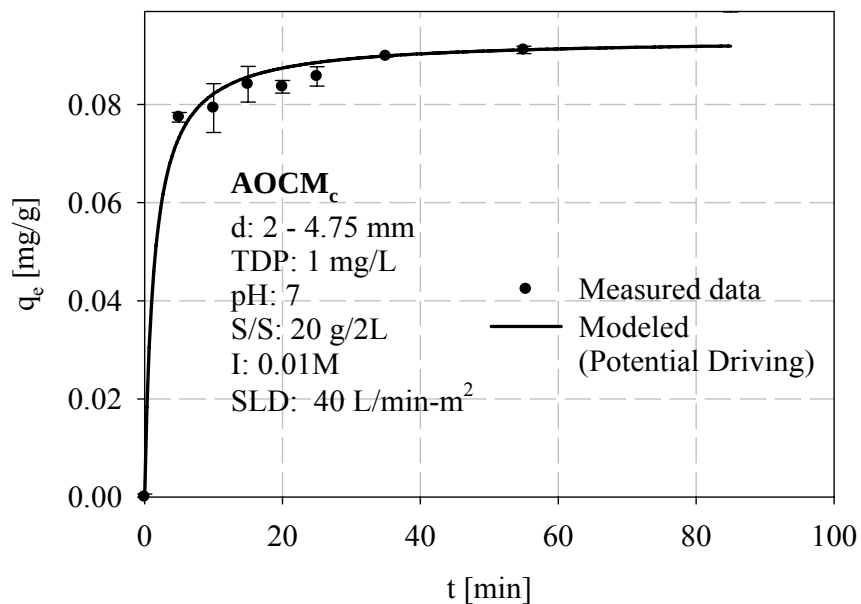


Figure 16 Phosphorus adsorption kinetics for AOCCM_c (2 - 4.75 mm)

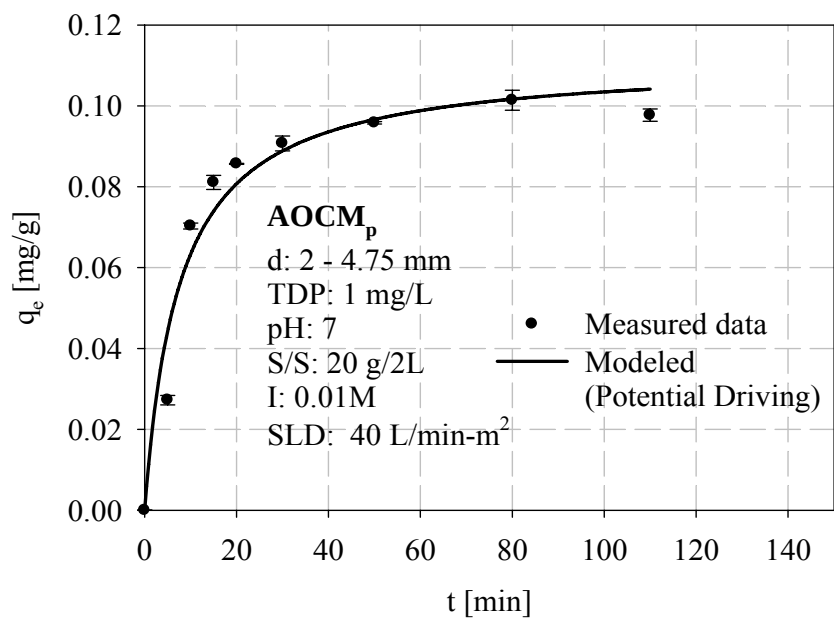


Figure 17 Phosphorus adsorption kinetics for AOCP_p (2 – 4.75 mm)

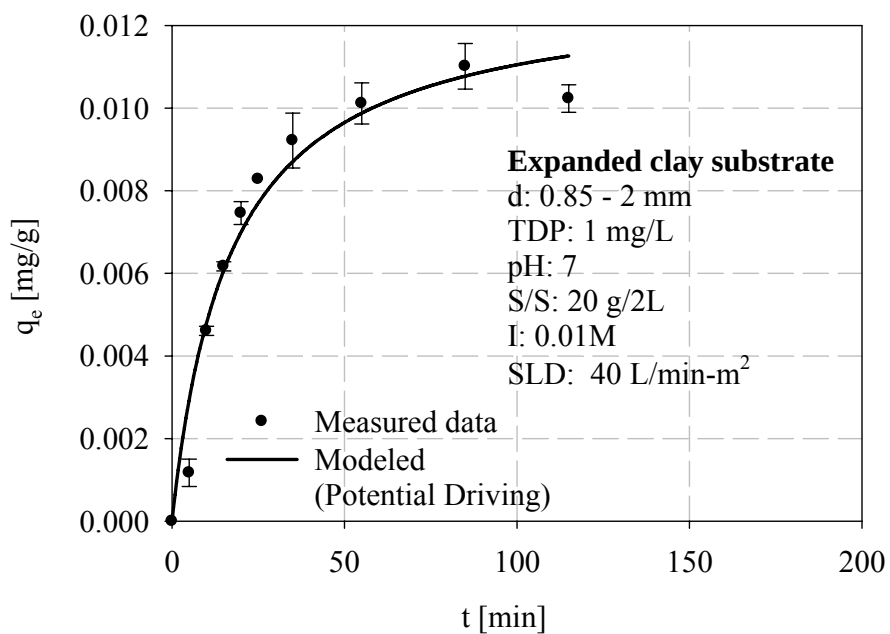


Figure 18 Phosphorus adsorption kinetics for Expanded clay substrate (0.85 – 2 mm)

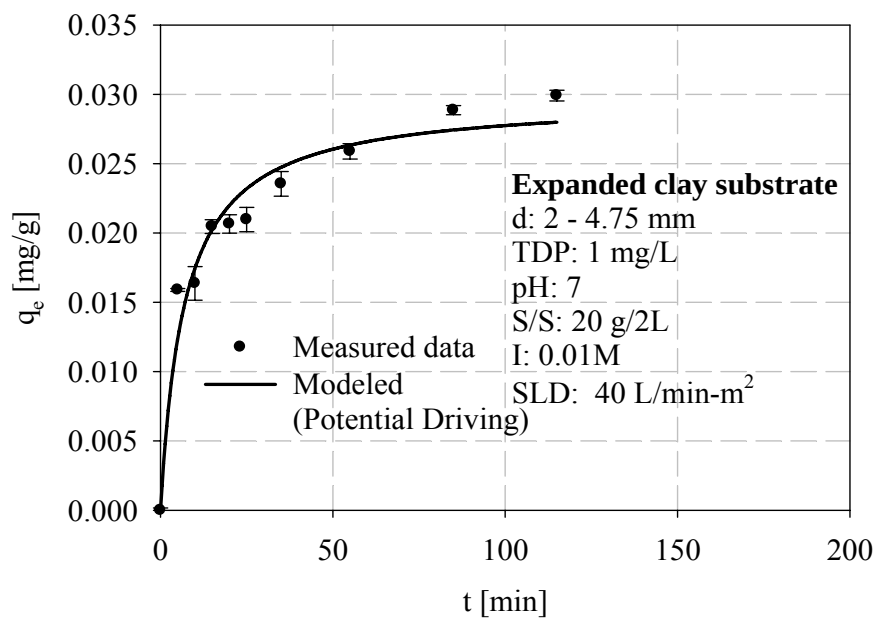


Figure 19 Phosphorus adsorption kinetics for Expanded clay substrate (2 – 4.75 mm)

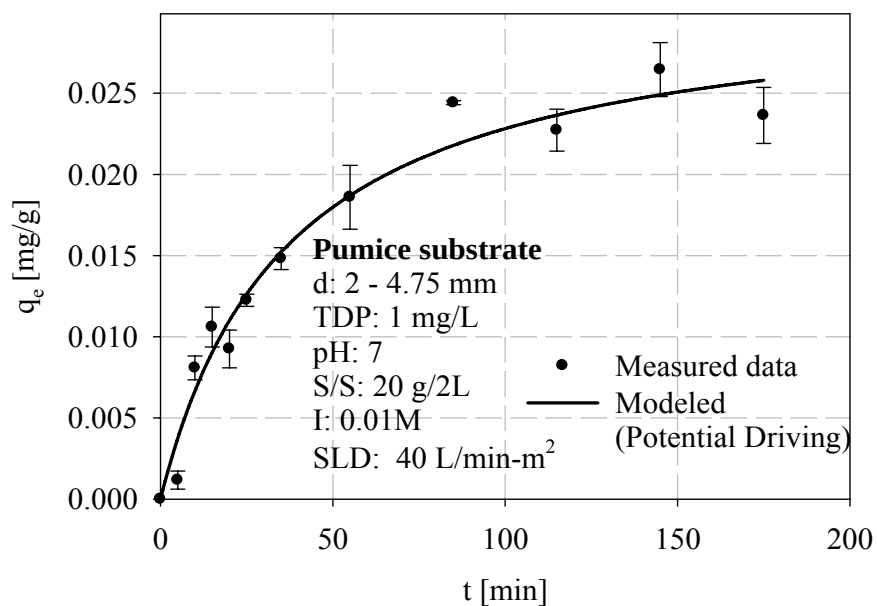


Figure 20 Phosphorus adsorption kinetics for Pumice substrate (2 – 4.75 mm)

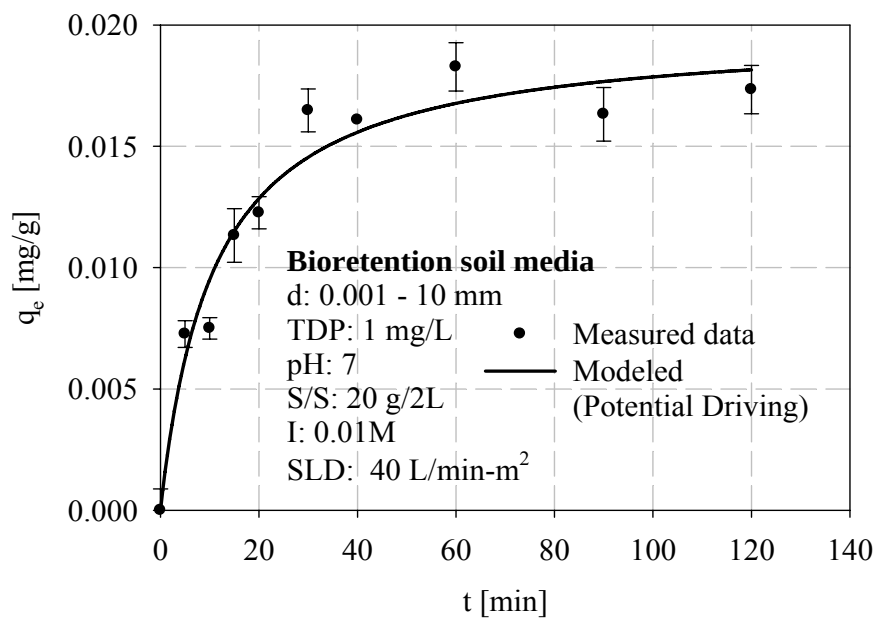


Figure 21 Phosphorus adsorption kinetics for Bioretention soil media (0.001 – 10 mm)

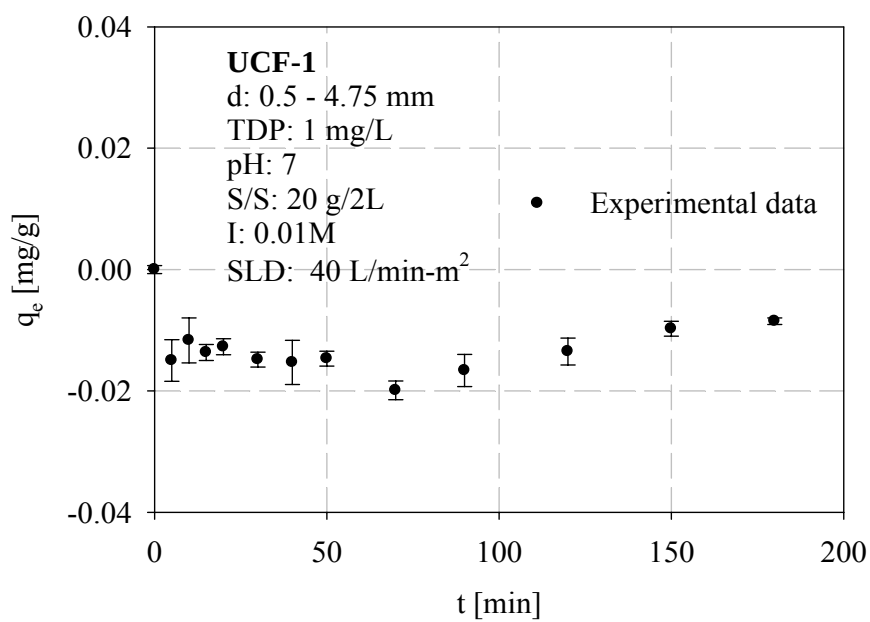


Figure 22 Phosphorus adsorption kinetics for UCF-1 (0.5 – 4.75 mm)
(Experimental data (negative q_e) cannot fit in a pseudo second order model.)

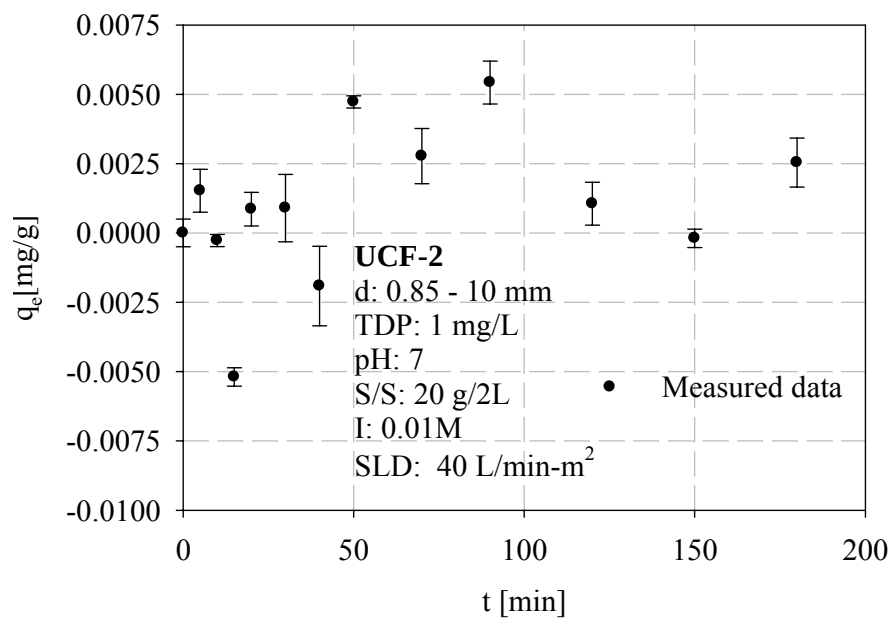


Figure 23 Phosphorus adsorption kinetics for UCF-2 (0.85 – 10 mm)
(Experimental data (negative q_e) cannot fit in a pseudo second order model.)

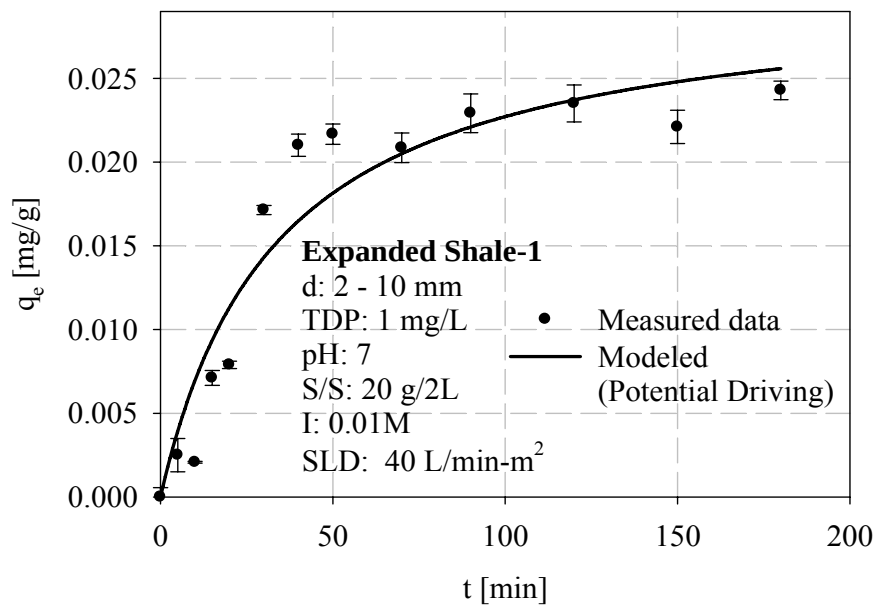


Figure 24 Phosphorus adsorption kinetics for Expanded Shale -1 (2 - 10 mm)

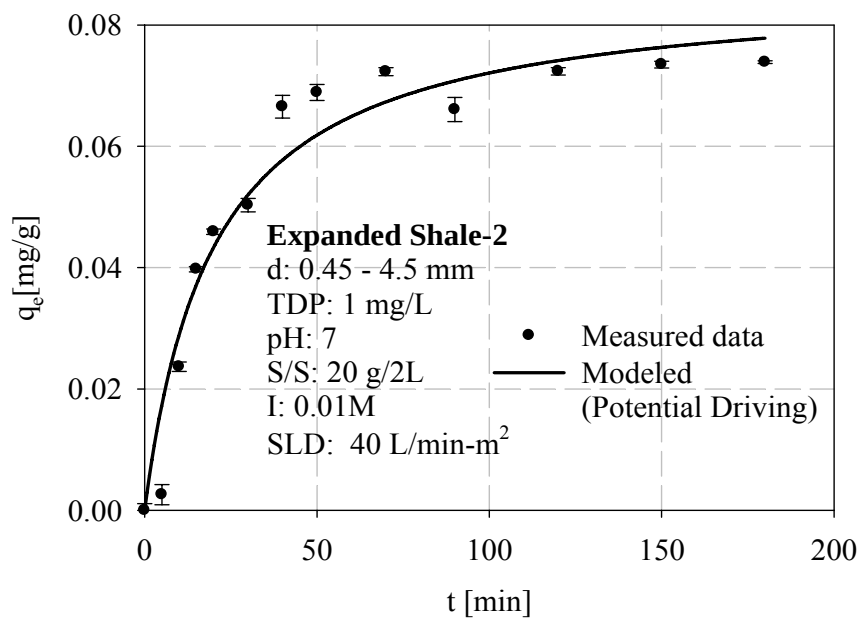


Figure 25 Phosphorus adsorption kinetics for Expanded Shale - 2 (0.45 – 4.5 mm)

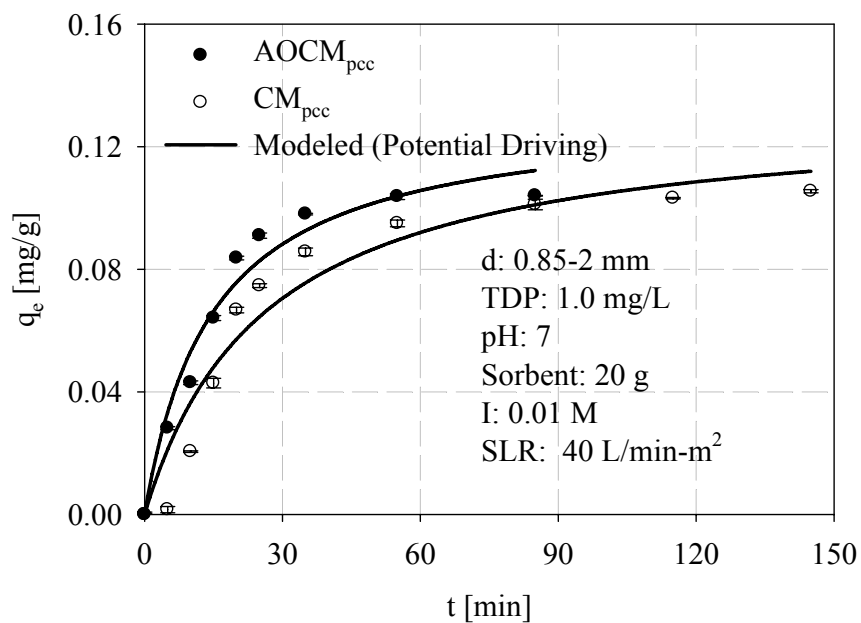


Figure 26 Phosphorus adsorption kinetics for AOCM_{pcc} and CM_{pcc} (0.85 – 2 mm)

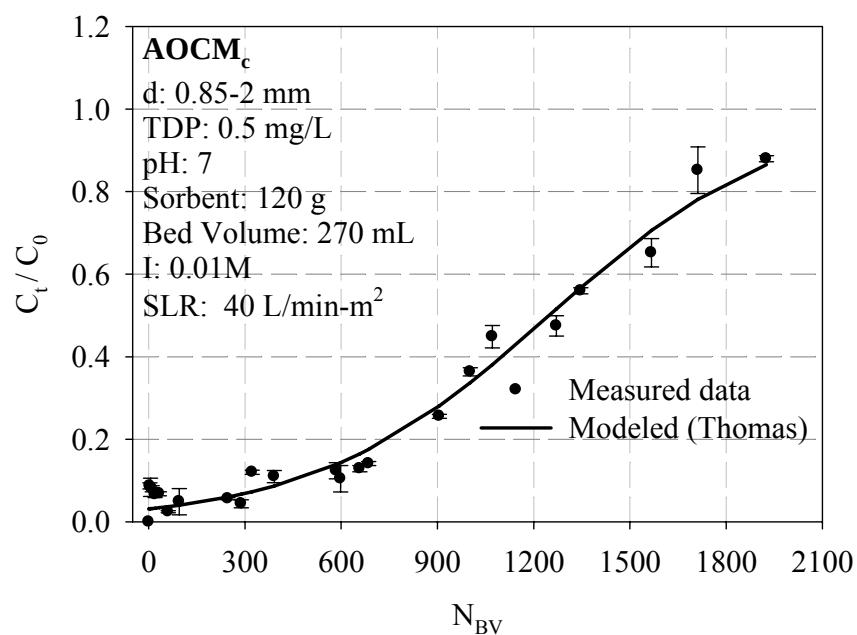


Figure 27 Phosphorus breakthrough test for AOcMc (0.85 – 2 mm)

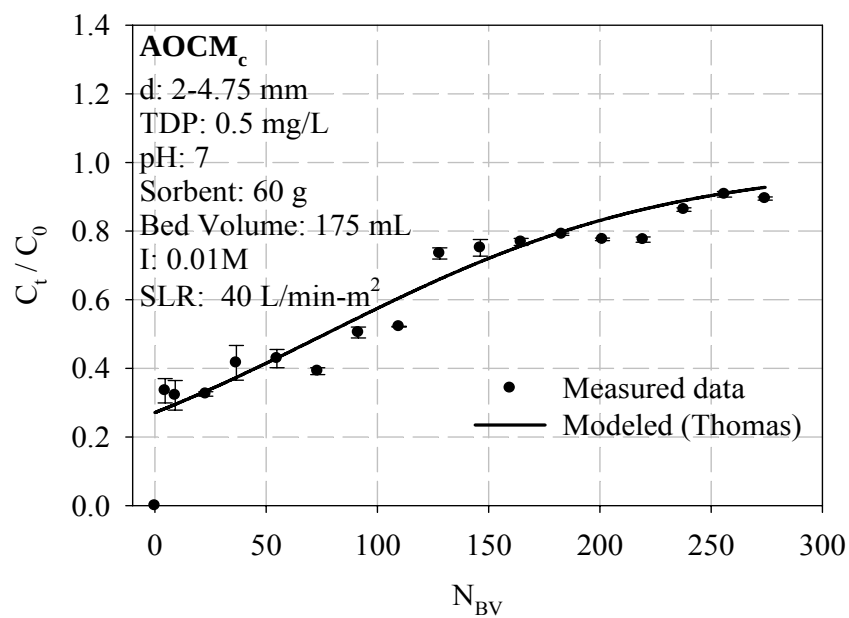


Figure 28 Phosphorus breakthrough test for AOcMc (2 – 4.75 mm)

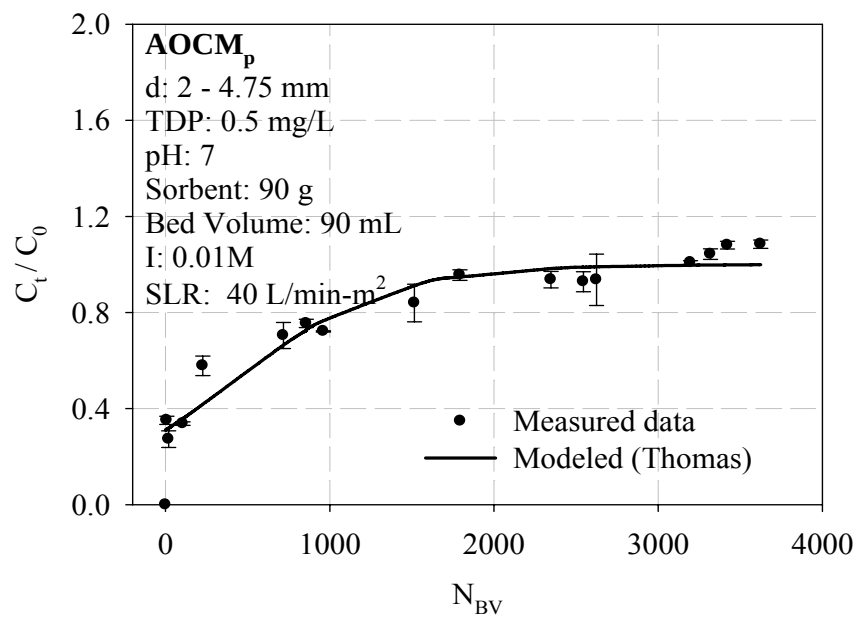


Figure 29 Phosphorus breakthrough test for AOCP (2 – 4.75 mm)

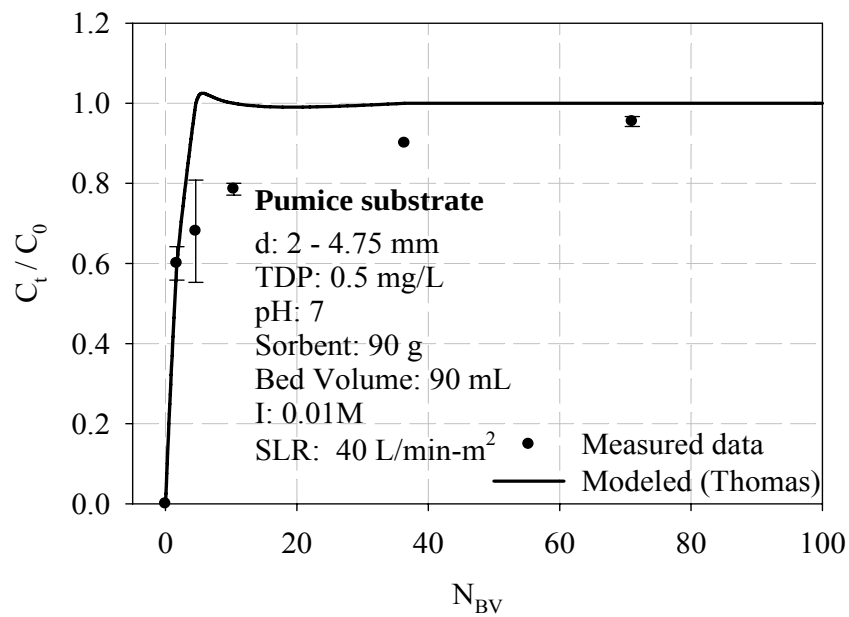


Figure 30 Phosphorus breakthrough test for Pumice substrate (2 – 4.75 mm)

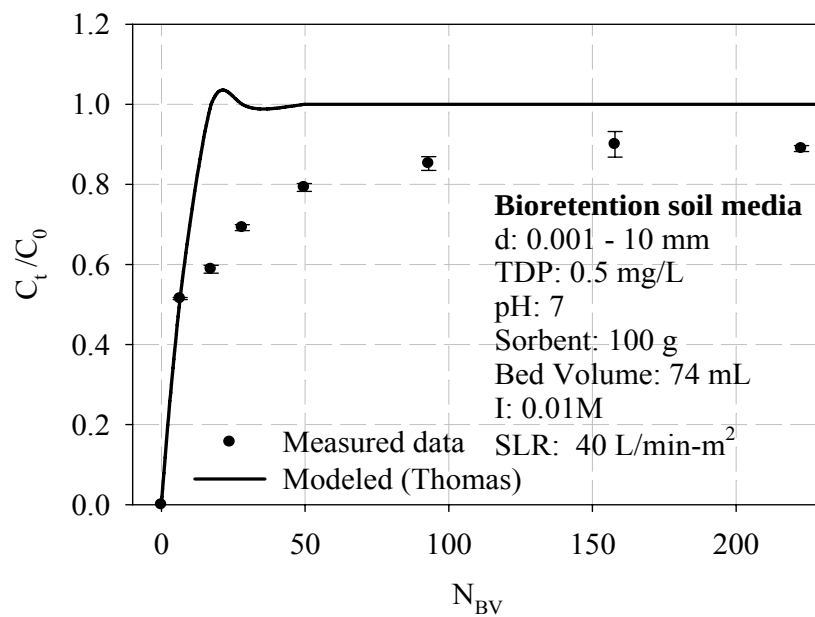


Figure 31 Phosphorus breakthrough test for Bioretention soil media(0.001 – 10 mm)

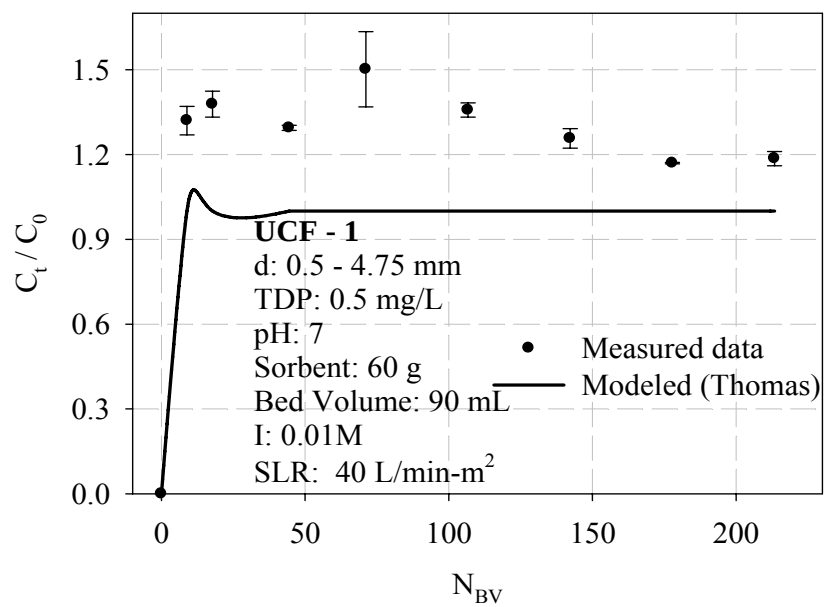


Figure 32 Phosphorus breakthrough test for UCF-1 (0.5 – 4.75 mm)

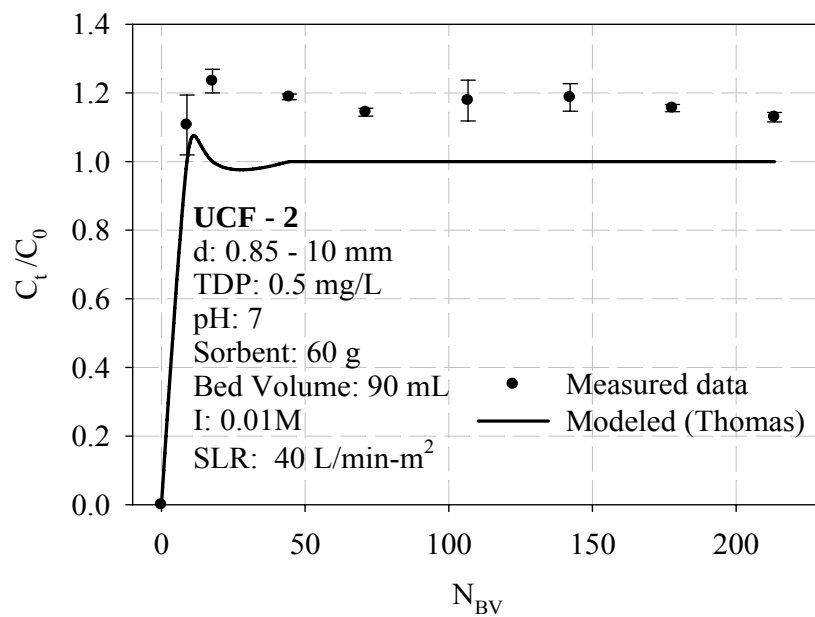


Figure 33 Phosphorus breakthrough test for UCF-2 (0.85 – 10 mm)

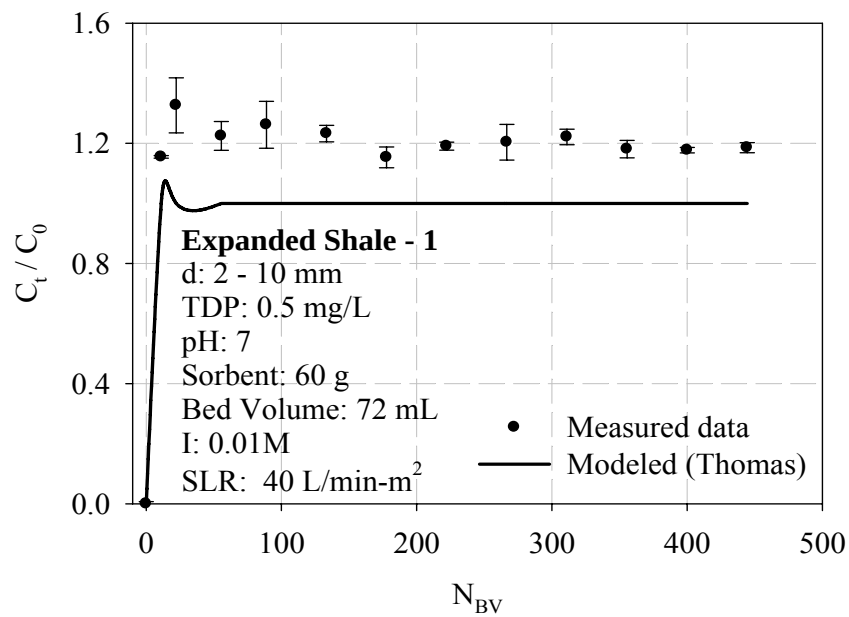


Figure 34 Phosphorus breakthrough test for Expanded Shale-1 (2 – 10 mm)

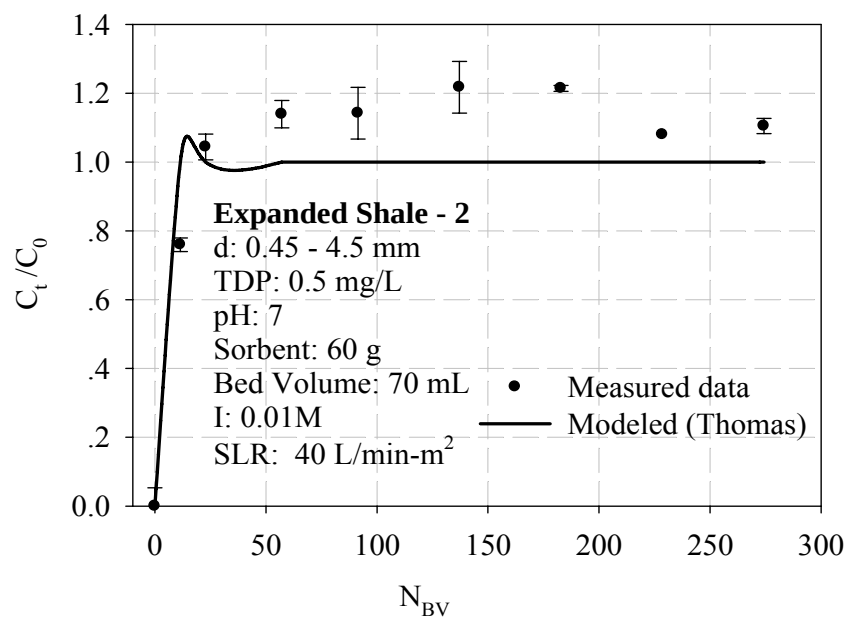


Figure 35 Phosphorus breakthrough test for Expanded Shale - 2 (0.45 – 4.5 mm)

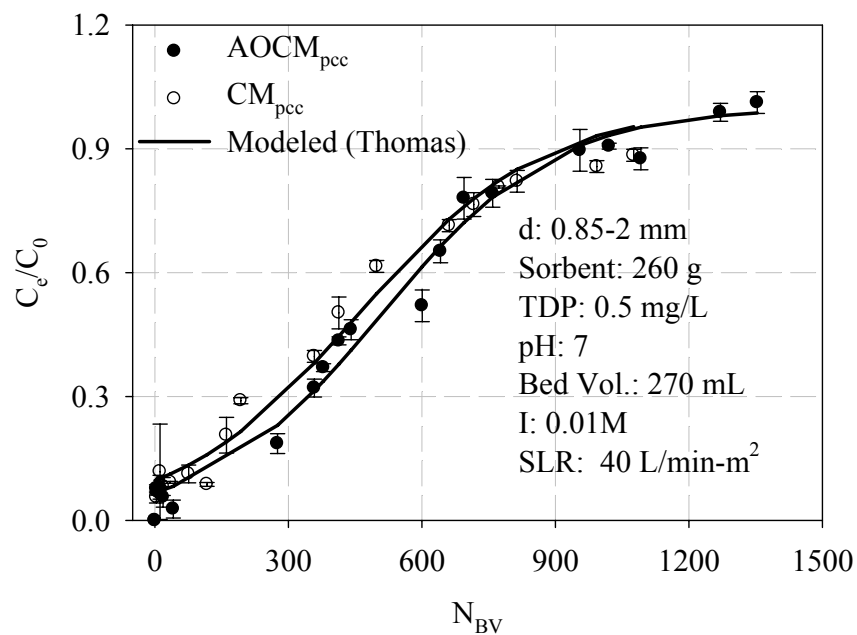


Figure 36 Phosphorus breakthrough test for AOCP_{pcc} and CM_{pcc} (0.85 – 2 mm)

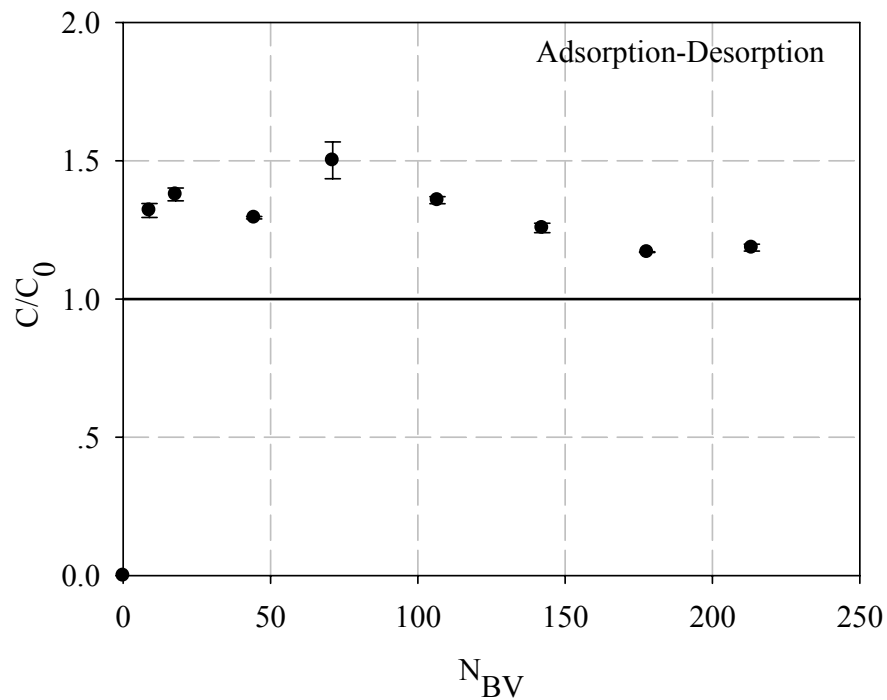


Figure 37 Phosphorus Adsorption-Desorption test for UCF-1 media (0.5 – 4.75 mm). The distance and area between the data and the C/C_0 line = 1.0 represents phosphorus desorption in terms of concentration and mass, respectively.

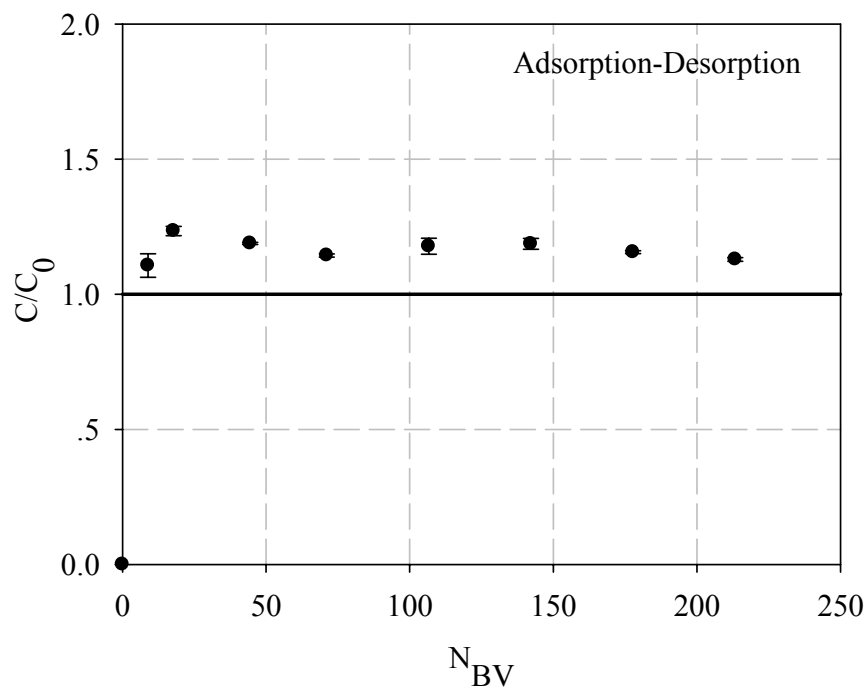


Figure 38 Phosphorus Adsorption-Desorption test for UCF-2 (0.85 – 10 mm). The distance and area between the data and the C/C_0 line = 1.0 represents phosphorus desorption in terms of concentration and mass, respectively.

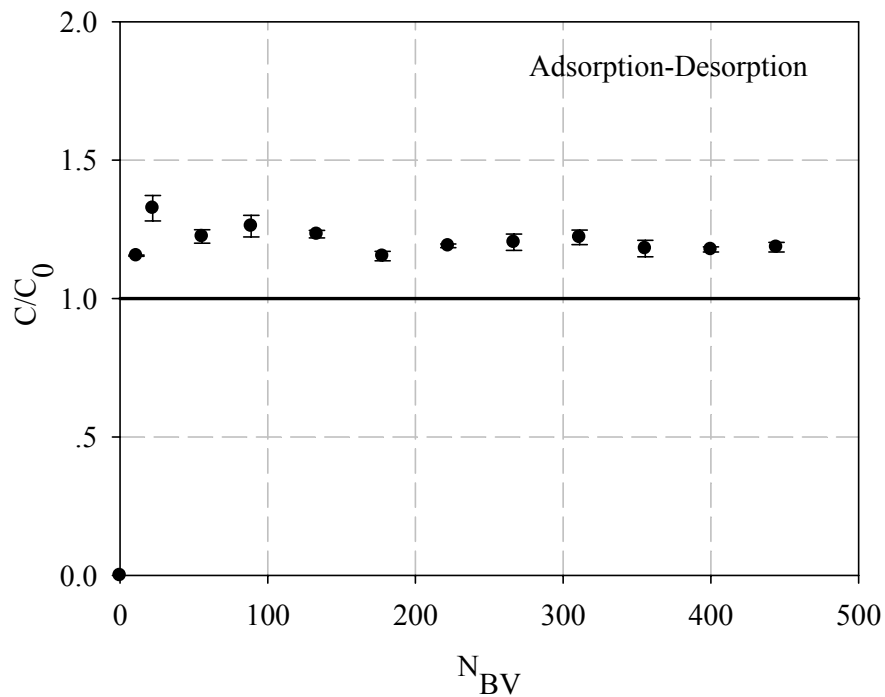


Figure 39 Phosphorus Adsorption-Desorption test for Expanded Shale -1 (2 - 10 mm). The distance and area between the data and the C/C_0 line = 1.0 represents phosphorus desorption in terms of concentration and mass, respectively.

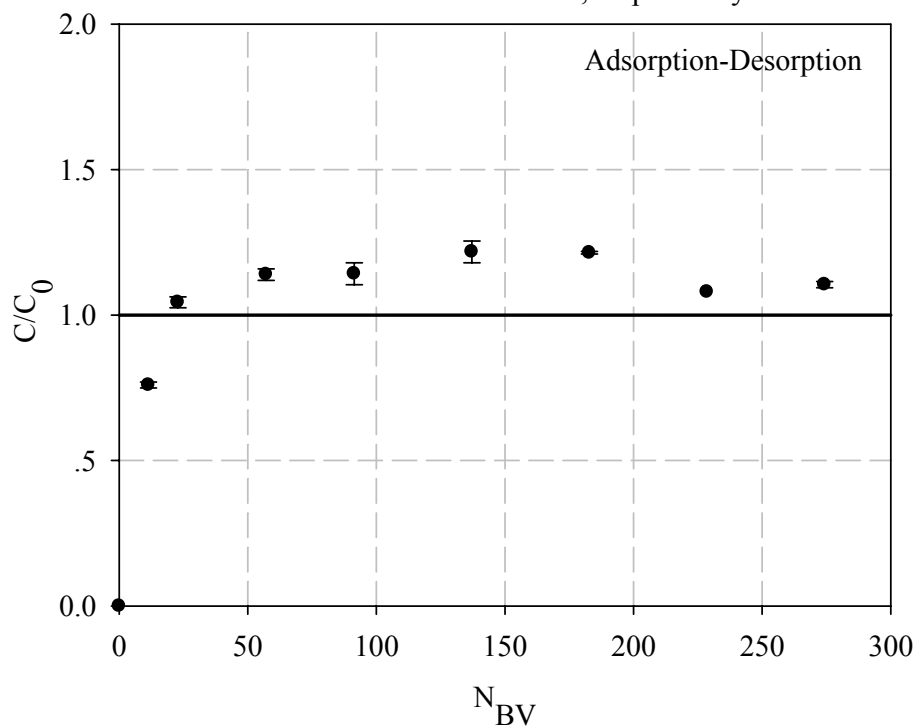


Figure 40 Phosphorus Adsorption-Desorption test for Expanded Shale -2 (0.45 - 4.5 mm). The distance and area between the data and the C/C_0 line = 1.0 represents phosphorus desorption in terms of concentration and mass, respectively.

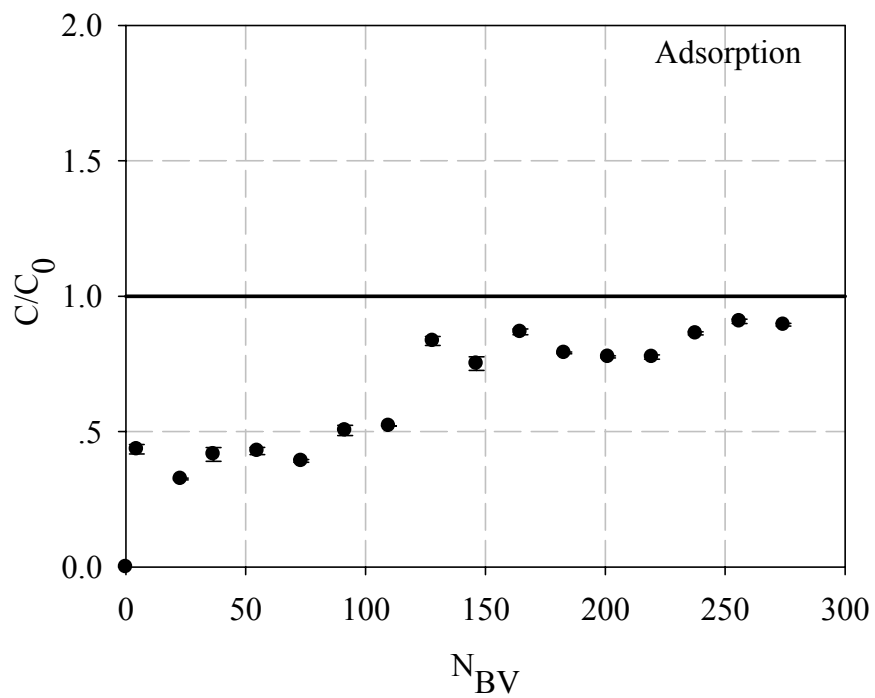


Figure 41 Phosphorus Adsorption test for AOCCM_C (2 – 4.75 mm). This media did not exhibit any desorption and all data are below the C/C_0 line = 1.0; therefore the distance and area between the data and the C/C_0 line = 1.0 represents phosphorus adsorption in terms of concentration and mass, respectively.

CHAPTER 5: FIELD-SCALE TESTING OF THE ENGINEERED SOIL MEDIA FILTER SYSTEM

List of Tables	5-ii
List of Figures	5-iv
INTRODUCTION	5-1
METHODOLOGY	5-2
Experimental Site.....	5-2
Sorptive Filter System and Monitoring System.....	5-2
Calibration Procedure and Hydraulic Conductivity Test.....	5-4
Monitoring Methodology	5-6
Rainfall and Runoff Analysis.....	5-8
Data Analysis and Elaboration.....	5-12
RESULTS AND DISCUSSION	5-15
Events Hydrology	5-15
Filter System Head Loss	5-16
Rainfall and Runoff Water Chemistry	5-17
Particulate Matter (PM)	5-19
Particle Size Distribution (PSD)	5-21
Phosphorus	5-22
Nitrogen	5-23
Metals.....	5-25
Soil Filter Media	5-26
Drainage Management	5-28
CONCLUSIONS.....	5-31
REFERENCES	5-34

List of Tables

Table 1 Physical-Chemical Analyses Performed for the Monitored Rainfall Runoff Events.....	5-41
Table 2 Summary of standard methods for each analysis.....	5-42
Table 3 Summary of standard methods for each analysis (Continue)	5-43
Table 4 Summary of YSI Sensor Characteristics	5-43
Table 5 Monitored rainfall-runoff events characteristics.....	5-44
Table 6 Rainfall-runoff events characteristics and maximum and average filter surface loading rates.	5-45
Table 7 Rainfall Physical-Chemical characteristics	5-46
Table 8 Rainfall quality characteristics (Turbidity - Ions).....	5-47
Table 9 Summary of EMCs and range of variation of influent runoff quality characteristics (Physical-Chemical characteristics).....	5-48
Table 10 Summary of EMCs and range of variation of Influent runoff quality characteristics (Turbidity –Ions - DOC)	5-49
Table 11 Summary of EMCs and range of variation of effluent runoff quality characteristics (Physical-Chemical characteristics).....	5-50
Table 12 Summary of EMCs and range of variation of effluent runoff quality characteristics (Turbidity –Ions - DOC)	5-51
Table 13 Summary of EMCs and range of variation of influent particle size fractions	5-52
Table 14 Summary of EMCs and range of variation of effluent particle size fractions	5-53
Table 15 Influent and effluent event mean d_{15} , d_{50} and d_{85} and range of variation within each monitored storm event	5-54
Table 16 Summary of EMCs and range of variation of influent dissolved, particulate bound and total phosphorus	5-55
Table 17 Summary of EMCs and range of variation of effluent dissolved, particulate bound and total phosphorus	5-56
Table 18 Summary of event mean value and range of variation of the dissolved fraction (f_d) and partition coefficient (k_d) of phosphorus for influent and effluent runoff.....	5-57
Table 19 Summary of EMCs and range of variation of influent nitrate, nitrite, ammonia and dissolved, particulate bound and total nitrogen.....	5-58
Table 20 Summary of EMCs and range of variation of effluent nitrate, nitrite, ammonia and dissolved, particulate bound and total nitrogen.....	5-59
Table 21 Summary of event mean value and range of variation of the dissolved fraction (f_d) and partition coefficient (k_d) of nitrogen for influent and effluent runoff.....	5-60
Table 22 Summary of EMCs and range of variation of influent metals.....	5-61
Table 23 Summary of EMCs and range of variation of effluent metals.....	5-61

Table 24 Summary of mean concentration values and range of variation of quality characteristics of stored runoff into the filter system during inter event retention periods (Physical-Chemical characteristics).....	5-63
Table 25 Summary of mean concentration values and range of variation of quality characteristics of stored runoff into the filter system during inter event retention periods (Ions).....	5-64

List of Figures

Figure 1 University of Florida Reitz Union paved surface parking facility in Gainesville, FL. Particular of the monitored inlet.....	1
Figure 2 Contour lines showing the monitored area relative elevations.....	2
Figure 3 Catchment area	2
Figure 4 Experimental treatment system	3
Figure 5 Monitoring system location and design.....	4
Figure 6 Monitoring system design. Detail of the influent sampling section and inlet A.	5
Figure 7 Monitoring system as installed. The flow rate measurement system: Parshall flume and drop box.	6
Figure 8 Rain gauges in the area of interest.....	6
Figure 9 Parshall Flume calibration set-up	7
Figure 10 Comparison between the Parshall flume theoretical curve and the calibration one.....	7
Figure 11 Hydraulic conductivity set-up and testing for engineered soil media	8
Figure 12 Hydraulic Conductivity Test experimental data and interpolating curve.....	8
Figure 13 Hyetograph, hydrograph, water level in the Parshall flume and influent sampling time for the 20 March 2008 event	9
Figure 14 Influent and Effluent Flow rate for 20 March 2008 event.....	9
Figure 15 Head Loss, Influent Flow rate and influent and effluent sampling starting time	10
Figure 16 Total precipitation and total number of events for each month between August 1999 and July 2008 in Gainesville, FL (Gainesville Regional Airport station).....	10
Figure 17 Hyetograph and hydrograph for the 20 March 2008	11
Figure 18 Hyetograph and hydrograph for the 16 May 2008	11
Figure 19 Hyetograph and hydrograph for the 03 June 2008	12
Figure 20 Hyetograph and hydrograph for the 10 June 2008	12
Figure 21 Hyetograph and hydrograph for the 21 June 2008	13
Figure 22 Hyetograph and hydrograph for the 08 July 2008.....	13
Figure 23 Hyetograph and hydrograph for the 15 July 2008.....	14
Figure 24 Hyetograph and hydrograph for the 29 July 2008.....	14
Figure 25 Hyetograph and hydrograph for the 08 August 2008	15
Figure 26 Hyetograph and hydrograph for the 12 August 2008	15
Figure 27 Hyetograph and hydrograph for the 19 August 2008	16
Figure 28 Hyetograph and hydrograph for the 10 September 2008	16

Figure 29 Hyetograph and hydrograph for the 20 September 2008	17
Figure 30 Hyetograph and hydrograph for the 08 October 2008.....	17
Figure 31 Hyetograph and hydrograph for the 23 October 2008.....	18
Figure 32 Head Loss – Flow Rate behavior during the whole monitoring program	18
Figure 33 Detailed Head Loss – Flow Rate curves for 4 events.....	19
Figure 34 Mean and range of influent and effluent PSD of the 20 March 2008 rainfall event.....	20
Figure 35 Mean and range of influent and effluent PSD of the 16 May 2008 rainfall event.....	21
Figure 36 Mean and range of influent and effluent PSD of the 3 June 2008 rainfall event.....	22
Figure 37 Mean and range of influent and effluent PSD of the 10 June 2008 rainfall event.....	23
Figure 38 Mean and range of influent and effluent PSD of the 21 June 2008 rainfall event.....	24
Figure 39 Mean and range of influent and effluent PSD of the 8 July 2008 rainfall event.....	25
Figure 40 Mean and range of influent and effluent PSD of the 15 July 2008 rainfall event.....	26
Figure 41 Mean and range of influent and effluent PSD of the 29 July 2008 rainfall event.....	27
Figure 42 Mean and range of influent and effluent PSD of the 8 August 2008 rainfall event.....	28
Figure 43 Mean and range of influent and effluent PSD of the 12 August 2008 rainfall event.....	29
Figure 44 Mean and range of influent and effluent PSD of the 19 August 2008 rainfall event.....	30
Figure 45 Mean and range of influent and effluent PSD of the 10 September 2008 rainfall event	31
Figure 46 Mean and range of influent and effluent PSD of the 20 September 2008 rainfall event	32
Figure 47 Mean and range of influent and effluent PSD of the 8 October 2008 rainfall event.....	33
Figure 48 Mean and range of influent and effluent PSD of the 23 October 2008 rainfall event.....	34
Figure 49 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 20 March 2008 event.....	35
Figure 50 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 16 May 2008 event.....	36

Figure 51 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 3 June 2008 event.....	37
Figure 52 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 10 June 2008 event.....	38
Figure 53 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 21 June 2008 event.....	39
Figure 54 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 8 July 2008 event.....	40
Figure 55 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 15 July 2008 event.....	41
Figure 56 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 29 July 2008 event.....	42
Figure 57 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 8 August 2008 event.....	43
Figure 58 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 12 August 2008 event.....	44
Figure 59 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 19 August 2008 event.....	45
Figure 60 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 10 Sept 2008 event.....	46
Figure 61 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 20 September 2008 event.....	47
Figure 62 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 8 October 2008 event.....	48
Figure 63 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 23 October 2008 event.....	49
Figure 64 Box plot representation for flow rate and constituent concentration description.....	50
Figure 65 Coupled relationship between flow rate, influent and effluent sediment solid mass concentration and removal efficiency.....	50
Figure 66 Coupled relationship between flow rate, influent and effluent settleable solid mass concentration and removal efficiency.....	51
Figure 67 Coupled relationship between flow rate, influent and effluent suspended solid mass concentration and removal efficiency.....	51
Figure 68 Coupled relationship between flow rate, influent and effluent SSC concentration and removal efficiency.....	52
Figure 69 Coupled relationship between flow rate, influent and effluent dissolved phosphorus concentration and removal efficiency	52

Figure 70 Coupled relationship between flow rate, influent and effluent sediment phosphorus concentration and removal efficiency	53
Figure 71 Coupled relationship between flow rate, influent and effluent settleable phosphorus concentration and removal efficiency	53
Figure 72 Coupled relationship between flow rate, influent and effluent suspended phosphorus concentration and removal efficiency	54
Figure 73 Coupled relationship between flow rate, influent and effluent total phosphorus concentration and removal efficiency	54
Figure 74 Coupled relationship between flow rate, influent and effluent nitrate concentration and removal efficiency	55
Figure 75 Coupled relationship between flow rate, influent and effluent ammonia concentration and removal efficiency	55
Figure 76 Coupled relationship between flow rate, influent and effluent total dissolved nitrogen concentration and removal efficiency.....	56
Figure 77 Coupled relationship between flow rate, influent and effluent sediment total nitrogen concentration and removal efficiency.....	56
Figure 78 Coupled relationship between flow rate, influent and effluent settleable total nitrogen concentration and removal efficiency.....	57
Figure 79 Coupled relationship between flow rate, influent and effluent suspended total nitrogen concentration and removal efficiency.....	57
Figure 80 Coupled relationship between flow rate, influent and effluent total nitrogen concentration and removal efficiency	58
Figure 81 Temperature, conductivity and pH behavior during the filter retention time following the 8 October 2008 event.....	59
Figure 82 Redox Potential behavior of the runoff stored into the filter system during retention time	60
Figure 83 Nitrate-N behavior of runoff stored into the filter system during retention time	60

INTRODUCTION

This chapter examines the in-situ testing phase of the project and the objective are to assess the nitrogen, phosphorous and particulate matter removal of the engineered soil filter media described in the previous chapter. This chapter examines the intra- and inter-event behavior and management of such a system.

The detailed investigation of the engineered soil media with respect to mass transfer behavior carried out in the first part of the project through isotherms, kinetics, breakthrough, and desorption evaluations resulted in the choice of a soil-based oxide media as compared to a suite of other media. This media was prepared and a treatment system based on the engineered soil was designed and constructed.

The scope of the field testing includes the in-situ intra-event data collection and analysis of 15 rainfall-runoff events, treatment thereof, and inter-event drainage management. Specifically, this chapter assesses the intra-event transport and fate of phosphorus and particulate matter (PM), and the inter-event fate of nitrogen species as well as the treatment and fate of these constituents through the clay-based oxide media filtration that provided surface complexation (ion exchange-adsorption-chemical precipitation) for dissolved phosphorus species and filtration of PM-bound TP.

The inter-event behavior of the engineered soil filter media system is examined after each captured event for a period of up to 13 days between captured events in order to examine the water chemistry drainage management strategies where the water surface in the soil filter system is maintained under two separate conditions: (1) a retention runoff level below the soil filter system resulting in an unsaturated soil filter condition, but with sufficient retention to saturate the settled sludge layer at the bottom of the system, or (2) a retention runoff level above the soil filter system resulting in prolonged saturated conditions for the entire system.

METHODOLOGY

Experimental Site

The area of interest is the University of Florida Reitz Union paved surface parking facility watershed in Gainesville, FL. The catchment drains to inlet A shown in Figure 1. In order to evaluate the catchment dimensions in terms of drained area a survey of the monitored paved surface parking facility was performed. The aim of the survey was to evaluate the topographic contour lines and thus the paved surface parking facility area drained by the inlet of interest. The surveying equipment used is constituted by a theodolite, steel surveying tape and an elevation rod. Due to the topography of the catchment, two benchmarks were needed as starting (control) points for subsequent surveys to establish the elevation of nearby points. The surveyed area was preliminarily defined through the observation of the University of Florida as-built maps. In particular the UF drainage system map allowed evaluation of the potential drainage area which is constituted by two main sub-catchments: the parking area located at the south-east side referred to inlet A and the access road along the northwest side. The entire area was successively divided in 100-square-foot plots. The measured points were the junctions of the resulting 10-foot-side grid. Field measurements were reported in terms of differentials in height between horizontal planes and the survey points in the rectilinear survey grid. The contour lines were drawn (Figure 2). The paved surface parking facility area drained by the inlet collecting runoff is shown in Figure 3. Considering the low slope values characterizing the monitored area, particularly the paved surface parking facility area (approximate E-W 3% and N-S 1.5% slope), the contributing area extension has the potential to be influenced by rainfall intensity and wind direction. Depending on the storm event, the watershed area can vary from 400 to 600 m², with a calibrated median range of approximately 450 to 500 m².

Sorptive Filter System and Monitoring System

The monitoring station design was driven by the monitoring procedures related to the physical-chemical processes investigated. Several processes are analyzed in this phase of the project with the focus of field-scale testing of the soil-based filter media selected from the bench scale testing. Nutrients and particulate matter (PM) removal efficiency are investigated in saturated and unsaturated conditions. Rainfall-runoff chemistry is monitored across the treatment system during rainfall events and at the same time any stored runoff chemistry is measured during dry weather periods between storm events.

The treatment system is shown in Figure 4. The system consists in a lysimeter tank (22'' internal diameter, 36'' high) containing a soil mesocosm (18.5'' diameter, 22'' high). The treatment system dimensions are designed based on the hydraulic flow rates determined from the site characterization study. The treatment system is equipped with an inlet and a drainage system (for inter-event periods monitoring) located at the height of 8'' from the bottom of the system. Gate valves are installed at the latter sections as shown in Figure 4. The bypass system and the outlet consist of 3'' pipes, and the latter equipped with a gate valve. Flow to and through the system is gravity-driven. The pressure in the system is less than 2 lb/in² (psi); corresponding to the maximum head due to the difference in elevation between the water level at the upstream sample collection section and the outlet section of the system. The runoff filters through the soil and drains by gravity through the outlet. In order to investigate the head loss caused by the soil

media during rainfall events, continuous head measurement is performed at the upstream and downstream sections of the filter media. Two 1-psi pressure transducer (model PDCR-1830 1 psig) manufactured by DRUCK Inc. are used for this purpose. The lysimeter is equipped with a manometer consisting in 1" clear PVC pipe instrumented with a pressure transducer measuring the upstream head. Downstream head is measured through another pressure transducer installed into the drain pipe at the same elevation of the upstream transducer. Measured differences in water depth provided the head loss. Continuous data are acquired through a data logger connected to the pressure sensors. The data logger used is the CR1000 model manufactured by Campbell Scientific Inc. and the logger is powered by battery.

In order to continuously monitor influent runoff chemistry indices quality into the lysimeter before intra-event treatment and during inter-event periods a multi-parameters sensor is installed in the cylindrical tank at the elevation of 6" from the bottom of the lysimeter (Figure 4). The sensor model is YSI 600XLM-M Multi-Parameter Water Quality Logger. Such sensor measures continuously and automatically the water chemistry parameters: pH, redox potential, conductivity and temperature. The YSI has an internal battery and data storage capacity.

During rainfall events, influent runoff is conveyed from the catchment to the treatment system. Runoff is transported to the treatment system after collection by catch basin inlet A. The cylindrical manhole is characterized by a 9 inches high inlet at the top and a 6 inches diameter outlet pipe at the bottom. For monitoring purposes runoff is bypassed through a 6" PVC pipe equipped with a butterfly valve connected at the inlet section of the manhole and conveyed to the filter media system located in the downstream toe of the slope (East side of the inlet) (Figure 5). Runoff samples are collected upstream and downstream of the treatment system. The upstream section is located 15 feet east from the inlet (Figure 6). Flow depth is measured by a 1 inch Parshall flume manufactured by Warminster Fiberglass Inc., for flow rate determination before discharging in a drop box. The Parshall flume is equipped with an ultrasonic sensor (model Shuttle Level Transmitter) for water depth measurement connected to a data logger (model 4-20mA) manufactured by MJK Inc. The upstream sample collection section is located at the drop box section. Duplicate influent samples are taken at each sampling time. From the drop box runoff is conveyed to the treatment system through a PVC pipe (Figure 5). The treatment system is located 31.5 feet west of the flow rate measurement system (Parshall flume). In Figure 7 the monitoring system is shown. From upstream to downstream, it is possible to observe the system set-up consisting of the Parshall flume, the drop box, the treatment system and the piping.

The site is equipped with two tipping bucket rain gauges manufactured by ISCO Inc. and by Texas Electronics Inc. (0.01 inches bucket capacity) located at the roof of the Stormwater Unit Operations and Processes (UOPs) laboratory of the research group. The watershed is located about 580 feet north-east of the UOP laboratory. Two additional rain gauges located at the Physics Department of the University of Florida at the west side of the catchment and at the Dental Tower of the University of Florida (W4DFU Weather Station - ID KFLGAIN10 of Weather Underground) at south-east side of the catchment are close to the catchment and provide a validation of rainfall intensity measurements (Figure 8).

The roof of the UOPs laboratory has been equipped also for the rainfall chemistry monitoring. In addition to the runoff samples, this rainfall is also collected before reaching the ground to characterize the atmospheric constituents washed-off by rainfall. Four acid-washed and DI water-rinsed Pyrex troughs are used for rainfall collection for the duration of an event.

Calibration Procedure and Hydraulic Conductivity Test

Calibration of MJK Ultrasonic Sensor for Flow Depth Measurements

A Shuttle Ultrasonic sensor (Unit # 200570) manufactured by MJK was mounted 30 inches above the invert surface of the 1 inch Parshall flume and at the 2/3(A) location on the flume. The ultrasonic sensor had an accuracy of ± 0.04 inches. The sensor is connected to a logic unit equipped with a display that converts the voltage signal to water depth once the sensor is installed and leveled in the system has been calibrated. Initial setup consisted in the unit selection (inches) and the adjustment of zero level selecting it as absolute reference value. First, the invert surface of the 1 inch Parshall flume was cleaned and dried. Once the surface had been prepared, a sensor measurement was obtained. This measurement was set to be the zero depth or “control” reading.

Successively a series of discrete depths were generated and measured for the expected range of flow depths in order to produce a calibration curve for the Parshall flume. Rectangular wooden blocks of measured height were placed on the clean, dry invert of the flume to a known (measured) height, directly underneath the ultrasonic sensor, and corresponding depth readings were noted. Depths were measured from 0.5 inches to 10 inches, in ten increments, utilizing appropriately-sized wooden blocks. Once this series of measurement pairs was completed a calibration curve was developed to establish a relationship between the measured value and the reference one corresponding to the distance from the sensor to the surface of the block. Replicated readings were made and standard deviations from replicated readings were calculated.

Parshall Flume calibration

A fiberglass Parshall flume (manufactured by Warminster Fiberglass) was installed as the flow measurement device located at the upstream sampling section of the monitoring system. An in-situ calibration of the flume was performed. The calibration phase was required considering the experiment is operated in a field set-up. The inlet section of the Parshall flume was modified to avoid any PM deposition in the system. Transport of PM drove the slope of the 6” influent pipe.

The influent configuration consisted of the flume mounted on a support, connected through the influent piping with a 6% slope. The system was equipped with a butterfly valve. In Figure 9 the in-situ calibration set up is shown. 20 reference flow rates in the range 0.1 to 8.2 L/s were generated. The flow rate was measured volumetrically. A minimum of three replicates for each run were performed. Water depth values were acquired every second through the MJK ultrasonic sensor. In Figure 10 the calibration curve resulting from the regression analysis fits the theoretical power law curve with slight deviation at very high flow rates.

Pressure Transducers calibration

The two 1-psi pressure transducer (model PDCR 1830 1 psig) manufactured by DRUCK Inc. were connected to the CR1000 data logger manufactured by Campbell Scientific Inc. During the calibration phase the real time data were acquired and monitored by using a notebook computer connected to the data logger. Initially pressure data were reported as mV and voltage reading was converted to water depth data (ft) through the development of a calibration curve for each pressure transducer. The calibration phase consisted in placing the transducers in a container

filled with water under static conditions. Water depth was physically measured with an engineering scale at a temperature of 20°C at a resolution of 0.01". The water depth measures were correlated with the voltage measures acquired through the data logger. After plotting voltage measures against the water depth a linear regression procedure provided the multiplier and offset parameters. The latter parameters are the input values needed by the data acquisition program to obtain the required data format for each sensor.

YSI 600 XLM sensor calibration

Conductivity:

Prior to calibration, the sonde was put into the Run mode and the sensor readings in air were observed to ensure that the conductivity reading were less than 3- μ S/cm in air. If the readings were much higher (>10 μ S/cm), a probe cleaning/maintenance procedure was needed. The conductivity cell and thermistor were subsequently fully immersed into the calibration/transport cup filled with standard solution (in the same range values as the runoff characteristic of the monitored watershed). After the conductivity readings stabilize and did not significantly change for approximately 30 seconds; at least 1 minute was required for temperature equilibrium to occur. After equilibration the stable value was entered in the software.

pH:

As for pH, a 2 point or 3 point calibration procedure can be performed. The procedure is very similar to the conductivity procedure and requires pH buffer solutions of 4, 7 and 10. At least 1 minute for temperature equilibration is required before a reading is taken. Once the calibration procedure is selected the buffer value is entered in the software and the mV reading at a given pH is entered once no significant changes are observed for approximately 30 seconds. Such procedure starts with pH 7 buffer and it is repeated for the other point after rinsing the sensors in de-ionized (DI). The mV readings for a pH 7 buffer should be in the range of -40 to +40, between 140 to 220 in pH 4 buffer and -140 to -220 in pH 10.

Redox (oxidation-reduction potential, ORP):

Unlike pH, YSI 6-series sondes only allowed a single point calibration for redox that requires an offset adjustment. Also for the redox calibration a standard solution was needed and the procedure is exactly the same performed for the other two parameters, pH and conductivity. The redox value, i.e. the voltage reading from the Ag/AgCl electrode, can be converted to an eH value, i.e., the voltage reading of the Standard Hydrogen Electrode (SHE), by adjusting the offset through two methods. In the first method, it was possible to add or subtract an offset voltage to the redox readings obtained with a practical reference electrode to account for the fixed difference between the SHE and the other reference system. For example, the potential of Zobell solution with the Ag/AgCl reference electrode using 4 M KCl is +228 mV while the same solution reading for the SHE is +428 mV. Therefore to convert redox readings taken under these conditions to eH, it is possible to add 200 mV to the redox voltage.

In the second method the software was programmed to add the offset voltage to the redox readings as the readings were displayed or logged. This method was implemented during calibration of the redox sensor in the YSI 6-series sonde. For example, when calibrating the probe with Zobell solution that has a redox reading of 228 mV for the YSI reference electrode it was possible to enter the redox value of this solution for the SHE. After the calibration is checked the difference between Ag/AgCl and SHE reference electrodes will automatically be

added to all displayed and logged redox values by the software, converting readings to eH with no further correction needed. The water temperature for which redox was determined influences the voltage output of the sensor. Temperature was accounted for in the calibration procedure through a manual input of the correct reference value corresponding to the standard temperature.

Hydraulic Conductivity Test

In order to assess the clogging (filter ripening) of the soil media an “empty-bed” head loss evaluation was performed; as typical for a water or wastewater filtration test. This test was conducted with clean water to provide the initial soil media head loss and hydraulic conductivity values before these values change due to filter ripening. Such behavior is compared over time with the intra-event head loss. Figure 11 illustrates the testing set-up. The system was connected to the water feed line equipped with a butterfly valve for flow rate control. The flow rate was measured volumetrically. A minimum of three replicates for each run were performed. Water head values were acquired every second through the two Druck pressure transducers located upstream and downstream the filter media and connected to the CR1000 data logger. Figure 12 summarizes the method, data and results with the regression analysis of the data.

Monitoring Methodology

From a practical point of view, a minimum of approximately 0.1 inches of rainfall was set as a threshold for a rainfall-runoff event, along with three previous dry days, slightly less than the (mean time between storms, MTBS) for Alachua County depending on the dry or wet season. Despite the current probabilistic and predictive tools and the proximate watershed location on campus; this depth constraint and spatial variability of rainfall events resulted in the capture of one qualifying event for every three to four events for which the monitoring team mobilized. Each mobilization required two hours of setup and calibration, and two hours of de-mobilization.

Whether or not a mobilization led to a successful capture of a qualifying event, the decision to mobilize began with monitoring of radar models and systems such as WSR-88D from the National Weather Service (NWS). Other radar tools included www.wunderground.com which also utilizes NWS data and algorithms. Graphical outputs from these models provide a reasonable estimate of rainfall intensity, trajectories, coverage area, duration and depth; once calibrated spatially and temporally. When a radar model (typically Wunderground) indicates that a rainfall event of sufficient intensity, spatial coverage and trajectory is entering Alachua County from any direction, with a trajectory and sufficient intensity, the monitoring team and site are mobilized; with the likelihood of the storm occurrence within two hours for the study watershed. Within two hours, the monitoring station is assembled; all the sensors consisting in the YSI multi parameter sensor, the MJK ultrasonic level sensor, the Druck pressure transducers connected to the CR1000 data logger, the rain gauge are checked, zeroed, programmed, synchronized and activated. Two synchronized stopwatches (influent and effluent) are used for the sampling phase. If the storm tracks in a direction that eventually does not cross the watershed, or dissipates before reaching the watershed, equipment at the site was de-mobilized and stored for the next event.

Runoff samples were taken manually at two sampling points upstream and downstream the treatment system at regular intervals in the range of two to five minutes at the beginning of the event but in general the frequency was decided based on radar and rainfall/flow intensity.

Automated sampling based on flow may provide adequate sampling of dissolved constituents but cannot representatively sample PM or constituents associated with PM. Since the behavior of a storm is not known a-priori, programming either volumetric or temporal increments of sampling for a storm of unknown duration is not possible unless the increments become very large. The ability to set sampling intervals based on flow volume intervals for the duration of the storm is uncertain at best. In many cases with auto-sampling, besides unrepresentative sampling, samples are either taken at too coarse of an interval to ensure sampling across the entire event, or sampling that occurs at too fine of an interval does not result in the entire capture of the runoff duration. Sampling intervals can be based on an approximate a priori knowledge of the seasonal weather patterns and information compiled from radar imagery systems (Sansalone and Cristina 2004; Appel and Hudak 2001), but on an event-scale this is still inadequate. If auto-samplers could obtain representative samples, a representative flow-weighting could be created by taking many (for example 30 to 50) individual autosampler volumes at shorter intervals during an event. While each sample would be non-representative, the flow-weighting of a composite sample for an event mean concentration (EMC) would be representative. However, even with 30 to 50 samples per event, an auto-sampler cannot representatively sample the hetero-disperse influent PSD (Sansalone and Kim 2008, Kim and Sansalone 2008). Additionally, auto-samplers could not meet the volumetric and replication requirements of this monitoring campaign. As a result, manual sampling of the full cross-section of flow was conducted throughout this study for influent and effluent samples, with mathematical compositing based on measured flow volume and time. This is a much more difficult and laborious process, but provides representative results and material balance checks (Sansalone and Kim 2008, Kim and Sansalone 2008). If there is a need for an accurate representation by a sampling method, the current, common and pragmatic paradigm of wastewater-style sampling and samplers for rainfall-runoff does not fulfill this need. Therefore the field monitoring phase was designed for manual sampling.

Three sets of replicate samples of distinct volumes, namely four at 0.5 L, two at 1.1 L (nominally 1 L), and two at 4.0 L were utilized for the influent. This scheme was also used for the effluent with the exception that the 4.0 L samples were replaced with 20.0 L samples (5 gallon buckets). The 4.0 L or 20.0 L samples were used to recover sufficient sediment-size PM from each sample. Paired and replicated 0.5 L replicate samples were utilized for particle size distribution (PSD) analysis of each sample with paired suspended sediment concentration (SSC) data. For a given replicate (A or B) a PSD sample was paired with an SSC sample to convert the PSD (on a volume % for a given particle size from 0.01 to 2000 μm) to a gravimetric concentration (mg/L) given a precisely-measured sample volume (nominally 500 mL). For each sample replicate the particle size analyzer (Malvern Instruments: Hydro 2000G Mastersizer) proved a volume % PSD that was converted to a gravimetric result using the paired SSC result.

The 1.1 L replicate samples were used for turbidity measurements. After the turbidity measured was conducted each sample was wet sieving in order to separate and collect sediment-size particles (larger than 75 μm). The nominal 1.0 L sieve filtrate (typically less than 1000 mL) was then placed in an Imhoff cone for one hour to recover the settleable-size fraction of PM (PSDs ranging from approximately 75 to 25 μm) for inorganic PM ($\rho_s \approx 2.6 \text{ g/cm}^3$) for each sample. The suspended PM fraction (nominally 25 to 1 μm) that remains suspended in the Imhoff Cone was recovered from the recovered supernatant using membrane filter and pressure or vacuum fractionation column.

The 1.1 L replicate samples were used for all the probe-based analyses of water chemistry indices and alkalinity (50 mL). The dissolved constituents such as ions, dissolved organic carbon (DOC), chemical oxygen demand (COD), Total Dissolved Nitrogen (TDN) and Total Dissolved Phosphorous (TDP) required a sample volume of approximately 200 mL taken from the supernatant of the settled runoff from the Imhoff Cone.

For rainfall collection, four acid-washed and DI water-rinsed Pyrex troughs were situated on the roof of the research facility where is located the rain gauge at a height of 5 m above the ground.

Flow rate was measured continuously through the Parshall flume. Rainfall depth at increments of 0.01" or one minute intervals was acquired with the rain gauges. Head loss through the filter media was measured continuously. The YSI sensor was programmed to obtain measurements every 15 seconds for the pH, conductivity, redox and temperature inside the system. During inter-event periods the chemistry of runoff subject to one of the drainage management methods was monitored by the YSI sensor and by manual sampling in order to examine the chemical reaction and development of anaerobic conditions and changes to nitrogen species. One manual sample per day was analyzed and pH, redox, temperature and conductivity were monitored with the frequency of 15 minutes by the YSI sonde.

Rainfall and Runoff Analysis

After collecting intra-event samples during a runoff event, samples are taken back to the laboratory for analysis (within six hours). The rainfall is also recovered for immediate analysis. After returning samples (or a subset of early samples for longer duration events) to the laboratory the first step in the analysis of samples is water chemistry indices for rainfall followed immediately by analysis of the 1.1 L runoff samples. The 1.1 L samples were used to determine water chemistry indices of runoff, specifically: pH, alkalinity, conductivity, temperature, redox, dissolved oxygen (DO), salinity and total dissolved solids (TDS). These indices were measured using calibrated probes and instruments or using titration methods. Probes whether for direct measurement or titration were calibrated before usage with at least a three-point calibration.

In parallel with measurements of water chemistry indices, laser diffraction was also conducted to determine PSDs from a set of 0.5 L runoff samples. The laser diffraction particle analyzer (Malvern Instruments: Hydro 2000G) was operated in a batch mode analysis. Before analysis, each sample was pre-screened through a #4 (2000 μm) sieve to ensure that PM or debris larger than 2000 μm were not introduced into the laser chamber. For samples taken during the initial runoff where PM were high and therefore obscuration was out of range and a volumetric dilution with a known volume of DI water to the nearest mL was required. For all samples, with or without dilution, the volume of the sample was required. Once a sample was introduced into the wet chamber of the analyzer multiple analyses were required (from three to ten) until stability (repeatability) across the gradation was achieved. Output from the instrument is percent finer by volume for each particle size. Elaboration of these data also requires a SSC analysis (concentration, volume and therefore mass) from the 0.5 L SSC sample that is paired with the 0.5 L PSD sample. The combination of a % particle volume distribution with the assumption of a mean particle density across the PSD allows SSC mass distribution across the PSD to convert % finer by volume to % finer by mass.

The SSC measurements were not as time sensitive as PSDs. SSC analysis was conducted within one day, otherwise samples were refrigerated. A paired 0.5 L sample was filtered through a nominal 1 μm glass fiber depth filter with a vacuum or pressure pump. The filters are washed with DI water, dried and weighed before use. After filtering a sample of known volume the filter and PM material separated on the filter were dried at 105 $^{\circ}\text{C}$. The difference in dry weight provides the mass of PM and the filtered volume permits conversion to a concentration (as SSC). To determine the sediment PM fraction, larger volume samples were required. The influent 4.0 L samples and the effluent 20.0 L samples were utilized to recover sufficient sediment PM for required analysis of this PM fraction. Samples were filtered by pouring the entire sample volume through a 75 μm (No. 200) sieve. Sediment PM was recovered from the sieve for each sample; using a spatula and a stainless-steel pick; collected and placed in a clean, labeled and tared Petri dish for drying, obtaining a dry weight and used for sediment-fraction PM analysis.

The 1.1 L samples were analyzed separately at the same time PSD analysis was conducted. These samples were first screened to separate the sediment PM fraction by using the 75 μm (#200) sieve, were also used for turbidity analysis. The actual volume of the nominal 1.1 L runoff sample was first measured (since approximately 100 mL per sample was utilized for turbidity) and this remaining nominal 1.0 L volume was determined precisely using a graduated cylinder. The runoff that was passed through the sieve was recovered and placed into an Imhoff Cone without the loss of any PM that had passed through the #200 sieve. Each Imhoff Cone with a precisely-measured volume of sample was settled for 60 minutes. The settleable PM settle to the bottom of the Imhoff cone. The settleable PM was carefully recovered from the Imhoff Cones by slowly decanting the supernatant from the cone and obtaining the PM from the bottom of the cone. The settleable PM was placed in clean, labeled and tared Petri dishes; which were dried, weighed and used for settleable-fraction PM analysis.

A volumetric fraction of the recovered supernatant from each Imhoff Cones (almost 200 mL) was then passed through a pressurized stainless-steel fractionation column fit with a prepared 0.45 μm membrane and an air pump. The filtrate was utilized immediately (or preserved) for determination of ions. Approximately 120 mL was required for nitrate (NO_3^-), nitrite (NO_2^-), ammonia ($\text{NH}_3\text{-NH}_4^+$), total dissolved nitrogen (TDN), total dissolved phosphorus as phosphate (PO_4^{3-}), sulfate (SO_4^{2-}), chloride (Cl^-), and dissolved chemical oxygen demand (COD). All ions were measured by a HACH DR 5600 spectrophotometer. The remaining filtrate solution was then divided in two vials for DOC (40 mL) and the dissolved metals (30 mL) concentrations. The samples in these vials were acidified and maintained at 4 $^{\circ}\text{C}$. The 0.45 μm membranes for each sample resulting from fractionation were preserved at 4 $^{\circ}\text{C}$ for suspended TP analysis.

The balance of the supernatant volume, approximately 800 mL from each nominal 1.1 L sample, (after 100 mL was removed for turbidity before the Imhoff Cone and 200 mL removed for ions after 60 minutes of settling in the Imhoff Cone) was then used to determine the suspended PM fraction; as truly total suspended solids (TSS). 100 to 200 mL from the recovered and well-mixed supernatant was used to separate the suspended solids through a vacuum pump and filters. The nominal 1 μm filters were then dried in the oven at 105 $^{\circ}\text{C}$. The filters were prepared in advance and tare-weighted before use. The difference in the tare filter weight and filter + TSS provides the mass of TSS. With a known volume of filtrate this is converted to a concentration.

Sulfate was analyzed by a HACH SulfaVer® 4 Reagent Powder Pillows (USEPA method 375.4). Sulfate ions in the sample react with barium in the SulfaVer 4 and form a precipitate of barium sulfate. The amount of turbidity formed is proportional to the sulfate concentration. Test results are measured at 450 nm. 10mL of sample was added to a square glass vial, and then a packet of SulfaVer® 4 Reagent was added in order to show color. 10 mL of sample without reagent was used as blank. HACH DR 5600 spectrophotometer was used to determine the absorbance. The analysis was conducted within the first 12 hours after the sample was collected; or samples were preserved at 4°C.

Chloride was analyzed by a HACH chloride test kit, including a Ferric Ion Solution and a Mercuric Thiocyanate Solution. 10mL of sample was first added to a square glass vial, then 1.0 ml of Mercuric Thiocyanate Solution and 0.5ml of Ferric Ion Solution were added and swirled in order to show a yellow-brown color. The blank sample was made with deionized (DI) water and adding reagents. The method allows samples to be stored at room temperature for 28 days since chloride analysis is not time sensitive.

COD was also analyzed by a HACH COD Digestion Reagent Vials. After adding 2 mL of sample into the COD Digestion Reagent Vials, the vial was heated at 150°C for 2 hours. Absorbance was measured through a HACH DR 5600 spectrophotometer. COD-free DI water was used as blank. Samples for COD can be stored. This analysis needs to be performed as soon as possible, but samples treated with sulfuric acid to a pH of less than 2 (about 2 mL per liter) and refrigerated at 4 °C can be stored up to 28 days. In this project, COD analysis was always conducted in the first 6 hours.

Alkalinity was analyzed through acid titration method. 0.02N sulfuric acid was used as the titrant, and 50ml of sample was needed for each run. Bromocresol Green was used as the indicator. A calibrated pH meter was also used for assistance.

DOC was measured through the UV- Persulfate TOC analyzer, DOHRMANN Phoenix 8000 (Standard Method 5310C/EPA 415.1 and 9060A/ ASTM D4779 and D4839). The DOC measurement involves 1) oxidizing the organic carbon in the sample, 2) detecting and quantifying the oxidized product (CO₂). The process utilizes persulfate oxidation along with UV irradiation. The CO₂ produced is convected by a stream of nitrogen gas to a nondisperse infrared detector sensitive to the absorption frequency of the carbon dioxide. 40 ml sample allowed performing three replicate measurements per sample. The sample was previously filtered through 0.45 µm filter and preserved at 4 °C after being acidified by adding 0.1 mL of sulfuric acid. The first 5 duplicate (A and B) influent samples were diluted by a dilution factor of 2 just before the analysis. The machine required calibration. A calibration curve was developed in order to convert absorbance readings to concentration values. Through a standard solution 7 reference samples with concentrations ranging from 0 to 150 mg/L were created and used. The coefficient of determination coefficient was 0.9 or higher.

As for metals measurement, the Inductively Coupled Plasma - Mass Spectrometry (ICPMS) was used.(Standard method 3120-B) 30 ml of filtrate after the fractionation was collected separately; this sub-sample was then acidified by adding 0.1mL of concentrated nitric acid to keep the pH below 2. The preserved samples can be stored for 6 month at 4°C. The analysis typically required 10 to 15 mL of samples.

Sodium ion was measured through a Glass Membrane Sodium Combination Ionic-Selective Electrode (Fisher Scientific Accumet). A sodium electrode ion strength adjuster was used for this analysis.

Nutrient Analysis: The following components of nutrients (Nitrogen, Phosphorus) were measured by the spectrophotometer (Hach DR 5600).

Phosphorus:

1. Total Dissolved Phosphorous (TDP)
2. Sediment-bound Total Phosphorus (Sediment-TP)
3. Settleable-bound Total Phosphorus (Settleable-TP)
4. Suspended-bound Total Phosphorus (Suspended-TP)

The method used for the measurement of phosphate (soluble reactive phosphorous) (orthophosphate) is Standard Method 4500-P-E Ascorbic Acid method. A HACH DR 5600 spectrophotometer was used to determine the concentration values of phosphate once calibrated. To determine the various fractions of PM-bound total phosphorus, small quantities (approximately 0.5 g, measured to the nearest 1 mg) of sediment and settleable PM were acid-digested. To determine the TP bound to suspended PM, the 0.45 μm membranes utilized from Imhoff Cone supernatant were acid-digested. The acid-digestion method converts all the forms of phosphorus associated with PM to ortho-phosphate which is measured according to the method explained above.

Nitrogen:

1. Nitrate (NO_3^-)
2. Ammonia ($\text{NH}_3\text{-NH}_4^+$)
3. Nitrite (NO_2^-)
4. Total Dissolved Nitrogen (TDN)
5. Sediment-bound Total Nitrogen (Sediment-TN)
6. Settleable-bound Total Nitrogen (Settleable-TN)
7. Suspended-bound Total Nitrogen (Suspended-TN)

For analysis of total dissolved nitrogen (TDN), and total nitrogen (TN) bound to sediments, settleable and suspended PM, persulfate digestion method was utilized. Sample fractions were utilized in the test, an alkaline persulfate digestion converts all forms of nitrogen to nitrate. Sodium metabisulfite is added after the digestion to eliminate halogen oxide interferences. Nitrate then reacts with chromotropic acid under strongly acidic conditions to form a yellow complex with an absorbance maximum at 410 nm. The absorbance was measured by a HACH DR 5600 spectrophotometer. For TDN analysis, the sample was the filtrate; For TN-sediment and TN-settleable, the sample was consist of a known mass of PM added to 2 mL of DI water; For TN-suspended, a 2 mL sub-sample of the Imhoff Cone supernatant was used, and the TN-suspended was calculate by subtracting the TDN fraction from the supernatant TN (containing TN-suspended and TDN).

Nitrate analysis was conducted immediately after fractionation. A HACH NitraVer® 5 Nitrate Reagent Powder Pillow was used (standard method 4500- NO_3^- -E Cadmium Reduction Method). 10mL of sample was added to a square glass vial, and then a reagent was added. 10 mL

of sample without reagent was used as blank. HACH DR 5600 spectrophotometer were used to determine the absorbance.

Ammonia analysis is also time sensitive and was conducted immediately after the end of the storm event. A HACH Low Range Test 'N Tube AmVer™ Nitrogen Ammonia Reagent was used to perform this analysis. The method used is called Salicylate Method. At first, 2 mL of sample was added to one AmVer™ Diluent Reagent Test 'N Tube™, in which Ammonia compounds combine with chlorine to form monochloramine. Then a packet of Ammonia Salicylate Reagent Powder Pillow and a packet of Ammonia Cyanurate Reagent Powder were added. After 20 minutes of reaction, a green solution is presented. 2 mL of DI water was prepared in the same way and used as a blank. Test results are measured by a HACH DR 5600 spectrophotometer.

Nitrite analysis requires immediate analysis. A HACH Test 'N Tube NitriVer 3 Nitrite vial was used. The method used is called Diazotization Method, Nitrite in the sample reacts with sulfanilic acid to form an intermediate diazonium salt. This couples with chromotropic acid to produce a pink colored complex directly proportional to the amount of nitrite present. 5ml of sample are needed. After adding sample to the vial which has reagent powder inside, 20 minutes reaction time is needed for color display. 5mL of DI water was prepared in the same way and used as a blank.

Table 1 summarizes the analyses performed for the influent and effluent sample as well as rainfall and stored runoff in the soil media filter system. Table 2 and Table 3 summarize the standard methods, sample volume, preservation and maximum holding time for each analysis. Table 4 summarizes the YSI sensor characteristics.

As part of the QA/QC protocol, each probe was calibrated one day before each analysis. For all the ions analysis procedures where the spectrophotometer was used, calibration curves were developed from known standards. Each calibration curve must include at least 5 data points and the coefficient of determination R^2 must be higher or equal to 0.99. Each time a new lot number of reagent was used, a new calibration curve was performed. The absorbance was then converted to concentrations by the specific calibration curve.

A data control procedure was performed immediately after the analysis was completed. Concentration values were checked to be within a reasonable range, based on literature values and experience. If any unusual result was found, the analysis was performed again.

Data Analysis and Elaboration

Volumetric rainfall-runoff coefficients

The runoff coefficient in this study is a volumetric based coefficient ranging from 0 to 1 which represents the fraction of runoff resulting from a given volume of rainfall across an event (Cristina and Sansalone 2003). The volumetric runoff coefficient can be expressed as the following equation 1:

$$C = \sum_n \frac{Q_n}{I_n A_w} \quad (1)$$

In this expression Q_n represents volumetric flow rate of the n th interval observed at the outlet in $[L^3/T]$; I_n is rainfall intensity of the n th interval in $[L/T]$; and A_w is contributing area of the watershed, respectively, in $[L^2]$. It is noted that during a storm the contributing area is not static.

Event Mean Concentration (EMC) and Removal Efficiency

As a comparative index, EMC is often used to characterize concentrations that represent a flow average concentration for the event (Huber 1993, Sansalone et al. 2005). The concentration of nutrients or PM transported in urban runoff can vary by orders of magnitude during individual storm events and EMC is often used to characterize the flow average concentration of the entire storm event as shown in equation 2.

$$EMC = \frac{M}{V} = \bar{C} = \frac{\int_0^{t_r} c(t)q(t)dt}{\int_0^{t_r} q(t)dt} \quad (2)$$

In this expression, M is the total mass of a constituent (for example, phosphorus) over the entire event duration; V is the total volume of flow over entire event duration; $\bar{C}$ is the flow-weighted average concentration for entire event; $c(t)$ is the time-variable constituent fraction; $q(t)$ is the time-variable flow; t_r is the duration of the event and t is time.

While effluent concentration and mass are the appropriate metric for evaluating effluent, mass removal can also be quantified as a percent removal (PR) for any constituent on an event basis using the inflow and outflow loads (Kim and Sansalone, 2008). The following modified equation is the basic equation for calculating the percent removal rate of nutrients or PM.

$$PR(\%) = \frac{\sum_{i=1}^n (V_{i-IN} \cdot C_{i-IN}) - \sum_{j=1}^m (V_{j-EFF} \cdot C_{j-EFF})}{\sum_{i=1}^n (V_{i-IN} \cdot C_{i-IN})} \times 100 \quad (3)$$

In equation 12, V_{i-IN} and V_{j-EFF} are the volume of influent flow and effluent flow during sampling period i and j ; C_{i-IN} and C_{j-EFF} are the mean concentration associated with period i and j ; and n and m are the total number of influent and effluent measurements taken during an event, respectively.

Particle Size Distribution

The influent PM loading to the system is a hetero-disperse gradation of PM transported by rainfall-runoff. During each event, discrete influent sample sets are taken from the full cross section of flow throughout the duration of each event. At each sampling time a discrete

duplicate influent sample set was taken. The number of sample sets varied depending on the event duration. Each influent sample set contained a 0.5 L sample for PSD and a paired 0.5 L sample for SSC. Since the laser diffraction instrument measured PSDs as relative particle volume concentrations [$\mu\text{L/L}$], paired samples (at each sample time) were required per sample set; one sample for laser diffraction and one sample for gravimetric analysis. For each sampling time the measured gravimetric mass [as SSC in mg/L] was distributed over the entire PSD (in $\mu\text{L/L}$ per particle size increment) for each sample. Mass based cumulative PSD for the laser diffraction PM was computed by the integration of gravimetric concentration of individual particle sizes for discrete samples, corresponding flow rates and sampling time intervals. This sample pairing and analysis methodology allowed the conversion of PM total volume concentration (total volume concentration, TVC in %) for each particle size increment to a gravimetric concentration [mg/L]. The same PSD-SSC pairing was conducted for each duplicate sample set. Laser diffraction (Malvern Mastersizer 2000) provided total volume concentrations (TVC) for 100 PM size increments with analysis limits that ranged from 0.02 to 2000 μm .

Nutrient Distribution between Dissolved and Particulate Bound Fractions

Nutrients partitioning has implications for the transport and fate (treatment) processes and the bio-availability of a nutrient. The distribution of nutrients between dissolved and particulate bound fraction is a time-dependent dynamic process influenced by rainfall and runoff pH and redox potential, runoff particulate matter load, hydrology and pavement residence time. The distribution of nutrients can be expressed by the dissolved fraction (f_d) as shown in the equation below.

$$f_d = \frac{M_d}{M_d + M_p} \quad (4)$$

M_d = dissolved mass of total nitrogen (mg);

M_p = particulate-bound mass of total nitrogen (mg).

If f_d is higher than 0.5, the pollutant is mainly in dissolved form. The equilibrium partitioning coefficient, k_d , for dilute solutions expresses the ratio of pollutant mass normalized to the dry mass of PM to the pollutant concentration in solution. Assuming a linear isotherm, a partitioning coefficient can also be used to evaluate the distribution between a dissolved and particulate-bound constituent. Therefore, the partitioning coefficient accounts for the presence of PM in runoff. The partitioning coefficient is defined as:

$$k_d = \frac{C_s}{C} \quad (5)$$

C_s = particulate-bound pollutant mass-based concentration (mg/kg)

C = dissolved pollutant volume-based concentration (mg/L)

There is an inverse relationship between the dissolved fraction, f_d , and the partition coefficient, k_d , for a given pollutant as shown by the following equation:

$$f_d = \frac{1}{1 + k_d m} \quad (6)$$

In this expression m = PM concentration as TSS (kg/L), classically, or SSC (kg/L).

RESULTS AND DISCUSSION

Events Hydrology

Event-based hydrological indices including previous dry hours (PDH), rainfall depth (h_{rain}), duration of event (d_{rain}), maximum rainfall intensity ($i_{\text{rain-max}}$), as well as runoff volume and maximum and average flow rate influent and effluent were measured and recorded for a total of 15 storm events occurring between March 20, 2008 and October 23, 2008 as shown in Table 5. Each event has been analyzed and described individually. In order to understand the level of information needed, the description of the first monitored event March 20th 2008 is illustrated as an example.

This rainfall-runoff event was characterized by 0.28 inches of rainfall depth and 36 minutes of rainfall duration. The average intensity of rainfall was 11.5 mm/hr while the maximum intensity over one minute was 46 mm/hr. The previous dry hours value (PDH) is 230 hours considering the previous significant storm event on the 7th March 2008 characterized by 3.13 inches of rainfall depth. Between the latter event and the monitored storm event there was another rainfall event that occurred on 17th March, but the relative low depth of 0.17 inches and the high duration of 14 hours makes this event negligible in terms of potential wash-off by runoff.

In Figure 13 the hyetograph and hydrograph are presented together with the water level monitored in the 1 inch Parshall flume with the corresponding sampling time. The maximum influent flow rate is 3.4 L/s while the average value is 0.5 L/s. In Figure 14 the influent and effluent hydrographs are presented. The influence of upstream sampling on the head loss is clearly illustrated in Figure 15 where the head loss is plotted against the elapsed time together with the influent flow rate and the influent and effluent initial sampling time. It is possible to observe that the head loss values decrease immediately after the influent sampling. In these cases for low influent flow rate, there was no runoff for the effluent and the pressure transducers recorded as head loading the system.

Monitored storm events across the field test program, varied in duration from 35 minutes to 197 minutes. Resulting peak flow rates ranged from 1 L/s to 13 L/s. Events varied in total runoff volume ranging from 300 L on June 3, 2008 to 31,270 L on July 8, 2008. The 15 rainfall-runoff events monitored throughout this evaluation were representative of the storm events in the Gainesville climatic region. In Figure 16 rainfall statistics between August 1999 and July 2008 are reported. The historical rainfall time series data utilized consist of 10 years of hourly data from the Gainesville Regional Airport (GNV) station. The seasonality of rainfall events for GNV can be observed. Delineation can be made between a wet season occurring between June and September and a dry season occurring between October and May. The field scale testing started in March 2008 and ended in November 2008, so rainfall events from both seasons were monitored.

The initial pavement residence time (IPRT), or time of concentration (t_c) referred in Table 5 is the time required for rainfall to satisfy abstractions including pavement surface wetting and depression storage filling as well as the airborne re-suspension, and atmospheric evaporation. In comparing all 15 storm events IPRT results generally varied in the range of 3 to 12 minutes (Table 5) with an mean value of 5 min. In addition, IPRT was also controlled by a complex combination of previous dry hours (PDH) and abstractions during each storm (Sansalone et al. 2005).

Based on the flow characteristics (event mean flow rate and peak flow) the 15 storm events have been classified in low flow (LF), medium flow (MF) and high flow (HF) events with event mean flow rates less than 0.3 L/s, 0.3-0.9 L/s and greater than 0.9 L/s, respectively and peak flow rates less than 3 L/s, 3 - 8 L/s and greater than 8 L/s, respectively. In particular LF events were the events 3, 9 and 12, 13, 14, 15; events 1, 5, 8, 10 and 11 were classified as MF events and the remaining 2, 4, 6 and 7 events were the HF events. Runoff coefficients (C) were calculated for the 15 storms resulting in a mean value of 0.5. The lowest runoff coefficient was observed on the June 03, 2008 event characterized by low rainfall depth and intensity, while the maximum value was observed on the July 8 event characterized by the highest runoff volume. Resulting values of the runoff coefficient are typical of urban catchments: a study by Cristina and Sansalone (2003) on a small urban catchment in Cincinnati, Ohio revealed a similar runoff coefficient, ranging between 0.2 and 0.4 for low intensity events and 0.6 to 0.8 for high intensity events. The site hydrology was described for each of the 15 events by rainfall hyetographs and runoff hydrographs plotted in Figure 17 to Figure 31. The elapsed time was initialized to zero at the beginning of rainfall. The hydrographs were observed to respond quickly to fluctuations in rainfall intensity.

With regard influent and effluent hydrograph, due to the drainage management strategies adopted, the only attenuation observed was near the beginning of the event where the flow and volume were relatively low, thus even a small peak was attenuated at the beginning of the event. For hydrographs with larger peaks, no attenuation occurred because no additional volumetric capacity remained in the system. Therefore it is not surprising to see that there is no significant lag between the peak of influent and the peak of effluent especially for those storm events with relatively high intensity. Furthermore, a slight transition in time was also observed between the falling limb of influent hydrograph and falling limb of effluent hydrograph for MF event. The system was started in a drained condition for the first 13 storms and a fully un-drained saturated condition for the last two events. A significant attenuation was observed between the influent and effluent flow in LF event. For the field testing the system, as a volumetric lysimeter was not designed to be effective in terms of hydrological attenuation. Due to high runoff flow rate overflow was experienced in storms 1, 2, 4, 6 and 7. The time at which the overflow occurred was recorded to calculate overflow volume and the treated runoff volume.

Filter System Head Loss

As a critical parameter for stormwater soil filter systems used as a BMP, head loss impacts hydraulics and treatment performance. Low head loss can be as much of an indication of a poorly designed filter as high head loss. High head loss is an indication of either an improperly designed filter or a need for maintenance. One of the most important evaluations for this project is the measurement of head loss as an indicator of maintenance frequency as a result of soil filter occlusion (filter ripening).

Usually an initial head loss spike was caused by resistance to flow in the porous system because the media, initially at residual moisture content and the trapped specific deposit must be re-imbibed in the re-wetting process. Therefore as runoff imbibes the media the initial wetting must be satisfied generating some initial resistance to flow. Initially the intensity of flow can exceed the hydraulic conductivity of the media so there is a momentary build up of head with a high initial flow rate. Observing the last two events where the stored runoff was not drained and the system operated in saturated condition it emerges that there is no resistance to flow in the first part of the event (Event 14 – 08 October 2008 in Figure 33). In general, increasing head loss is a function of increasing flow throughout each event and peak head loss across the media filters occurs at peak loading from a storm.

Results of head loss behavior as a function of the flow rate during the monitoring program illustrate the evolution of head loss from the first two events to the last events (Figure 33). At the beginning of the monitoring program the system shows higher head losses if compared to the hydraulic conductivity test performed in controlled condition, empty bed conditions and clean water, but still a monotonically increasing relationship between head loss and flow rate can be observed. Starting from the third storm event we can observe that the head loss - flow rate relationship forms a hysteretic loop as shown in Figure 33 for the 10 June event. For a given flow rate the head loss is lower in the rising limb of the hydrograph and higher in the decreasing limb. As the flow rate rises and falls, with multiple hydrograph peaks, the head loss - flow rate curve may even exhibit multiple loops as shown by the 29 July 2008 event curve. This behavior is explained by the filter ripening within each event. The higher is the flow rate and usually the higher is the turbulence inside the system, thus the re-suspension of particles in the system that emphasizes the higher load of particles associated with higher flow rates.

Despite the different behavior of the head loss within each event, the head loss values tend to be higher with the use of the soil filter as shown in Figure 32 where events were divided chronologically in 3 categories and the head loss is plotted against the flow rate for each category. Measured data are then interpolated and the increasing slope of the curves clearly shows the filter clogging in time. At the same time the measured data become more disperse and the behavior of the head loss is less clear in time as shown by the coefficient of determination, R^2 that decreases with time.

Rainfall and Runoff Water Chemistry

Water chemistry indices were analyzed for rainfall, runoff (influent) and effluent for 15 rainfall-runoff events. Analyzed indices include: pH, redox potential, conductivity, salinity, total dissolved solids (TDS), dissolved oxygen (DO), turbidity, alkalinity, chloride, sulfate, dissolved chemical oxygen demand (COD) and dissolved organic carbon (DOC). The event mean values and ranges of variation are shown in Table 7 to Table 12. In addition, pH, redox potential, conductivity, salinity and TDS inside the filter system were also continuously monitored during each storm event by a YSI multi-parameter sonde.

Rainfall pH in urban area is usually weakly acidic because of oxides of nitrogen and sulfur (NO_x and SO_x) compounds in the atmosphere. The measured rainfall pH at this experimental site ranged from 4.2 to 4.7, with a mean value of 4.6. As the weakly acidic rainfall comes in contact with the surface, thereby picking up deposited particles, the runoff consequently becomes

a mixture of neutral PH. The event-mean pH of runoff ranged from 7.1 to 8.2, with a mean value of 7.5. During the course of a storm event, influent pH slightly decreases (about 1 standard unit), due to the decreased amount of pollutants on the pavement surface.

Effluent event mean pH ranges from 6.5 to 7.0, with 6.9 as the mean value. The lower pH values of the effluent runoff are due to the low pH of the inter-event runoff inside the soil filter system between storm events. The water remaining inside the filter system had a pH of about 6, due to increase in microbial activity and the resulting generation of the dissolved CO₂. The phenomena occurring in the filter system are explained in detail in the *Filter drainage management* paragraph. The first few effluent samples generated by storm runoff passing through the filter are strongly influenced by this retention of runoff in the filter system. Monitored pH results in the soil filter system indicate that when the initial runoff mixes with retained filter runoff that there is an increase in effluent pH from approximately 6 to 7 due to the mixing of influent and stored runoff. After this retained volume is discharged the system pH closely mimics the influent runoff pH.

Rainfall and runoff typically have high redox values due to highly aerobic condition in the atmosphere and at the thin layer of runoff along the watershed surface allowing for re-aeration. Rainfall redox potential ranges between +229 mV and +559 mV, with the mean value of +388 mV. The runoff event-mean redox is similar to rainfall, ranging from +226 mV to +427 mV, with a mean value of +334 mV. The influent redox does not show a significant intra-event variation. The effluent event-mean redox is lower than the influent, ranging from +200 mV to +473 mV, with +353 mV as the mean value. This behavior is similar to the pH. The stored runoff in the system has low redox value (about -200 mV) and when mixed with influent runoff decreases the influent redox potential. The inter-event results indicate that effluent redox behavior would first experience a reduction during the mixing and elution of stored runoff. Once stored runoff was eluted, effluent redox was similar to influent redox. A similar result is observed for dissolved oxygen (D.O. with a range between 4.7 mg/L and 8.8 mg/L with the mean value of 6.8 mg/L. The influent event-mean D.O. is close to rainfall D.O., ranging from 3.6 mg/L to 8.1mg/L, with the mean value of 6.1mg/L, Influent D.O. does not vary significantly within each event. Effluent event-mean D.O. yields a lower value, ranging from 3.1 mg/L to 8.2 mg/L, with mean value of 4.6 mg/L.

Influent conductivity is much higher than rainfall, due the entrained particulate and dissolved matter in runoff. Conductivity for rainfall is usually very low ranging between 4.4µS/cm and 69.7µS/cm with the mean value of 21.1µS/cm. The event-mean conductivity for runoff ranges from 13.0 µS/cm to 214.9 µS/cm, with a mean value of 87.1µS/cm. Influent conductivity decreased during each event due to the decrease in pollutant mass washoff. Effluent conductivity is almost twice as high as the influent, due to the high conductivity generated by the stored runoff in the system. The event-mean conductivity for effluent ranges from 24.7 µS/cm to 373.3 µS/cm; with 155.2 µS/cm as the mean value.

Given that salinity and TDS significantly contribute to conductivity; these constituents have similar behavior to conductivity. Rainfall salinity is less than 100 mg/L with the mean value of 10mg/L. The event-mean salinity of runoff ranges from 0.1 mg/L to 111 mg/L, with a mean value of 28.4 mg/L. The event-mean salinity for effluent ranges from 3.6 mg/L to 164.3 mg/L, with 68.6 mg/L as the mean value. The rainfall total dissolved solids (TDS) range between 2.0

mg/L and 35.0 mg/L with the mean value of 10.4 mg/L. The event-mean TDS of runoff ranges from 6.5 mg/L to 105.4 mg/L, with the mean value of 42.8 mg/L. The event-mean TDS for effluent range from 12.3 mg/L to 183.2 mg/L, with 76.0 mg/L as the mean value.

Runoff temperature increased at the beginning of the event due to the heat transfer from the pavement and then decreased gradually. Rainfall temperature ranged from 17.1 °C to 23.9 °C with a mean value of 22.1°C. The event-mean temperature of runoff ranges from 19.7 °C to 27.8 °C, with the mean value of 23.5 °C. The event-mean temperature for effluent ranges from 21.0 °C to 25.4 °C, with 23.1 °C as the mean value.

The event-mean alkalinity of runoff is much higher than the rainfall, ranging from 9.5 mg/L to 56.7 mg/L as CaCO₃, with the mean value of 32.3 mg/L as CaCO₃. Influent alkalinity decreased during each event due to the gradual decrease of alkalinity-generating constituents available for washoff. The rainfall alkalinity is usually very low, essentially 0; indicating PM and infrastructure, and possibly soil from the raised vegetated islands are the major sources of alkalinity. As shown, rainfall alkalinity ranges from 0 to 6.0 mg/L as CaCO₃ with the mean value of 1.9 mg/L as CaCO₃. The event-mean alkalinity for effluent is higher than the influent, ranging from 14.0 mg/L to 105.2 mg/L as CaCO₃, with 50.9 mg/L as CaCO₃ as the mean value, due to the high alkalinity of the stored runoff in the system at the beginning of the event. During each event, effluent alkalinity decreases over time.

Chloride values in rainfall ranged from 500 µg/L to 1294 µg/L with the mean value of 740 µg/L. The event-mean chloride of runoff is much higher than rainfall, ranging from 532 µg/L to 26700 µg/L, with the mean value of 6565 µg/L. Influent chloride decreased during each event. Being a conservative ion in an aqueous systems, no significant variability is observed between influent and effluent chloride values. The event-mean chloride for effluent ranges from 506 µg/L to 30401µg/L, with 6901µg/L as the mean value.

The rainfall sulfate ranges from 71µg/L to 2425 µg/L with the mean value of 857 µg/L. The event-mean sulfate of runoff ranges from 51µg/L to 15183 µg/L, with the mean value of 5294 µg/L, which is much higher than the rainfall value. Influent sulfate decreased during each event. For effluent, the event-mean sulfide ranges from 1400 µg/L to 50398 µg/L, with 10280 µg/L as the mean value. The sulfide increase is due to the stored runoff inside the filter system with a transformation of sulfate to sulfide under low redox conditions.

The rainfall chemical oxygen demand (COD) ranges from non-detect to 33.8 mg/L with the mean value of 6.6 mg/L. The event-mean COD of runoff range from 18.2 mg/L to 259.0 mg/L, with the mean value of 93.0 mg/L, which is much higher than rainfall COD. The effluent event-mean COD ranges from 11.1mg/L to 169.4 mg/L, with 73.8mg/L as the mean value.

Particulate Matter (PM)

Particulate matter include sediment PM, settleable PM, suspended PM, turbidity, suspended sediment concentrations (SSC), and volatile suspended sediment concentration (VSSC) fractions for 15 rainfall-runoff events have been analyzed. The event-mean concentrations (EMC or values) and ranges of variation of influent and effluent runoff are shown in Table 1 and Table 2. While PSDs and PM are influenced by catchment geometry, land use and land use activities such as traffic, as well as geology and event hydrology, results are also influenced by differing

methodologies. For example, studies have concluded that automatic samplers are not designed to representatively sample coarser hetero-disperse PM of denser particles as compared to lighter and suspended wastewater flocs subject to steady flow for which such devices were designed (Furumai et al., 2002; Li et al., 2005). Automated samplers combined with measurements of PM (as TSS, compounding the accurate representation of PM) may be applied effectively for the suspended fraction in contrast to hetero-disperse source area PSDs.

The difficulty in comparing results with other studies is not only due to sampling methodology but also to the analyses performed. TSS is often used in many studies as a quick and common gravimetric index for PM. Studies show that coarse PM larger than 75 μm is easily separated from runoff (Andral et al., 1999) and less acutely bio-available, leading to decisions that treatment should be focused on the suspended PM fraction (Kim J. and Sansalone J., 2008). But the interest in the entire non-colloidal gradation, including suspended, intermediately-sized settleable PM and sediment PM, is important for several reasons. While larger particles have lower pollutant concentrations by definition (Sansalone and Buchberger, 1997; Roger et al., 1998; German and Svensson, 2002; Lau and Stenstrom, 2005), examination of the entire gradation indicates that pollutant mass is distributed across the gradation with a significant amount potentially associated with coarser fractions when such fractions dominate the gradation (Sansalone and Cristina, 2004). Results in Table 9 illustrate the high concentration of sediment PM. The event mean concentration (EMC) of sediment PM varied from 102 mg/L (08 July event) to 1835 mg/L (03 June event), with the median concentration of 296 mg/L (21 June event) and average EMC of 453 mg/L. From a hydraulic point of view, coarser PM can be retained in the treatment system, generate premature maintenance, is more labile than suspended PM; can cause clogging and generally reduce hydraulic properties of the drainage system.

These values are higher than concentrations reported in the literature. The rainfall turbidity ranges between 0.4 NTU and 5.1 NTU with the mean value of 1.9 NTU. The runoff event-mean turbidity ranges from 9.8 NTU to 162.3 NTU, with the mean value of 80.5 NTU. The effluent event-mean turbidity ranges from 4.3 NTU to 74.0 NTU, with 30.6 NTU as the mean value.

If compared with the PM data resulting from a monitoring program at a Baton Rouge, LA paved urban watershed (Ying G. and Sansalone J., 2008) it is possible to compare PM loads from each site. The Baton Rouge watershed is Interstate-10 over City Park Lake characterized by an average daily traffic (ADT) of 142000 vehicles. On a concentration basis the settleable fraction dominated the suspended as well as the sediment fraction for this source area watershed. In comparison the settleable and suspended concentrations; the finer PM from the Baton Rouge watershed was much higher than the Reitz Union paved surface parking facility site. On the contrary the sediment fraction in the Florida catchment is an order of magnitude higher than for Baton Rouge. Considering the same sampling methodology and analyses for both studies this difference is due mainly to the PM sources: concrete and tire abrasion by high traffic loads for Baton Rouge and biogenic material from raised vegetated curbed median strips with trees for the paved surface parking facility area in Gainesville.

The EMC of settleable PM for runoff (influent) varied from 16 mg/L (08 July event) to 159 mg/L (03 June event), with the median concentration of 53.1 mg/L (10 September event). The EMC of suspended PM for runoff (influent) varied from 15.3 mg/L (08 July event) to 95.7 mg/L (20 September event), with the median concentration of 59.9 mg/L (21 June event). The EMC of

SSC for runoff (influent) varied from 89.3 mg/L (15 July event) to 2049.9 mg/L (03 June event), with the median concentration of 400.5mg/L (21 June event).

The influence of the hydrology is evident in PM build-up and wash-off phases. The 3 June 2008 event shows the highest value of sediment and settleable PM despite the very low flow rate. This event was characterized by a significant previous dry period of 432 hours. The higher events in terms of flow rate being the 8 and 15 July 2008, illustrated the lowest EMCs. The PDH values were low, 141 and 66 hours respectively and the second event was also influenced by the intensity of the previous storm. The event mean VSSC/SSC fractions for runoff (influent) varied from 30% (15 July event) to 60% (03 June event), with an average value of 48%. These values are significant and higher than ratios reported in the literature and higher than the Baton Rouge watershed. For example for highway land use, PM from rainfall-runoff processes is largely inorganic, with a specific gravity in the range of 2.3 to 2.7 and a volatile fraction generally less than 30% (Sansalone et al., 1998).

Particle Size Distribution (PSD)

The normalized cumulative particle size distribution (PSD) data for influent and effluent are plotted in Figure 34 through Figure 48. The area bounded by the lower and upper curves represents the variation of the PSD curves during the storm, and is developed by plotting the maximum and minimum normalized values for each particle diameter. This result represents the envelope of all the PSD curves obtained for each sample of the storm. For example, in the 20 September event shown in Figure 46, the normalized value of the 20 μm particle diameter on the effluent PSD is 50%, but over the course of the storm, the value ranges from 26% to 72%. The percentages finer by mass, d_{15} , d_{50} and d_{85} values for each event are presented in Table 15 and Figure 49 through Figure 63. The d_{85} represents the particle diameter in which 85% of the particles by mass are less than or equal to that value. Similarly, d_{50} and d_{15} represents the particle diameter in which 50% and 15% of particles by mass are less than or equal to that value.

The width of the PSD influent envelope is indicative of the PSD variability as a function of hydrology, traffic and previous dry days. The figures also demonstrates that the influent PSD is very hetero-disperse, ranging from 2,000 to less than 1 μm . In contrast, the effluent PSD is more mono-disperse and much finer ranging from 100 to less than 1 μm . Effluent PSDs are significantly less variable than the influent PSDs.

The overall shape of the influent PSD was relatively consistent across the 15 storm events sampled. The average influent d_{15} , d_{50} and d_{85} ranged from 7 μm to 102 μm , 36 μm to 333 μm and 253 μm to 798 μm respectively across the 15 storm events. Interestingly, irrespective of influent PSD, and influent flowrate, the average effluent PSD does not deviate significantly across storm events. This suggests the selectivity in PSD and flow attenuation by the soil filter. The average effluent d_{15} , d_{50} and d_{85} ranged from 3 μm to 10 μm , 16 μm to 35 μm and 52 μm to 106 μm respectively across the 15 storm events. Due to the observation that the average effluent d_{50} shows a slight decreasing trend with time from the first storm event to the last storm event, it is hypothesized that in part due to the effects of filter clogging, the filter is able to selectively separate finer particles.

The incremental variations of the average influent and effluent d_{15} , d_{50} and d_{85} with respect to the runoff hydrograph of each individual storm event are shown in Figure 49 to Figure 63. The

values of d_{15} , d_{50} and d_{85} clearly mirror the hydrograph for both influent and effluent particles. The filter behavior is a function of flow rate, a key influencing variable of performance. This is confirmed by the relative parallel trends between influent and effluent d_{15} , d_{50} and d_{85} . It should be noted however, that the values of the d_{15} , d_{50} and d_{85} for the influent are clearly driven by hydrology and previous dry hours. This accounts for a slight deviation for the 15 July 2008 storm, due to the fact that the previous storm on 8 July 2008 was a very high intensity storm, and the influent PSD range is large, suggesting the entrainment and transport of a wide gradation and large mass of PM. This in turn resulted in a narrow influent PSD for the 15 July 2008 storm due to insufficient previous dry hours, and is correspondingly reflected in the plots for d_{15} , d_{50} and d_{85} .

The most intense events were the 10 June, 8 and 15 July and 19 August with peak flows of 11.0 L/s, 13.2 L/s, 13.1 L/s, 6.8 L/s respectively. The 10 June event experienced the highest d_{15} and d_{50} values of 102 μm and 333 μm respectively also because characterized by a really significant PDHs value. The least intense events were the 20 September and the 3 June event with peak flows of 1.08 L/s and 0.75 L/s and resulting d_{50} and d_{85} values of 79 μm and 411 μm , and 152 μm and 779 μm respectively. The difference between the two events is due to the availability of PM on the watershed, a function of the PDHs that for the June event are double. Storm 15 had even lower d_{50} and d_{85} values than 20 September, however, because the storm was composed of two clearly defined peaks, pavement washout conditions prevailed for the second half the storm.

Phosphorus

The measured total dissolved phosphorus (TDP), Sediment P, Settleable P, Suspended P and total phosphorus (TP) concentrations are presented in Table 16 and Table 17 in terms of EMCs values and range of variation for the 15 monitored events for influent and effluent runoff. Median, mean and standard deviation values were also calculated for the EMCs of all monitored events for each P fraction.

In general P concentration values resulting from the watershed are significant and suggest the requirement for concentration and load control before discharging in water bodies. It has been reported that the EMC for total phosphorus in urban runoff is 0.33 mg/L and dissolved phosphorus is 0.12 mg/L (USEPA 1984), and Brown et al. (2003) reported that a total phosphorus concentration of 0.3 mg/L is adequate to describe both new and old urban development. The P concentration values resulting from the Reitz Union paved surface parking facility were much higher. The TP mean EMC value of 3.5 mg/L is an order of magnitude higher than concentrations reported in the literature. Since traffic was low, and not generally a significant source of nutrients, the only significant sources of N and P in the catchment are biogenic. These sources are raised vegetated curbed median strips with trees and vegetation. As a result of leaf fall, vegetation die off or maintenance such as grass-cutting significant loads of biogenic material are deposited on the impervious pavement and washed off. Additionally, identification of the coarse and more volatile fraction of this biogenic PM is due to the sampling methodology adopted for this study that sampled the entire cross-section of flow and the floatable or gross PM. In this study 20 L samples were collected at the influent every 2 to 5 minutes depending on the hydrograph. In a normal monitoring program through automatic sampling the sampling frequency is fixed, missing many times the peak of the flow and usually the intake of the sampler is equipped with a strainer to avoid any intake pipe clogging. Such an automated sampling methodology is like having a pre-filtration of the sample. Additionally the

sample volume capacity in automatic sampler is usually 1 to 2 L, thus limiting many times the type and number of analyses that need to be performed.

Results indicated that the EMCs of each P fraction varied by an order of magnitude for both influent and effluent over a range of hydrological events. These trends of variation did not follow the increasing order of event statistics. This is possibly due to the hydrologic complexity and stochastic response for a small watershed subjected to urban loadings, traffic loadings, during and between events and antecedent dry period. However it is possible to observe that the events with the highest P values were the 3 June and 29 July one (TP EMC > 6 mg/L), characterized by a significant PDH affecting the availability of material (particulate matter and biogenic material) on the surface and a medium to low flow rate and rainfall intensity that influenced the average pavement residence time (APRT) and thus the dissolved P concentration. The two events characterized by the highest flow rate, the 8 and 15 July events, showed the lowest TP EMCs also because characterized by the lowest PDH values. It is noted that the EMCs are only endpoint information and cannot impart any information regarding process behavior.

The distribution of P between particulate bound and dissolved fraction was also investigated in this study. Table 18 shows the mean value and the range of variation of the distribution coefficient (f_d) and the equilibrium coefficient (K_d) for each event with regards to influent and effluent flow. It is clear from the mean value calculated for all the monitored event, 0.31, that the form in which P is more likely to distribute is the particulate-bound form. With respect to the different PM fractions, the suspended and sediment PM had the highest affinity to P. This result is due to the high sediment concentrations, noting that the biogenic PM material, the main P source for this watershed, is largely in the sediment PM fraction, being defined as the particles larger than 75 μm . The sampling methodology that consisted of collecting the full cross section influent and effluent flow, allowed consideration of the larger anthropogenic and biogenic material often ignored in many studies due to automatic sampling. At the same time PM analysis revealed a very low settleable concentration for the watershed. The affinity of a constituent to suspended PM is due to the larger specific surface area. However, the gravimetric mass of suspended PM is low so the P mass associated with suspended PM is also relatively low. PM-bound P concentration, i.e. phosphorus content per particulate mass in each gradation, [mg/g], generally increases with decreasing particle size as would be expected given that PM phase concentration is normalized to particulate mass which decreases with smaller particle size.

Events with higher flow rate had generally lower values of the f_d coefficient due to the more significant transport of PM and thus of PM-bound P. For medium to low flow rate events and higher APRT it is possible to observe higher f_d values within the event; thus a predominant dissolved fraction. With respect to effluent flow, the partitioning of P revealed a predominant suspended fraction due to the very low concentration of dissolved and sediment P and the absence of settleable PM.

Nitrogen

Dissolved nitrogen species (NO_3^- -N, NH_3 -N, NO_2^- -N, TDN) and PM-bound total nitrogen (sediment-TN, Settleable-TN, Suspended-TN) based on 15 monitored events have been analyzed for this project (NO_2^- -N are only available for the last five monitored events). The event-mean concentration (EMC) and range of variation are presented in Table 19 and Table 20. Median, mean and standard deviation values were also calculated for the EMCs of all monitored events

for each N species and fractions. In general, nitrogen concentrations from the experimental site are typical of urban rainfall-runoff, albeit somewhat higher. For example, Duncan et al. (2005) reported that the mean nitrate-N concentration of storm flow in Melbourne, Australia is 740 µg/L, while the value for this site is 1042 µg/L.

Since the watershed is a paved surface parking facility with raised vegetated islands, the major sources of nutrients are largely biogenic with anthropogenic contributions. These biogenic sources can be the vegetated curbed median strips with trees and some soil cover. Results indicated that the EMCs of each N fraction varied by an order of magnitude for both influent and effluent over a range of hydrological events. Concentrations of most nitrogen species were highly variable during storm events, which are caused by variations in aerial deposition and rainfall quality, traffic loading and past and present catchment activities (Duncan, et al., 2005). However, the trend within each storm is more predictable, which always shows a decrease along with time.

For each event, the initial NO_3^- -N concentration was always high with an average initial value of 2594 µg/L. NO_3^- -N concentration dramatically decreased during each event and the final NO_3^- -N concentration was about only 14% of its initial value (average final value = 362 µg/L). The event mean concentration (EMC) of nitrate-nitrogen for runoff varied from 363 µg/L (12 August event) to 2663 µg/L (8 July event), with the median concentration of 680 µg/L (16 May event), while the mean concentration of rainfall is 741 µg/L. The 8 July event was characterized by the highest runoff flow rate and rainfall duration, and 12 August event has only 93 hours of PDH.

NH_3 -N is a less predominant species of dissolved nitrogen in runoff, the ratio of NO_3^- -N: NH_3 -N is about 10:1 (nitrite concentration is negligible). NH_3 -N includes both ammonium and ammonia in the equilibrium aqueous phase. According to the pH of runoff (approximately 7 for this watershed), the major form of NH_3 -N should be ammonium (NH_4^+). For each event, the initial NH_3 -N concentration was always high (mean value 309 µg/L), then NH_3 -N concentration dramatically decreased during each event, and the final NH_3 -N concentration was about only 7% of its initial concentration (mean value 20 µg/L). The event mean concentration (EMC) of ammonia-N for runoff varied from 4 µg/L (10 September event) to 326 µg/L (20 March event) with the median concentration of 70 µg/L (20 September event), while the mean concentration of rainfall is 88 µg/L.

The index, total dissolved nitrogen (TDN) represents almost half of the total nitrogen. TDN includes both inorganic (TIN) and organic (TON) nitrogen in the aqueous phase, therefore the difference between TDN and TIN (NO_3^- -N, NH_3 -N and NO_2^- -N) is TON. The event mean concentration (EMC) of TDN for runoff varied from 937 µg/L (12 August event) to 4469 µg/L (08 July event), with the median concentration of 2150 µg/L (08 August event), while the mean concentration of rainfall is 1153 µg/L. The TDN concentration behavior during events showed a significant decrease in time ranging from an average initial value of 7382 µg/L to an average final concentration value of 1077 µg/L.

The event mean concentration (EMC) of sediment-TN for runoff varied from 120 µg/L (15 July event) to 5608 µg/L (03 June event), with the median concentration of 778 µg/L (08 August

event, 10 September event). The initial sediment-TN concentration (mean initial value of 6785 µg/L) decreased during each event. The final sediment-TN concentration was less than 1% of its initial concentration (mean value 45 µg/L). The event mean concentration (EMC) of settleable-TN for runoff varied from 53 µg/L (15 July event) to 689 µg/L (03 June event), with a median concentration of 298 µg/L (10 September event, 20 September event). A significant decrease was observed during each event with average values ranging from 969 µg/L to 24 µg/L. The event mean concentration (EMC) of suspended-TN for runoff varied from 157 µg/L (23 October event) to 2000 µg/L (08 August event), with a median concentration of 717 µg/L (16 May event, 03 June event). An mean decrease of the concentration value of 90% occurred during each event.

The event mean concentration (EMC) of TN (sum of all TN fractions) for runoff varied from 1386 µg/L (15 July event) to 10967 µg/L (03 June event), with a median concentration of 4522 µg/L (19 August, 08 August events). The initial average TN concentration was 15513 µg/L while the final TN concentration was approximately 10% of the initial value (mean value 1685 µg/L).

The distribution of N between PM-bound and dissolved fraction was also investigated in this study. According to the mean EMCs for each nitrogen species, the ratio of TDN: sediment-TN: settleable-TN: suspended-TN is 7:4:1:2, which means that quantitatively, the dissolved fraction is close to the sum of the PM fractions. Among the different PM-bound fractions, the sediment and suspended fraction had the highest capacity for N. This result is due to the high sediment concentrations noting that the biogenic material is a major N source for this watershed. As with phosphorus and PM the sampling methodology of manually collecting the full cross section influent and effluent flow, allow sampling of biogenic and coarse anthropogenic material; often unaccounted for by automatic sampling and sub-sampling. The settleable concentrations for the watershed are very low since there is a low fraction of settleable PM while the larger suspended PM fraction with higher specific surface area results in higher suspended PM mass and total surface area with higher TN mass associated with the suspended fraction. The mass-based particulate-bound nitrogen concentration, i.e. nitrogen mass per PM mass in each gradation, [mg/kg], generally increases with decreasing particle size as would be expected given that solid phase concentration is normalized to particulate mass which decreases with smaller particle size.

The dissolved fraction (f_d) and equilibrium partitioning coefficient (k_d) and the range of variation are reported in Table 21. Events with higher flow rate had generally lower f_d values due to the more significant transport of PM and thus of PM-bound TN. For medium to low flow rate events with higher average pavement residence time (APRT), higher f_d values within the event can be observed, which implies that dissolved fraction is the predominant species. As shown, the event mean f_d values varied from 0.35 (08 October event) to 0.78 (21 June event), with the median of 0.60 (16 May event, 10 September event). The mean k_d values of runoff for each event varied from 2649 L/kg (16 May event) to 56967 L/kg (15 July event), with the median of 11973 L/kg (08 August event, 10 September event).

Metals

Metal elements, only analyzed in dissolved form, were evaluated for all 15 rainfall-runoff events, including with a focus on calcium, magnesium, copper, lead, zinc and sodium. Among these constituents, calcium and magnesium are mainly due to inorganic compounds such as

limestone and are important for affecting the hardness of water; copper, lead and zinc are typically related to vehicular traffic and infrastructure and are important for metals toxicity; sodium is a very common cation, and it is especially useful examining soil swelling. The EMCs of these constituents and ranges of variation are summarized in Table 22 and Table 23.

Results indicate that runoff event mean concentration (EMC) of magnesium ranges from 0.85 to 3.5 mg/L, with a mean value of 2.0 mg/L. Runoff EMC of calcium ranges from 7.5 to 28.2 mg/L, and the mean value is 13.5 mg/L. A previous study in Baton Rouge, LA shows higher values with the mean runoff EMC of magnesium of 5.9 mg/L and calcium of 126 mg/L (Dean, et al., 2005). The lower concentrations observed are a direct result of lower traffic load across the watershed of this study. The Baton Rouge site is a concrete-paved roadway with higher levels of abraded concrete material that was capable of going into solution. Effluent magnesium and calcium concentration are almost twice than the influent generated from the PM trapped within the soil filter system. This PM is labile when subject to changing chemistry conditions and microbiological activity during the retention period. This resulted in an increase in dissolved concentrations. Concentrations of copper, zinc and lead are low (lower than 100 µg/L), which can be explained by less anthropogenic and traffic loads. In addition, EMCs for copper, zinc and lead do not show significant difference between influent and effluent, which means the soil filter does not have a significant adsorptive impact on these divalent cations and their complexes. Given the net positive charge on the soil porous media (due to oxides of Al) a significant adsorption of cations would not be expected. On an intra-event basis the influent concentration tends to decrease over time as expected due to the decrease of pollutants on the pavement.

Soil Filter Media

The removal efficiency of PM, P, and N of the porous soil filter system is presented through a box plots which summarize the statistical measures of median, upper and lower quartiles and minimum and maximum values of the incremental constituents concentrations across each individual event. As an index of pollutant reduction, the EMC are presented as cross marks in all cases. The same plots are used for flow rates as shown in Figure 64. Figures for each particulate matter constituents are shown in Figure 65 through Figure 68. As shown, the mean removal efficiency for SSC is significant, at 85%. The removal efficiency for sediment PM exceeds 90% with settleable and suspended PM removal efficiencies of 60% and 50% respectively. Figure 65 illustrates that the sediment PM removal efficiency results is lower for the 16 May 2008 and 8 and 15 July 2008 events characterized by the highest flow rates irrespective of the influent PM concentration that varied significantly between the events (848 mg/L, 102 mg/L and 58 mg/L respectively). The significant removal efficiencies for sediment PM remain constant during the entire monitoring program, suggesting that the filter clogging phenomenon described in the *Head loss* paragraph of the present report, is not affecting the sediment removal efficiency. Trapping the sediment PM in the filter has significant implications for maintenance of any system.

Removal efficiency for settleable PM was influenced by both flow rate and influent concentrations. The highest flow rate events were the 16 May 2008; and 8 and 15 July 2008 which showed the lowest removal efficiency, at the same time the highest removal efficiency was experienced in the 3 June, 29 July and 19 August events characterized by the highest influent concentration values (Figure 66). With regard to the suspended PM fraction, the removal efficiency showed significant variability with no clear behavior if compared to the other

fractions. Re-suspension of PM in the stored runoff in the system occurring at the beginning of the events likely influenced the effluent concentrations and thus the removal efficiency. Observing results in Figure 68 regarding SSC removal efficiency, results indicate that the efficiency does not show significant variability throughout the monitoring program despite increased filter ripening after 15 rainfall events.

The measured TP, TDP, sediment P, settleable P and suspended P concentrations are presented as the box plots in Figure 69 through Figure 73. Usually EMC values cannot be used in a mechanistic evaluation of a treatment process, but only tabulated as a nominal index or part of statistical analysis, since an EMC cannot impart any information regarding process behavior; only endpoint information. Thus, changes in phosphorus loads were determined from influent and effluent concentrations and flow data to quantify the performance of the system. TP, TDP and particulate P (PP) removal efficiency was calculated over the 15 storm events monitored. Flow rate and removal efficiency values for each event and for each P fraction have been reported in the same plots.

Dissolved phosphorus removal through chemical adsorption and particulate phosphorus (PP) removal by physical filtration were observed. High removal efficiencies were observed for sediment P and TDP. In particular results indicated that the TDP and sediment TP removals ranged from 18 to 97% with average removal efficiency of 67% and from 70 to 99%, with average value of 87% respectively. Minton et al. (1996) claims that values for mean removal can be misleading as the range of removal rates for each individual event can be very large. Among 15 storm events monitored in this study, 13 events reached a TP removal above 70% and 10 events reached a TDP removal above 60%. In this respect, the soil media filter illustrated excellent removal capability for dissolved phosphorus and particulate phosphorus in spite of uncontrolled hydraulic and hydrologic event characteristics including the flow rate, previous dry period, the duration and intensity of the storm, and the urban loading frequency.

Particular attention is given to flow rate which has critical influence on phosphorus removal; noting there was little flow attenuation provided by the lysimeter housing the soil media filter. The lower the flow rate and the higher the time of contact between the media and the runoff the more effective is the media for adsorption and filtration. As shown in the figures, relatively low percentage mass removals of TP (less than 50%) are observed in May 16, July 8, July 15 events which generated considerably high flow (greater than 400 L/min) compared to other events monitored in this study. Typically high flow events are associated with lower suspended TP and dissolved P. Such a phenomenon is less evident for TDP removal. In general, dissolved phosphorus removal by soil media is more likely controlled by adsorption onto the media surface sites. This functionality of adsorption based soil media depends on surface area, pore size, charge, and ability to not desorb, specifically as quantified through conducting sorption isotherms, kinetics and breakthrough analyses (Wu et al. 2008). On the other hand, particulate phosphorus removal is expected to correlate with the PM gradations as well as PM removals. It is noted that the lowest removal efficiency of dissolved P (18%) was experienced for the 19 August event. This event was characterized by a medium to low influent EMC of 0.4 mg/L and by a medium to low total runoff volume of 1461 L. The difference between this event and the other events consists in the quality of the stored runoff inside the filter system at the beginning of the rainfall event and the hydrologic characteristics. After a period of 6 days from the previous event the dissolved phosphorus concentration in the filter was 5.5 mg/L, a high value. Phosphorus concentration values increase during retention periods due to desorption of

phosphorus. Furthermore the phosphorus solubility increases under decreased pH and redox conditions (more detailed on the stored runoff chemistry will be provided in the Drainage Management section). The first effluent sample concentrations were a mixture of stored runoff and influent runoff mixed in the system. The concentration of the first samples were higher, thus causing an apparent decrease in removal efficiency calculated as a function of the mass influent and mass effluent due to the stored runoff quality. This event differed also because of the low volume and because of the low duration of the event. The hydrograph is a single high flow peak and a short duration. This category of event in general is associated with lower removal efficiencies. The combination of hydrologic characteristic and high concentration in the filter explain the uniqueness of this event.

Generally high levels of particulate phosphorus or TP removal can be achieved when capturing high levels of PM. A previous research study identified that higher concentrations of particulate-bound phosphorus [mg/g] is associated with finer PM fractions (Vaze et al., 2004) consistent with the definition of increasing PM concentration with decreasing PM size. Given the higher biogenic PM load that is sediment-size or larger high concentrations of P were observed to be associated with the sediment fraction. Besides the evident ripening of the soil filter (head loss) difference in removal efficiency as a function of the time/events are muted. Dissolved P removal efficiency remains more or less constant and very high during the whole monitoring program. The same can be observed for particulate P. The main variables affecting the removal efficiency are hydrology, PDHs, influent runoff quality, stored runoff quality and filter clogging. Besides this variability the filter maintained high performance for P removal.

The measured NO_3^- -N, NH_3 -N, NO_2^- -N and TDN, sediment-TN, Settleable-TN, Suspended-TN concentrations are presented as the box plots in Figure 74 through Figure 80. TN, TDN and particulate-bound TN removal efficiency was calculated over the course of 15 storm events monitored. Flow rate and removal efficiency values for each event and for each N fraction have been reported in the same plots. Physical filtration has been observed for some particulate bound TN fractions. As shown in the figures, the filter system has a significant removal capacity on sediment-TN (mean 90%) and settleable-TN (mean 70%); suspended-TN does not show obvious treatment efficiency due to its fine particle size. However, it is noted that this media adsorption system is not designed for intra-event dissolved nitrogen species treatment, therefore, the results do not favor removal for NO_3^- -N, NH_3 -N, NO_2^- -N and TDN. The correlation between flow rate and removal efficiency is not evident. As shown in Table 20, where effluent N species concentrations are reported, the ratio of TDN: sediment-TN: settleable-TN: suspended-TN is about 50:1:2:14. Therefore, the dissolved part is the predominant part of pollutant for runoff effluent, which is caused by the repartitioning of particulate bound N, and the degradation of the biogenic materials in the soil filter. Suspended TN is the predominant fraction among the particulate bound TN. In addition, finer particles tend have higher nitrogen concentration due to higher specific surface area (Vaze et al., 2004), which is consist to the mass-based particulate-bound nitrogen concentration of this report. The dissolved fraction and equilibrium partition coefficient of effluent are listed in Table 21 and the mean f_d value is 0.93.

Drainage Management

Water chemistry indices for inter-event retention periods were monitored between each rainfall-runoff event. The mean concentrations and range of variation are shown in Table 24 and Table 25. Monitored water chemistry indices include pH, conductivity, salinity, TDS, redox

potential, alkalinity, turbidity, nitrate-nitrogen, ammonia-nitrogen, total dissolved nitrogen (TDN), total dissolved phosphorus as phosphate (TDP), sulfate, chloride, dissolved chemical oxygen demand (COD) and dissolved organic carbon (DOC).

The hydraulic retention time (HRT) ranges from 87 hours to 385 hours in the soil filter lysimeter. During each retention period, multiple samples were manually taken and the sampling frequency changed from 2 sample per day to one per day after the first 3 days of retention. The number of total samples per retention period ranged from 7 to 17, with 13 samples as the average. pH, conductivity, salinity, TDS, redox potential were monitored throughout the entire retention period.

The most significant phenomenon occurring in the filter system is the variation of redox conditions. It can be observed that redox potential quickly decreased from about +200 to -200mV during each retention period, which means that oxygen was quickly consumed by the microbial organisms inside the system until anaerobic conditions were reached. Nitrate-nitrogen decreased from about 3000 $\mu\text{g/L}$ to 100 $\mu\text{g/L}$ which indicates that nitrate had become an electron acceptor through de-nitrification after oxygen was depleted. The end product of nitrate is nitrogen gas. Sulfate also decreased from about 3000 $\mu\text{g/L}$ to 50 $\mu\text{g/L}$, which means sulfate also become an electron acceptor by reducing into sulfide. COD increased from about 50 mg/L to 200 mg/L which can be explained by the increase of reduced-state pollutants such as ammonia and sulfide.

Since ammonia-nitrogen increased from about 60 $\mu\text{g/L}$ to 2000 $\mu\text{g/L}$, and the total dissolved nitrogen increased, it is reasonable to assume that ammonia concentration value is not due to the transformation of nitrate, but to the mineralization of organic matter. Dissimilatory nitrate to ammonia (DNRA), which is a complicated biogeochemical reaction under extreme anaerobic conditions, is not likely to happen in this system due to the strict requirement of such a reaction (Tiedje, 1988). However, more detailed research such as isotope element tracing will be needed in order to specify the pathway of ammonia. Based on this assumption, a routine cleaning maintenance (or “back wash”) is recommended in order to reduce ammonia concentration.

The results indicate that pH decreased slightly from 7 to 6, and alkalinity increased from about 50mg/L to 250 mg/L as CaCO_3 , which can also be explained by the activity of microorganisms. When oxygen is consumed by microbial organism, carbon dioxide is generated, which would hydrolyze into carbonate and bicarbonate ions. As this reaction occurs, pH would decrease and alkalinity would increase.

Another important phenomenon observed in this system is the decomposition of particulate material and repartitioning of particulate bound pollutants. During every rainfall-runoff event, a significant amount of particulate matter, including natural materials (grit, sand, soils, etc), anthropogenic materials (atmospheric deposition, vehicular deposition, etc), biogenic (leaves, grass, etc) materials and watershed microorganisms, will be flushed into the filter system and trapped there becoming a source of pollutants and microbial activity. During the retention period, some complex processes occur both physical-chemically and biologically. For example, large particles will break down to small particles, the solubility of particulate bound pollutant changed by the change of pH and redox, and polymeric materials degraded into monomers by microbiological consumption, etc. When the next storm event occurs, part of the stored

pollutants will be flushed out, meanwhile “new” pollutants will come into the system and the cycle of processes starts over again.

Conductivity, salinity and TDS increase during each retention period, which indicates that particulate bound constituents are decomposed, in part, and become dissolved ions. In particular conductivity increased from about 100 $\mu\text{S}/\text{cm}$ to 500 $\mu\text{S}/\text{cm}$, salinity increased from about 0.1 ppt to 0.3 ppt, TDS increased from about 100 mg/L to 300 mg/L. It is interesting to observe that conductivity and pH variation is affected by temperature: the daily highest conductivity and pH appear at the mid-afternoon, which is usually the hottest time of the day. This behavior is possibly due to microorganism activity. Temperature, conductivity and pH are plotted against the filter retention time in Figure 81 for the 8 October event where it is possible to observe the clear behavior of these parameters.

Nutrients concentration (TDN and TDP) and DOC all increased during each retention period. As shown in Table 25. TDN increased from about 2500 $\mu\text{g}/\text{L}$ to 6500 $\mu\text{g}/\text{L}$ while TDP increased from about 500 $\mu\text{g}/\text{L}$ to 2000 $\mu\text{g}/\text{L}$. DOC increased from 10 to 70 mg/L. Biogenic materials such as leaves and grass are the main source of nutrients. Since the dissolved inorganic nitrogen (DIN), which is mainly nitrate and ammonia, does not increase significantly, it means that the increase of TDN is contributed by dissolved organic nitrogen (DON). TDP result can be explained by the same reason. In addition, the increase of TDP can also be explained by the repartitioning of particulate bound phosphorus into soluble phase under low pH and reduced conditions. DOC shows an increase as well and the result is due to the microbiological reaction that consumed insoluble macromolecules and simple small molecules such as methanol (which is easily solvable).

Turbidity does not vary significantly because of the particles settling occurring in the first few hours of the retention period. The sampling method adopted consisting in a slow drainage of the stored runoff aimed at avoiding any turbulence in the system that can cause particle re-suspension. As shown, turbidity is stabilized at about 15 NTU. Chloride is a stable element and cannot be utilized by microorganism. The concentration of chloride is stabilized at about 25 mg/L. The inter-event comparison is also addressed in this report. As the time that microorganisms grown in the soil filter system increases, the rate of oxygen consumption became higher. As shown in Figure 82, the time that redox reach -200mV is about 250 hours for 16 May event while for the 08 October event is only 5 hours. This indicates that the microbial consortium has acclimated and became more efficient. In addition, nitrate-N behavior during the retention period of two events is reported in Figure 83. It is possible to observe that the regression curve of the first few events is zero-order linear function, while the regression curve became first-order exponential decay towards the last events. The 16 May event data is linear while the 08 October is modeled with an exponential decay.

CONCLUSIONS

A detailed investigation of the engineered clay-based media with respect to mass transfer behavior (adsorption) and filtration was carried out in the first part of the project through isotherms, kinetics, breakthrough, and desorption evaluations resulted in the choice of a clay-based oxide media as compared to a suite of other media. This media was further investigated through field testing that consisted in intra-event data collection and analysis of 15 rainfall-runoff events, treatment thereof, and inter-event drainage management.

Results of the head loss behavior as a function of the flow rate during the monitoring program illustrate the evolution of head loss from the first events in which a series of relations can be observed for the head loss-flow rate relationship that formed a hysteretic loop. For a given flow rate the head loss was lower in the rising limb of the hydrograph and higher in the decreasing limb. This behavior is explained by the filter ripening within each event. Higher flow rates cause higher turbulence inside the system, thus the re-suspension of particles in the system that emphasizes the higher load of particles associated with the peak of flow rates. Despite the different behavior of the head loss within each event, the head loss values tended increased with increasing volume treated by the soil filter, showing a clear ripening of the filter.

Particulate matter including sediment PM, settleable PM, suspended PM, turbidity, suspended sediment concentrations (SSC), and volatile suspended sediment concentration (VSSC) fractions for 15 rainfall-runoff events have been analyzed. Results illustrate the high concentration of sediment PM. The event mean concentration (EMC) of sediment PM varied from 102 mg/L to 1835 mg/L, with the site mean EMC of 453 mg/L. If compared with the PM data resulting from a monitoring program at a Baton Rouge, LA paved urban watershed, considering the same sampling methodology and analyses for both studies, this difference is due mainly to the PM sources: concrete and tire abrasion by high traffic loads for Baton Rouge and biogenic material from raised vegetated curbed median areas with trees for the paved surface parking facility area in Gainesville. The influence of the impervious surface hydrology is evident in PM build-up and wash-off phases.

The overall shape of the influent event mean PSD was relatively consistent across the 15 monitored storm events. Interestingly, irrespective of influent PSD, and influent flowrate, the average effluent PSD does not deviate significantly across storm events. This suggests the selectivity in PSD and flow attenuation by the soil filter. Due to the observation that the average effluent d_{50} shows a slight decreasing trend with time from the first storm event to the last storm event, it is hypothesized that in part due to the effects of filter clogging, the filter is able to selectively separate finer particles.

The filter behavior is a function of flow rate, a key influencing variable of performance. This is confirmed by the relative parallel trends between influent and effluent d_{15} , d_{50} and d_{85} . It should be noted however, that the values of the d_{15} , d_{50} and d_{85} for the influent are clearly driven by the impervious surface hydrology.

In general P concentration values generated from the watershed were significant and confirmed the requirement for concentration and load control before discharging in water bodies. The TP mean EMC value of 3.5 mg/L is higher than concentrations reported in the literature.

Since traffic was low, and not generally a significant source of nutrients, the only significant sources of N and P in the catchment are biogenic. These sources are raised vegetated curbed median strips with trees and vegetation. Additionally, identification of the coarse and more volatile fraction of this biogenic PM is due to the sampling methodology adopted for this study that sampled the entire cross-section of flow and the floatable or gross PM. Results indicated that the EMCs of each P fraction varied by an order of magnitude for both influent and effluent over a range of hydrological events. These trends of variability did not follow the increasing order of event statistics. This is possibly due to the hydrologic complexity and stochastic response for a small watershed subjected to urban loadings, traffic loadings, during and between events and antecedent dry period.

The distribution of P between particulate bound and dissolved fraction was also investigated in this study. The form in which P is more likely to distribute is the particulate-bound form. With respect to the different PM fractions, the suspended and sediment PM had the highest affinity to P. This result is due to the high sediment concentrations, noting that the biogenic PM material, the main P source for this watershed, is largely in the sediment PM fraction, being defined as the particles larger than 75 μm . At the same time PM analysis revealed a very low settleable concentration for the watershed. The affinity of a constituent to suspended PM is due to the larger specific surface area. Events with higher flow rate had generally lower values of the f_d coefficient due to the more significant transport of PM and thus of PM-bound P. For medium to low flow rate events and higher APRT it is possible to observe higher f_d values within the event; thus a predominant dissolved fraction. With respect to effluent flow, the partitioning of P revealed a predominant suspended fraction due to the very low concentration of dissolved and sediment P and the absence of settleable PM.

Dissolved nitrogen species (NO_3^- -N, NH_3 -N, NO_2^- -N, TDN) and PM-bound total nitrogen (sediment-TN, Settleable-TN, Suspended-TN) based on 15 monitored events have been analyzed for this project. In general, nitrogen concentrations from the experimental site are typical of urban rainfall-runoff, albeit somewhat higher. The major sources of nutrients are largely biogenic with anthropogenic contributions. Concentrations of most nitrogen species were highly variable during storm events. However, the trend within each storm is more predictable, which always shows a decrease along with time. The event mean concentration (EMC) of TN (sum of all TN fractions) for runoff varied from 1386 $\mu\text{g/L}$ (15 July event) to 10967 $\mu\text{g/L}$ (03 June event), with a median concentration of 4522 $\mu\text{g/L}$ (19 August, 08 August events). The distribution of N between PM-bound and dissolved fraction was also investigated in this study. Quantitatively, the dissolved fraction is close to the sum of the PM fractions. Among the different PM-bound fractions, the sediment and suspended fraction had the highest affinity for N.

Metal elements were analyzed in dissolved form for all 15 rainfall-runoff events, with a focus on calcium, magnesium, copper, lead, zinc and sodium. The relatively low concentrations are explained by less anthropogenic and traffic loads. EMCs for copper, zinc and lead do not show significant difference between influent and effluent runoff, which means the soil filter does not have a significant adsorptive impact on these divalent cations and their complexes.

The removal efficiency of PM, P, and N of the porous soil filter system has been investigated. The mean removal efficiency for SSC is significant, at 85%. The removal efficiency for sediment PM exceeds 90% with settleable and suspended PM removal efficiencies of 60% and 50%

respectively. The sediment PM removal efficiency is lower for the 16 May 2008 and 8 and 15 July 2008 events characterized by the highest flow rates irrespective of the influent PM concentration that varied significantly between the events (848 mg/L, 102 mg/L and 58 mg/L respectively). The significant removal efficiencies for sediment PM remain constant during the entire monitoring program, suggesting that the filter clogging phenomenon is not affecting the sediment removal efficiency. Trapping the PM in the filter has significant implications for regular maintenance of any system.

High removal efficiencies were observed for sediment P and TDP. In particular results indicated that the TDP and sediment TP removals ranged from 18 to 97% with average removal efficiency of 67% and from 70 to 99%, with average value of 87% respectively.

Particular attention has been given to flow rate which has critical influence on phosphorus removal; noting there was little flow attenuation provided by the lysimeter housing the soil media filter. The lower the flow rate and the higher the time of contact between the media and the runoff the more effective is the media for adsorption and filtration.

It is noted that the lowest removal efficiency of dissolved P was experienced for the 19 August event. The difference between this event and the other events consists in the quality of the stored runoff inside the filter system at the beginning of the rainfall event and the hydrologic characteristics. After a period of 6 days from the previous event the dissolved phosphorus concentration in the filter was 5.5 mg/L, a high value. Phosphorus concentration values increase during retention periods due to desorption of phosphorus. Furthermore the phosphorus solubility increases under decreased pH and redox conditions. The first effluent sample concentrations were a mixture of stored runoff and influent runoff mixed in the system. The concentration of the first samples were higher, thus causing an apparent decrease in removal efficiency calculated as a function of the mass influent and mass effluent due to the stored runoff quality. Besides the evident ripening of the soil filter (head loss) difference in removal efficiency as a function of the time/events are muted. Dissolved P removal efficiency remains more or less constant and very high during the whole monitoring program. The same can be observed for particulate P.

Physical filtration was clearly observed for some particulate bound TN fractions. The filter system has a significant removal capacity on sediment-TN (mean 90%) and settleable-TN (mean 70%); suspended-TN does not show significant treatment efficiency due to its fine particle size. However, it is noted that this media adsorption system is not designed for intra-event dissolved nitrogen species treatment, therefore, the results do not favor removal for NO_3^- -N, NH_3 -N, NO_2^- -N and TDN. The correlation between flow rate and removal efficiency is not evident. The dissolved part is the predominant part of the pollutant in runoff effluent, which is caused by the repartitioning of particulate bound N, and the degradation of the biogenic materials in the soil filter. Suspended TN is the predominant fraction among the particulate bound TN. In addition, finer PM can have higher nitrogen concentration (by definition) due to higher specific surface area (m^2/g) which consists of mass-based particulate-bound nitrogen concentration of this report.

Water chemistry indices for inter-event retention periods were monitored between each rainfall-runoff event. The most significant phenomenon occurring in the filter system is the variation of redox conditions. It can be observed that redox potential quickly decreased from about +200 to -200mV during each retention period, which means that oxygen was quickly consumed by the microbial organisms inside the system until anaerobic conditions were reached.

Nitrate-nitrogen decreased from about 3000 µg/L to 100 µg/L which indicates that nitrate had become an electron acceptor through de-nitrification after oxygen was depleted. The end product of nitrate is nitrogen gas. Sulfate also decreased from about 3000 µg/L to 50µg/L, which means sulfate also become an electron acceptor by reducing into sulfide. COD increased from about 50 mg/L to 200 mg/L which can be explained by the increase of reduced-state pollutants such as ammonia and sulfide. Ammonia-nitrogen increased from about 60 µg/L to 2000 µg/L due to the mineralization of organic matter.

Another important phenomenon observed in this system is the decomposition of particulate material and repartitioning of particulate bound pollutants. During the retention period, some complex processes occurred both physical-chemically and biologically: large particles break down to small particles, the solubility of particulate bound pollutant changed by the change of pH and redox, and polymeric materials degraded into monomers by microbiological consumption. Conductivity, salinity and TDS increased during each retention period, which indicates that particulate bound constituents are decomposed, in part, and become dissolved ions. It is interesting to observe that conductivity and pH variation is affected by temperature due to microorganism activity. Nutrients concentration (TDN and TDP) and DOC all increased during each retention period. Since the dissolved inorganic nitrogen (DIN), which is mainly nitrate and ammonia, did not increase significantly, it means that the increase of TDN is contributed by dissolved organic nitrogen (DON). The increase of TDP can also be explained by the repartitioning of particulate bound phosphorus into soluble phase under low pH and reduced conditions. DOC shows an increase due to the microbiological reaction that consumed insoluble macromolecules and simple small molecules such as methanol. As the time that microorganisms grown in the soil filter system increases, the rate of oxygen consumption became higher. The time that redox reach -200mV decreased from about 250 hours in the second monitored event (16 May 2008) to only 5 hours in the last ones (08 October 2008). This result indicates that the microbial consortium has acclimated and became more efficient.

REFERENCES

- Aldridge, K. T., and Ganf, G. G. (2003) "Modification of Sediment Redox Potential by Three Contrasting Macrophytes: Implications for phosphorus adsorption/desorption." *Mar. Freshwater Res.*, 54 (1), 87–94.
- Appan, A., and Wang, H. (2000). "Sorption Isotherms and Kinetics of Sediment Phosphorus in a Tropical Reservoir." *J. Environ. Eng.*, 126(11), 993-998.
- Bailey, S.E., Olin, T.J., Bricka, R. and Adrian, D.D. (1999). "A review of potentially low-cost sorbents for heavy metals.", *Wat. Res.*, 33(11), 2469–2479.
- Barrett, M. E., L. B. Irish, J. F. Malina, and R. J. Charbeneau. 1998. "Characterization of highway runoff in Austin, Texas, area." *Journal of Environmental Engineering* 124(2): 131-137.
- Barrett, M. E., Walsh, P. M., Malina, J. F., and Charbeneau, R. J. (1998). "Performance of

- Vegetative Controls for Treating Highway Runoff.” *J. Environ. Eng.*, 124(11), 1121-1128.
- Bartone, D. M., and Uchirin, C. G. (1999). “Comparison of Pollutant Removal Efficiency for Two Residential Storm Water Basins.” *J. Environ. Eng.*, 125(7), 674-677.
- Bickford, G, Toll, J, Hansen, J, Baker, E, Keessen, R (1999). “Aquatic Ecological and Human Health Risk Assessment of Chemicals in Wet Weather Discharges in the Sydney Region, New South Wales, Australia.”, *Marine Pollution Bulletin* 39, 335-345.
- Brown, P.A., Gill, S.A. and Allen, S.J. (2000b). “Metal removal from wastewater using peat”. *Wat. Res.*, 16, 3907–3916.
- Bubba, M. D., Arias, C. A., and Brix, H. (2003). “Phosphorus Adsorption Maximum of Sands for Use as Media in Subsurface Flow Constructed Reed Beds as Measured by the Langmuir Isotherm.” *Water Res.*, 37, 3390-3400.
- Chang, N. B., Wanielista M. and O’ Reilly, A. (2007) “Use of Alternative Sorption Media for Removing Nutrients Associated with stormwater BMPs.” World Environmental and Water Resources Congress 2007: Restoring Our Natural Habitat
- Characklis, G.W. and Wiesner, M.R. (1997). “Particles, Metals, and Water Quality in Runoff from Large Urban Watershed”, *J. of Environ. Eng. Div. ASCE*, 123(8), 753–759.
- Chau, K. W., and Jin, H. (1998). “Eutrophication Model for a Coastal Bay in Hong Kong.” *J. Environ. Eng.*, 124(7), 628-638.
- Colandini, V., Legret, M., Brosseaud, Y., and Balades, J. D. (1995). “Metallic pollution in clogging materials of urban porous pavement.” *Water Sci. Technol.*, 32(1), 57–62.
- Comings, K. J., Booth, D. B., and Horner, R. R. (2000). “Storm Water Pollutant Removal by Two Wet Ponds in Bellevue, Washington.” *J. Environ. Eng.*, 126(4), 321-330.
- Davis, A.P., Shokouhian, M., Sharma, H. and Minami, C. (2001) "Laboratory Study of Biological Retention (Bioretention) for Urban Storm Water Management." *Water Environ. Res.*, 73(1), 5-14.
- Davis, A.P., Shokouhian, M., Sharma, H. and Minami, C. (2005) "Water Quality improvement Through Bioretention Media: Nitrogen and Phosphorus Removal." *Water Environ. Res.*, 78 (3), 284-293.
- Davis, A. P., Shokouhian M., Sharma H., and Minami C., 2001. Laboratory study of biological retention for urban stormwater management. *Water Environment Research* 73(1): 5-14.
- Davis, A.P., Shokouhian M., Sharma H., Henderson C., Winogradoff D., and Coffman L.,

1998. "Bioretention for treatment of urban stormwater runoff: laboratory and field results." In Proc. WEFTEC '98, Surface Water Quality and Ecology I & II, 421-434. Orlando, FL: Water Environment Federation.
- Dechesne, M., Barraud, S., and Bardin, J. P. (2005). "Experimental Assessment of Stormwater Infiltration Basin Evolution." *J. Environ. Eng.*, 131 (7), 1090-1098.
- Denman, L., Breen, P. F., and May, P. B. (2006) "An Investigation of the Potential to Use Street Trees and Their Root Zone Soils to Remove Nitrogen from Urban Stormwater." In A. Deletic and T. Fletcher, eds., Proceedings, 7th International Conference on Urban Drainage Modeling, and 4th International Conference on Water Sensitive Urban Design, Melbourne, Australia, 2-7 April 2006.
- Dodds, W. K., Jones, J. R., Welch, E. B. (1998). "Suggested Classification of Stream Trophic State: Distribution of Temperate Stream Types by Chlorophyll, Total Nitrogen, and Phosphorus." *Water Res.*, 32(5), 1455-1462.
- Erickson, A. J., Gulliver J. S. and Weiss P. T. (2007) "Enhanced Sand Filtration for Storm Water Phosphorus Removal." *ASCE Journal of Environmental Engineering*, 133 (5), 485-497.
- Ermilio, J.R., and Traver R. G., 2006. "Hydrologic and Pollutant removal Performance of a Bio-Infiltration BMP, paper presented at the EWRI Water Congress, Omaha, Nebraska, May 2006."
- Ferguson, B. K.(1995). 'Storm-water infiltration for peak-flow control', *J. Irrig. and Drainage Engineer.* 121(6), 463-466.
- Field, R. and Turkeltaub, R. (1981). "Urban Runoff Receiving Water Impacts: Program Overview." *ASCE Journal of the Environmental Engineering Division*, 107(1), 83-100.
- Florida Department of Environmental Protection (FDEP), 2006, "Stormwater Treatment Areas: Experiences with Nitrate Removal", Carrie Kelly, Port St. Lucie.
- Forbes, M. G., Dickson, K. R., Golden, T. D., Hudak, P., and Doyle, R. D. (2004). "Dissolved Phosphorus Retention of Light-Weight Expanded Shale and Masonry Sand Used in Subsurface Flow Treatment Wetlands." *Environ. Sci. Technol.*, 38(3), 892-898.
- Foy, R.H., Gibson, C.E., Champ, T., 1996. The effectiveness of restricting phosphorus loading from sewage treatment works as a means of controlling eutrophication in Irish lakes. In: Giller, P.S., Miller, A.A. (Eds), *Disturbance and Recovery of Ecological Systems*. Royal Irish Academy, Dublin, Ireland, 134-152.
- Fujita, S. (1993). "Infiltration in congested urban areas of Tokyo." *Proc., 6th Int. Conf. on Urban Storm Drainage*, Vol. 1, J. Marsalek and H. Torno, eds., IAHR/IAWQ Joint Committee on Urban Storm Drainage, 993-998.
- Gervin, L., and Brix, H. (2001). "Removal of Nutrients from Combined Sewer Overflows and

- Lake Water in a Vertical-Flow Constructed Wetland System.” *Water Sci. Technol.*, 44(11-12), 171-176.
- Gilberta J. K. and Clausenb J. C. (2006) “Stormwater runoff quality and quantity from asphalt, paver, and crushed stone driveways in Connecticut”, *Water Research* 40 826 – 832
- Hecky, R.E., Kilham, P., 1988. Nutrient limitation of phytoplankton in freshwater and marine environments: a review of recent evidence on the effects of enrichment. *Limnology and Oceanography* 33, 796-822.
- Henderson, C., Greenway, M., and Phillips I. (2006) “Removal of Dissolved Nitrogen, Phosphorus and Carbon from Stormwater Biofiltration Mesocosms.” In A. Deletic and T. Fletcher, eds., “Proceedings, 7th International Conference on Urban Drainage Modeling, and 4th International Conference on Water Sensitive Urban Design”, Melbourne, Australia, 2-7 April 2006.
- Hogland, W., and Niemczynowicz, J. (1986). “The unit superstructure—A new construction to prevent groundwater depletion.” *Conjunctive water use, Proc. of the Budapest Symp.*, Budapest, Hungary, International Association of Hydrological Sciences, Publ. No. 156, 513–522.
- Hogland, W., Niemczynowicz, J., and Wahlman, T. (1987). “The unit superstructure during the construction period.” *Sci. Total Environ.*, 59, 411–424.
- Hsieh, C. H. and Davis, A. P. (2005) “Multiple- event Study of Bioretention for Treatment of Urban Storm Water Runoff.” *Water Science & Technology*, 51 (3-4), 177-181.
- Hunho K., Seagren E.A., Davis A.P., (2003). “ Engineered Bioretention for Removal of Nitrate from Stormwater Runoff.” *Water Envions. Res.*, July-Aug 2003.
- Jahangir-Issa (1998). “Rainwater and its infiltration importance in Iran.” *Proc., 3rd Int. Conf. on Innovative Technologies in Urban StormDrainage*, Vol. 2, 475–485.
- Kadlec, R. H. and Knight R. L., 1996. “*Treatment Wetland*”. Boca Raton, FL: CRC Press
- Lee, J. H., Bang, K. W., Ketchum, L. H., Choe, J. S. and Yu, M. J.(2002). “First flush analysis of urban storm runoff”, *Sci. Total Environ.* 193, 163–175.
- Lucas, W. C. and Greenway, M (2007) “A Study of Hydraulic and Nutrient Retention Dynamics in Vegetated and Non-Vegetated Bioretention Mesocosms.” World Environmental and Water Resources Congress 2007: Restoring Our Natural Habitat
- Lucas, W.C. and Cosgrove J. F., 2005, “Bioretention Systems – A White Paper”, TRC Omni Environmental Corporation.
- Ma, J. and Sansalone, J. J. (2007) “Mass Transfer Behavior of Media for Treatment of Stormwater Phosphorus.” World Environmental and Water Resources Congress 2007: Restoring Our Natural Habitat.

- McPherson, T. M., Burian, S. J., Turin, H. J., Stenstorm, M. K. and Suffet, I. H. (2002) "Comparison of the Pollutant loads in Dry and Wet Weather Runoff in a Southern California Urban Watershed." *Water Science and Technology*, 45 (9), 255-261.
- N.C. DENR. 1997. *Stormwater Best Management Practice Design Manual*. Raleigh, NC: North Carolina, Department of Environment and Natural Resources – Division of Water Quality.
- Rushton B. (2002) "Infiltration Opportunities in Paved surface parking facility Designs Reduce Runoff and Pollution", Seventh Biennial Stormwater Research & Watershed Management conference May 22-23
- Rushton, Betty. 1999. Low Impact Paved surface parking facility Design Reduces Runoff and Pollutant Loads. Annual Report # 1. Aquarium Parking Lot, Tampa, Florida.
- Sansalone, J. J.(1999). "In-situ performance of a passive treatment system for metal source control ", *Water Sci. Technol.* 39(2), 193–200.
- Sansalone, J.J., and Teng, Z. (2005). "Transient Rainfall-Runoff Loadings to a Partial Exfiltration System: Implications for Urban Water Quantity and Quality." *J. Environ. Eng.*, 130(9), 990-1007.
- Sansalone J. J. and Kim J.Y.. (2008). "Transport of Particulate Matter Fractions in Urban Source Area Pavement Surface Runoff". *J. Environ. Qual.* 37:1883–1893 (2008).
- Schindler, D.W., 1977. Evolution of phosphorus limitation in lakes. *Science*. 195, 260-262.
- Schmitt T., Fillmore L., Prelewicz G, Wheeler J., Hatoum W.(1999) "Summary of Three Innovative Stormwater BMPs", Sixth Biennial Stormwater Research & Watershed Management Conference
- Schueler, T. R. (1987). *Controlling urban runoff: A practical manual for planning and designing urban BMPs*, Dept. of Environmental Programs, Metropolitan Washington Council of Governments, Washington, D.C.
- Seo, D. C., Cho, J. S., Lee, H. J., and Heo, J. S. (2005). "Phosphorus Retention Capacity of Filter Media for Estimating the Longevity of Constructed Wetland." *Water Res.*, 39(11), 2445-2457.
- Shukla, A., Zhang, Y.-H., Dubey, P., Margrave, J.L. and Shukla, S.S. (2002). "The role of sawdust in the removal of unwanted materials from water". *J. Hazard. Mat.*, 137–152.
- Sieker F. (1998). "On-site stormwater management as an alternative to conventional sewer systems: A new concept spreading in Germany", *Water Science and Technology*, 38 (10), 65-71

- Smith, D. P. (2007) “Dual Stage Filter for Inorganic Nitrogen Removal from Stormwater.”, World Environmental and Water Resources Congress 2007: Restoring Our Natural Habitat.
- Smith, R.A., Alexander, R.B., Lanfear, K.J., 1993. Stream water quality in the conterminous United States – Status and Trends of Selected Indicators during the 1980s (Water Supply Paper 2400.). US Geological Survey.
- Smith, R.A., Alexander, R.B., Wolman, M.G., 1987. Water-quality trends in the nation’s rivers. *Science* 235, 1507-1615.
- Stenstrom, R. S., Clausen, J. C., and Askew, D. R. (2002). “Treatment of Parking Lot Stormwater Using a StormTreat System.” *Environ. Sci. Technol.*, 36(20), 4441-4446.
- Teng, Z., and Sansalone, J.J. (2004). “In situ partial exfiltration of rainfall runoff. II: particle separation.” *J. Environ. Eng.*, 130(9), 1008-1020.
- U.S. Department of Agriculture. Summary Report: 1997 National Resources Inventory (Revised December 2000), Natural Resources Conservation Service, Washington, DC.
- United States Environmental Protection Agency (USEPA) – Low Impact Development Center – “Low Impact Development (LID) A Literature Review”, Oct 2000, EPA-841-B-00-005.
- U.S. Environmental Protection Agency (USEPA). (1999) “Preliminary data summary of urban storm water best management practices.” *EPA-821-R-99-012*, Washington, D.C.
- U.S. EPA (1996) National Water Quality Inventory – 1996 Reports Congress. U. S. Environmental Protection Agency, Office of Water: Washington, D. C., Sec. 1.
- U.S. EPA (1986) *Quality Criteria for Water*, EPA 440/5-86-001.
- Visvanathan, C., Werellagama, D. R. I. B., and Aim, R. B. (1996). “Surface Water Pretreatment Using Floating Media Filter.” *J. Environ. Eng.*, 122(1), 25-33.
- Wang, G. T., Chen, S., Barber, M. E., and Yonge, D. R. (2004). “Modeling Flow and Pollutant Removal of Wet Detention Pond Treating Stormwater Runoff.” *J. Environ. Eng.*, 130(11), 1315-1321.
- Wu, J. S., Allan C. J., Saunders W. L., and Evett. J. B. 1998. “Characterization and pollutant loading estimation for highway runoff.” *Journal of Environmental Engineering* 124(7): 584-592.
- Wu, J. S., Holman, R. E., and Dorney, J. R. (1996). “Systematic Evaluation of Pollution Removal by Urban Wet Detention Ponds.” *J. Environ. Eng.*, 122(11), 983-988.
- Yu, S.L., Zhang X., Earles A., and Sievers M., 1999., “Field Testing of Ultra-urban BMPs”. Proceedings of the 26th Annual Water Resources Planning and Management Conference, E. Wilson, editor, American Society of Civil Engineers, June 6-9, 1999, Tempe Arizona.

Yu, S. L. (1993). *Stormwater management for transportation facilities*, National Cooperative Highway Research Program, Synthesis of Highway Practice, Transportation Research Board, Washington, D.C.

Table 1 Physical-Chemical Analyses Performed for the Monitored Rainfall Runoff Events

Subject Analysis	Analysis	Influent	Effluent	Filter System	Rainfall
Probe based analysis	pH	•	•	•	•
	Redox	•	•	•	•
	Dissolved Oxygen	•	•	•	•
	Conductivity	•	•	•	•
	Temperature	•	•	•	•
	Salinity	•	•	•	•
	TDS	•	•	•	•
	Turbidity	•	•	•	•
	Alkalinity	•	•	•	•
Ions analysis	Sulfate	•	•	•	•
	Chloride	•	•	•	•
	DOC	•	•	•	•
Particulate matter analysis	Suspended PM	•	•		
	Settleable PM	•	•		
	Sediment PM	•	•		
	SSC	•	•		
	PSD	•	•		
Phosphorus analysis	TP-Dissolved	•	•	•	•
	TP-Suspended	•	•		
	TP-Settleable	•	•		
	TP-Sediment	•	•		
Nitrogen analysis	TN-Dissolved	•	•	•	•
	TN-Suspended	•	•		
	TN-Sediment	•	•		
	TN-Settleable	•	•		
	Nitrate-N	•		•	•
	Nitrite-N	•		•	•
	Ammonia (NH ₃ -N)	•		•	•
Metals analysis	Metal-Dissolved	•	•	•	•
Chemical Oxygen Demand	COD	•	•	•	•

Table 2 Summary of standard methods for each analysis

Sample Holding Time	Analysis performed	Sampled from	Volume used	Standard Method	Preservation	Maximum Holding time
Time Sensitive (0-12 hours)	pH	1.1L bottle	N/A	S.M. ¹ . 4500-H ⁺ B	Analyzed immediately	24h
	Redox	1.1L bottle	N/A	S.M.2580	Analyzed immediately	24h
	Dissolved Oxygen	1.1L bottle	N/A	S.M. 4500-O-G	Analyzed immediately	24h
	Conductivity/ Salinity/TDS	1.1L bottle	N/A	S.M.2510	Analyzed immediately	24h
	Temperature	1.1L bottle	N/A	S.M.2550	Analyzed immediately	No storage allowed
	Turbidity	1.1L bottle	20mL	S.M.2130	Analyzed immediately	24h
	Alkalinity	1.1L bottle	50mL	S.M.2320	Analyzed immediately	24h
	PSD	0.5L bottle	500mL	S.M.2560-D	Analyzed immediately	N/A
	Imhoff Cone (Settleable PM)	1.1L bottle	1000mL	S.M.2540-F	Analyzed immediately	7d
	Fractionation (Suspended PM)	1.1L bottle	200mL	S.M.2540-D	Analyzed immediately	7d
	Wet sieving (Sediment PM)	4L bottle (Influent) 5 Gallon bucket (effluent)	4L (Influent) 5Gallon (effluent)	J.J. Sansalone & J.Y. Kim., (2008) ²	Analyzed immediately	7d
	Nitrate analysis	Filtrate	10mL	Cadmium Reduction Method	Analyzed immediately	24h at 4°C
	Ammonia analysis	Filtrate	2mL	Salicylate Method	Analyzed immediately	24h
	Nitrite analysis	Filtrate	5mL	Diazotization Method	Analyzed immediately	24-48h at 4°C
	TDN	Filtrate	2mL	Persulfate Digestion Method	Analyzed immediately	24h
	TDP	Filtrate	10mL	USEPA method 365.2 and S.M. 4500-P-E Ascorbic Acid Method	Analyzed immediately	Up 48h at 4°C
	Sulfate	Filtrate	10mL	SulfaVer 4 Method	Analyzed immediately	7d at 4°C
	COD	Filtrate	2mL	Reactor Digestion Method(USEPA approved)	Analyzed immediately	28d if acidified and stored at 4°C

¹ S.M. : Standard Method² J. Sansalone and J-Y Kim*. (2008). Transport of Particulate Matter Fractions in Urban Source Area Pavement Surface Runoff. J. Environ. Qual. 37:1883–1893 (2008).

Table 3 Summary of standard methods for each analysis (Continue)

Sample Holding Time	Analysis performed	Sampled from	Volume used	Standard Method	Preservation	Maximum Holding time
6-36 hours	SSC	0.5L bottle	500mL	ASTM D-3977-97	N/A	N/A
	Chloride	Filtrate	10mL	Mercuric Thiocyanate Method	Kept in room temperature	28 days
Not Time sensitive (24 hrs or Preserve)	Metal-dissolved	Filtrate	30mL	S.M. 3030 B	0.1mL concentrated Nitric Acid	Up to 6month
	Sodium	Filtrate	N/A	Ion-Selective Electrode (ISE)	Refridgate at 4°C	N/A
	DOC	Filtrate	40mL	EPA 415.1 and 9060A Standard Method 5310 C ASTM D4779 and D4839	0.1mL concentrated Sulfuric Acid	Longer than 3 weeks
	TP-Suspended	Suspended PM	0.1g	S.M. 4500-P-B Acid Hydrolysis S.M. 4500-P-E Ascorbic Acid Method	Refridgate at 4°C	N/A
	TP-Settleable	Settleable PM	0.5g	S.M. 4500-P-B Acid Hydrolysis S.M. 4500-P-E Ascorbic Acid Method	dessicator	N/A
	TP-Sediment	Sediment PM	0.5g	S.M. 4500-P-B Acid Hydrolysis S.M. 4500-P-E Ascorbic Acid Method	dessicator	N/A
	TN-Suspended	Supernatant	2mL	Persulfate Digestion Method	dessicator	N/A
	TN-Sediment	Settleable PM	0.1g	Persulfate Digestion Method	dessicator	N/A
	TN-Settleable	Sediment PM	0.1g	Persulfate Digestion Method	dessicator	N/A

Table 4 Summary of YSI Sensor Characteristics

Monitored Parameter	Sensors	range	Resolution	Accuracy	Sampling frequency
Conductivity /Salinity/TDS	YSI 6560 Cond/Temp probe	0 to 100mS/cm	0.001 or 0.1 mS/cm	+/- 0.5% of reading	15 sec/sample for Intra-event 15 min/sample for inter-event
Temperature	YSI 6560 Cond/Temp probe	-5 to +45 deg C	0.01 deg C	+/- 0.15 deg C	15 sec/sample for Intra-event 15 min/sample for inter-event
pH	YSI 6565 Combo pH/ORP Probe kit	0-14 units	0.01 units	+/- 0.2 unit	15 sec/sample for Intra-event 15 min/sample for inter-event
Redox	YSI 6565 Combo pH/ORP Probe kit	-999 to +999 mV	0.1mV	+/- 20mV	15 sec/sample for Intra-event 15 min/sample for inter-event
The probes were assembled on a YSI 600XL-B-O sonde					

Table 5 Monitored rainfall-runoff events characteristics

Event #	Rainfall-runoff event	PDH (hr)	d _{rain} (min)	h _{rain} (in)	i _{rain-max} (mm/hr)	IPRT (min)	V _{runoff} (L)	C (-)	Q _{inf-max} (L/s)	Q _{inf-avg} (L/s)	Q _{eff-max} (L/s)	Q _{eff-avg} (L/s)	n _{inf} (-)	n _{eff} (-)
1	20 March	230	36	0.28	45.7	2	2065	0.58	3.40	0.88	2.24	0.52	12	11
2	16 May	960	62	0.42	91.4	12	2213	0.41	8.75	0.90	5.29	0.53	13	13
3	03 June	432	69	0.08	15.2	8	308	0.30	0.75	0.11	0.45	0.07	9	8
4	10 June	168	94	1.21	152.4	2	8002	0.52	10.96	1.61	3.95	1.09	16	15
5	21 June	144	127	0.26	61.0	6	1132	0.34	3.98	0.34	3.70	0.34	7	6
6	8 July	141	197	2.92	167.6	4	31268	0.84	13.17	2.14	3.88	1.47	20	20
7	15 July	66	79	2.45	167.6	9	22438	0.72	13.07	3.60	3.39	1.28	16	15
8	29 July	309	35	0.22	30.5	6	1411	0.50	3.69	0.55	2.57	0.47	12	12
9	8 August	191	42	0.12	30.5	3	474	0.31	2.16	0.14	1.51	0.10	10	10
10	12 August	93	90	0.64	45.7	7	3866	0.48	3.92	0.62	2.79	0.69	15	13
11	19 August	117	57	0.17	45.7	4	1461	0.68	6.78	0.81	4.44	0.30	10	10
12	10 September	264	56	0.32	30.5	4	1569	0.39	1.96	0.47	1.65	0.38	13	11
13	20 September	234	36	0.11	45.7	3	509	0.36	1.09	0.24	0.71	0.20	11	11
14	8 October	431	180	0.23	30.5	3	1557	0.53	2.75	0.14	1.34	0.06	13	15
15	23 October	334	56	0.14	30.5	3	978	0.55	1.46	0.29	1.15	0.28	15	15
	Median	230	62	0.26	45.7	4	1557	0.50	3.69	0.55	2.57	0.38	13	12
	Mean	274	81	0.64	66.0	5	5284	0.50	5.19	0.86	2.60	0.52	13	12
	SD	221	50	0.88	53.0	3	9112	0.16	4.30	0.95	1.47	0.44	3	3

PDH, d_{rain}, h_{rain}, i_{rain-max}, IPRT, V_{runoff}, C, Q_{inf-max}, Q_{inf-avg}, Q_{eff-max}, Q_{eff-avg}, n_{inf} and n_{eff} represent previous dry hours, duration of rainfall, rainfall depth, maximum rainfall intensity, initial pavement residence time, runoff volume, runoff coefficient, maximum influent flow rate, average influent flow rate, maximum effluent flow rate, average effluent flow rate, number of influent and number effluent samples, respectively

Table 6 Rainfall-runoff events characteristics and maximum and average filter surface loading rates.

Event #	Rainfall-runoff event	$i_{\text{rain-max}}$ (mm/hr)	V_{runoff} (L)	$Q_{\text{inf-max}}$ (L/s)	$Q_{\text{inf-avg}}$ (L/s)	Surface Loading Rate _{max} (L/min*m ²)	Surface Loading Rate _{avg} (L/min*m ²)
1	20 March	45.7	2065	3.40	0.88	275.5	63.9
2	16 May	91.4	2213	8.75	0.90	650.5	65.2
3	03 June	15.2	308	0.75	0.11	55.3	8.6
4	10 June	152.4	8002	10.96	1.61	485.7	134.0
5	21 June	61.0	1132	3.98	0.34	455.0	41.8
6	8 July	167.6	31268	13.17	2.14	477.1	180.8
7	15 July	167.6	22438	13.07	3.60	416.9	157.4
8	29 July	30.5	1411	3.69	0.55	316.0	57.8
9	8 August	30.5	474	2.16	0.14	185.7	12.3
10	12 August	45.7	3866	3.92	0.62	343.1	84.8
11	19 August	45.7	1461	6.78	0.81	546.0	36.9
12	10 September	30.5	1569	1.96	0.47	202.9	46.7
13	20 September	45.7	509	1.09	0.24	87.3	24.6
14	8 October	30.5	1557	2.75	0.14	164.8	7.4
15	23 October	30.5	978	1.46	0.29	141.4	34.4
Median		45.7	1557	3.69	0.55	316.0	46.7
Mean		66.0	5284	5.19	0.86	320.2	63.8
SD		53.0	9112	4.30	0.95	180.2	53.9

Average Filter Surface = 0.49 m²

Table 7 Event Mean Rainfall Physical-Chemical characteristics

Rainfall Parameter	Alkalinity (CaCO₃) [mg/L]	pH [s.u.]	Redox [mV]	DO [mg/L]	Temperature [°C]	Conductivity [μS/cm]	Salinity [ppt]	TDS [mg/L]
20 March	2.0	4.7	388.5	8.6	22.5	69.7	0.0	35.0
16 May	1.0	4.6	415.7	8.2	17.1	21.1	0.0	10.0
03 June	6.0	4.9	322.2	6.3	23.9	22.1	0.1	10.8
10 June	4.0	4.9	280.6	4.7	22.0	10.0	0.0	5.0
21 June	2.0	4.9	329.0	7.5	22.5	9.3	0.0	5.0
08 July	5.8	4.8	426.4	6.6	21.5	4.4	0.0	2.0
15 July	1.0	4.6	559.1	5.3	23.0	8.4	0.0	4.0
29 July	2.0	4.7	377.1	4.8	22.9	36.1	0.0	18.0
08 August	2.0	4.3	362.1	5.6	21.4	17.9	0.0	9.0
12 August	1.0	4.3	386.6	8.2	22.8	6.9	0.0	3.0
19 August	0.0	4.3	363.4	5.4	22.8	6.9	0.0	3.0
10 September	0.0	4.5	383.8	6.5	22.9	7.9	0.0	4.0
20 September	0.0	4.4	396.0	6.5	23.1	26.0	0.0	13.0
08 October	0.0	4.2	433.3	8.8	21.1	17.6	0.0	9.0
23 October	1.0	4.6	489.8	8.8	21.6	51.9	0.0	25.0

Table 8 Event Mean Rainfall quality characteristics (Turbidity - Ions)

Rainfall Parameter	Cl⁻ [µg/L]	SO₄²⁻ [µg/L]	PO₄³⁻ [µg/L]	NH₃-N [µg/L]	NO₃⁻-N [µg/L]	TDN [µg/L]	COD [mg/L]	Turbidity [NTU]	NO₂⁻-N [µg/L]
20 March	1294	2425	1	163	181	460	6.75	5.1	N/A
16 May	549	2346	55	116	452	800	5.16	1.4	N/A
03 June	544	2189	58	344	1629	2420	3.75	4.7	N/A
10 June	586	1890	68	169	1403	2351	1.25	3.2	N/A
21 June	1162	1929	53	118	1403	2971	5.00	3.2	N/A
08 July	500	71	100	18	1062	1346	2.50	2.1	N/A
15 July	1000	214	200	60	531	1346	2.50	1.3	N/A
29 July	498	71	100	39	133	242	5.16	1.0	N/A
08 August	1200	71	500	18	573	699	5.00	1.7	N/A
12 August	510	71	500	2	789	838	5.00	1.8	N/A
19 August	504	279	300	51	658	918	2.50	0.4	1.1
10 September	581	138	184	57	546	561	2.50	0.5	0.5
20 September	636	279	213	69	789	918	2.50	0.4	0.9
08 October	570	346	205	49	307	867	0.00	0.4	0.8
23 October	965	527	62	41	658	1020	0.00	0.6	0.4

Table 9 Summary of EMCs and range of variation of influent runoff quality characteristics (Physical-Chemical characteristics)

Influent Runoff	pH [s.u.]	Redox [mV]	D.O. [mg/L]	Temperature [° C]	Conductivity [µS/cm]	Salinity [mg/L]	TDS [mg/L]	Alkalinity as CaCO ₃ [mg/L]
20 March	7.4 (7.6 - 7.2)	351.6 (369.7 - 343.5)	7.5 (8.4 - 5.8)	22.2 (22.5 - 22.0)	83.6 (150.4 - 44.9)	9.9 (50.0 - BDL)	40.7 (73.8 - 22.0)	26.8 (56.0 - 10.0)
16 May	7.0 (7.2 - 6.4)	226.9 (295.4 - 24.1)	3.9 (5.2 - 0.2)	23.4 (24.0 - 22.3)	86.0 (552.5 - 46.6)	24.1 (300.0 - BDL)	42.6 (272.0 - 22.5)	36.3 (171.0 - 24.0)
03 June	7.2 (7.4 - 7.0)	366.9 (377.4 - 360.4)	3.6 (5.5 - 1.4)	27.8 (28.5 - 26.8)	200.9 (343. - 130.9)	110.5 (150.0 - 100.0)	98.6 (168.0 - 64.0)	56.7 (108.0 - 26.0)
10 June	7.3 (7.6 - 6.9)	372.0 (385.0 - 349.6)	6.6 (7.4 - 5.6)	22.6 (23.0 - 21.9)	56.1 (273.2 - 27.7)	7.4 (100.0 - BDL)	27.5 (134.0 - 14.0)	20.4 (119.0 - 9.0)
21 June	7.9 (8.2 - 7.4)	350.2 (356.0 - 347.8)	5.8 (7.2 - 4.6)	23.7 (24.2 - 22.8)	72.1 (161.0 - 37.2)	14.9 (100.0 - BDL)	35.3 (79.5 - 18.5)	43.4 (54.0 - 16.5)
08 July	7.7 (8.4 - 7.5)	344.5 (546.3 - 318.8)	6.3 (7.7 - 5.2)	22.0 (23.0 - 21.8)	15.7 (131.1 - 8.0)	1.0 (100.0 - BDL)	7.7 (64.0 - 4.0)	10.6 (62.0 - 7.0)
15 July	7.1 (7.8 - 6.8)	390.0 (432.9 - 373.5)	7.5 (8.4 - 3.2)	22.5 (22.9 - 22.4)	13.0 (126.8 - 7.6)	0.1 (100.0 - BDL)	6.5 (62.0 - 4.0)	9.5 (52.0 - 5.0)
29 July	7.3 (7.6 - 6.9)	427.1 (448.2 - 406.9)	4.1 (5.0 - 3.1)	26.8 (27.6 - 26.0)	98.8 (228.9 - 39.4)	35.6 (100.0 - BDL)	49.3 (116.5 - 19.0)	30.9 (60.0 - 17.0)
08 August	7.5 (7.6 - 7.2)	415.8 (461.3 - 396.1)	7.1 (8.5 - 5.3)	24.9 (25.4 - 24.1)	95.8 (160.6 - 82.5)	11.1 (100.0 - BDL)	47.0 (78.5 - 40.5)	40.2 (54.7 - 34.4)
12 August	7.4 (7.6 - 6.5)	369.7 (397.5 - 332.8)	5.4 (6.0 - 1.2)	22.6 (23.1 - 22.5)	36.3 (435.5 - 23.5)	2.3 (150.0 - BDL)	17.8 (211.0 - 11.5)	21.1 (85.0 - 14.0)
19 August	8.4 (8.5 - 7.2)	278.0 (328.9 - 242.7)	7.1 (9.2 - 5.7)	22.9 (23.3 - 22.9)	44.5 (111.5 - 30.5)	3.5 (100.0 - BDL)	21.7 (54.3 - 15.0)	38.9 (49.0 - 18.0)
10 September	7.7 (8.0 - 6.8)	268.1 (464.3 - 235.1)	6.2 (6.8 - 4.5)	24.6 (28.8 - 23.4)	72.0 (276.2 - 43.8)	16.8 (100.0 - BDL)	34.9 (135.5 - 21.0)	26.4 (66.0 - 18.0)
20 September	7.4 (7.7 - 8.0)	227.2 (246.4 - 217.0)	5.0 (5.2 - 4.1)	22.5 (22.8 - 22.1)	109.3 (199.1 - 73.2)	37.9 (100.0 - BDL)	53.5 (97.5 - 35.5)	48.3 (76.0 - 25.0)
08 October	7.5 (7.9 - 5.4)	323.8 (439.8 - 308.9)	6.9 (7.7 - 4.3)	25.0 (25.0 - 25.0)	107.8 (342.0 - 53.4)	39.9 (200.0 - BDL)	52.8 (167.0 - 26.0)	35.5 (85.0 - 18.0)
23 October	7.1 (7.6 - 6.8)	307.8 (346.7 - 292.6)	6.1 (7.7 - 2.3)	19.7 (20.4 - 19.3)	214.9 (532.0 - 114.5)	111.0 (250.0 - 100.0)	105.4 (260.5 - 56.0)	39.6 (59.0 - 30.0)
Median	7.4	350.2	6.2	22.9	83.6	14.9	40.7	35.5
Mean	7.5	334.6	5.9	23.5	87.1	28.4	42.8	32.3
SD	0.4	62.2	1.3	2.0	57.8	36.0	28.4	13.3

*Salinity Detection limit = 0.1ppt, BDL= Below Detection Limit

Table 10 Summary of EMCs and range of variation of Influent runoff quality characteristics (Turbidity –Ions - DOC)

Parameters	Cl ⁻ [µg/L]	SO ₄ ²⁻ [µg/L]	Turbidity (NTU)	COD [mg/L]	DOC [mg/L]
20 March	10280 (28341 - 2425)	8468 (23612 - 39)	75.1 (220.7 - 9.1)	81.1 (236.9 - 28.8)	18.3 (40.1 - 9.0)
16 May	8041 (38857 - 3322)	3484 (32431 - 118)	123.6 (420.8 - 42.4)	259.0 (1723.1 - 71.3)	22.7 (220.6 - 2.5)
03 June	22619 (32980 - 17144)	11337 (22421 - 472)	104.0 (279.3 - 14.6)	208.0 (332.5 - 143.8)	110.0 (191.6 - 65.5)
10 June	3520 (30398 - 166)	7058 (15182 - 0)	68.0 (404.5 - 7.8)	104.5 (652.5 - 25.0)	26.8 (190.2 - 4.9)
21 June	1467 (2717 - 375)	2106 (11298 - 0)	52.7 (77.4 - 6.4)	44.1 (108.8 - 11.3)	31.2 (61.9 - 12.6)
08 July	631 (2555 - 0)	512 (8649 - 35)	12.3 (130.0 - 1.8)	35.1 (88.1 - 28.2)	2.8 (33.2 - 1.2)
15 July	558 (3533 - 207)	3649 (32579 - 474)	9.8 (47.8 - 3.1)	18.2 (92.5 - 6.3)	2.7 (26.3 - 1.6)
29 July	3547 (7215 - 1569)	5769 (17413 - 22)	80.0 (241.3 - 12.8)	87.1 (171.3 - 30.0)	37.3 (75.6 - 11.8)
08 August	532 (1214 - 328)	877 (5411 - 0)	71.5 (261.3 - 12.7)	118.0 (155.0 - 101.3)	55.0 (82.4 - 33.5)
12 August	2178 (59946 - 818)	8783 (27500 - 325)	30.6 (127.3 - 6.6)	36.0 (501.3 - 13.8)	10.9 (148.2 - 3.4)
19 August	1462 (3748 - 816)	51 (3355 - 0)	162.3 (332.5 - 29.2)	22.4 (58.8 - 10.0)	10.8 (26.5 - 6.1)
10 September	1998 (23619 - 381)	2965 (52294 - 65)	64.6 (159.8 - 17.3)	66.2 (628.8 - 12.5)	242.6 (242.6 - 7.2)
20 September	6804 (15163 - 2858)	4761 (16807 - 87)	130.8 (227.8 - 22.7)	110.1 (187.5 - 58.8)	53.4 (88.1 - 28.0)
08 October	8141 (39035 - 948)	4402 (22121 - 43)	125.7 (278.0 - 14.8)	103.8 (291.3 - 27.5)	50.1 (196.8 - 16.8)
23 October	26700 (59417 - 8939)	15183 (36028 - 851)	96.6 (191.0 - 16.7)	101.3 (250.0 - 16.8)	56.3 (180.0 - 16.2)
Median	3520	4402	75	87	31
Mean	6565	5294	81	93	49
SD	8017	4246	44	67	60

Table 11 Summary of EMCs and range of variation of effluent runoff quality characteristics (Physical-Chemical characteristics)

Effluent Runoff	pH [s.u.]	Redox [mV]	D.O. [mg/L]	Temp. [°C]	Cond. [µS/cm]	Salinity [mg/L]	TDS [mg/L]	Alkalinity as CaCO ₃ [mg/L]
16 May	7.0 (7.2 - 6.7)	371.9 (377.1 - 5.0)	8.2 (8.6 - 8.0)	22.1 (22.3 - 21.9)	161.0 (346.0 - 56.6)	70.0 (150.0 - BDL)	78.8 (169.5 - 28.0)	19.8 (27.0 - 9.0)
16 May	7.0 (7.1 - 6.6)	200.2 (298.8 - 100.3)	3.7 (5.3 - 0.2)	22.4 (23.1 - 21.9)	135.5 (1218.5 - 55.6)	38.7 (600.0 - BDL)	66.6 (597.0 - 27.5)	33.4 (89.0 - 13.0)
03 June	6.9 (7.0 - 6.9)	346.3 (364.2 - 314.4)	0.5 (2.3 - 0.1)	25.4 (26.3 - 24.4)	373.3 (666.5 - 260.4)	164.3 (300.0 - 100.0)	183.2 (329.0 - 127.5)	70.2 (92.0 - 55.0)
10 June	7.1 (7.2 - 6.9)	419.1 (454.3 - 290.0)	6.7 (7.2 - 2.1)	22.3 (22.7 - 22.2)	54.5 (442.5 - 30.4)	11.0 (200.0 - BDL)	26.7 (216.5 - 15.0)	16.7 (131.0 - 10.0)
21 June	7.0 (7.2 - 6.7)	253.9 (377.1 - 5.0)	3.9 (5.0 - 0.9)	22.2 (22.3 - 21.9)	156.4 (346.0 - 56.6)	52.7 (150.0 - BDL)	76.6 (169.5 - 28.0)	71.9 (27.0 - 9.0)
08 July	7.2 (7.1 - 6.6)	381.0 (298.8 -)	5.9 (6.8 - 1.9)	22.5 (23.1 - 21.9)	35.7 (1218.5 - 55.6)	7.9 (600.0 - BDL)	17.5 (597.0 - 27.5)	17.7 (89.0 - 13.0)
15 July	6.9 (7.0 - 6.9)	430.3 (364.2 - 314.4)	6.2 (7.5 - 5.1)	21.9 (26.3 - 24.4)	24.7 (666.5 - 260.4)	3.6 (300.0 - 100.0)	12.3 (329.0 - 127.5)	14.0 (92.0 - 55.0)
29 July	7.1 (7.2 - 6.9)	473.3 (454.3 - 290.0)	4.2 (4.7 - 2.5)	24.2 (22.7 - 22.2)	115.9 (442.5 - 30.4)	53.4 (200.0 - BDL)	55.7 (216.5 - 15.0)	38.0 (131.0 - 10.0)
08 August	6.5 (6.6 - 6.5)	461.1 (494.9 - 412.2)	3.5 (5.4 - 1.8)	24.8 (25.1 - 24.2)	279.4 (490.5 - 155.9)	130.1 (200.0 - 100.0)	137.0 (240.5 - 76.5)	105.2 (175.8 - 61.2)
12 August	7.0 (7.2 - 6.5)	454.4 (469.6 - 393.8)	5.2 (5.9 - 0.5)	21.7 (22.0 - 21.4)	47.0 (385.5 - 22.3)	5.1 (200.0 - BDL)	23.4 (189.0 - 11.5)	20.8 (160.0 - 12.0)
19 August	6.8 (7.0 - 6.4)	251.2 (256.1 - 244.5)	4.4 (6.2 - 1.5)	22.6 (22.7 - 22.4)	181.6 (530.0 - 39.0)	92.1 (300.0 - BDL)	89.0 (259.5 - 19.0)	89.7 (258.0 - 20.0)
10 September	6.8 (7.0 - 6.3)	303.8 (305.9 - 287.1)	5.2 (6.3 - 2.6)	24.2 (25.1 - 23.3)	123.1 (645.5 - 46.1)	79.1 (300.0 - BDL)	60.1 (311.5 - 22.5)	47.8 (271.0 - 20.0)
20 September	6.7 (6.9 - 6.5)	271.0 (301.2 - 247.8)	4.6 (5.1 - 3.3)	24.2 (24.6 - 23.7)	206.1 (497.0 - 98.3)	116.2 (200.0 - 100.0)	101.1 (243.5 - 48.0)	95.6 (249.0 - 43.0)
08 October	6.7 (6.9 - 6.2)	288.2 (356.2 - 257.7)	3.1 (6.7 - 1.7)	25.0 (25.0 - 25.0)	178.4 (531.0 - 70.2)	89.4 (300.0 - BDL)	87.3 (260.5 - 34.0)	60.9 (223.0 - 22.0)
23 October	6.8 (6.9 - 6.6)	383.2 (441.2 - 310.8)	7.8 (8.7 - 6.6)	21.0 (21.7 - 20.1)	255.2 (503.0 - 128.6)	115.3 (200.0 - 100.0)	125.1 (247.0 - 63.0)	62.4 (201.0 - 22.0)
Median	6.9	371.9	4.6	22.5	156.4	70.0	76.6	47.8
Mean	6.9	352.6	4.9	23.1	155.2	68.6	76.0	50.9
SD	0.2	86.9	1.9	1.4	97.5	50.1	47.8	31.0

*Salinity Detection limit = 0.1ppt, BDL= Below Detection Limit

Table 12 Summary of EMCs and range of variation of effluent runoff quality characteristics (Turbidity –Ions - DOC)

Rainfall-runoff event	Cl ⁻ [µg/L]	SO ₄ ²⁻ [µg/L]	Turbidity (NTU)	COD [mg/L]	DOC [mg/L]
20 March	1241 (24718 - 2741)	1400 (2874 - 39)	52 (116 - 4)	60 (79 - 30)	17 (28 - 7)
16 May	6795 (10136 - 3475)	7473 (6496 - 719)	74 (132 - 13)	134 (310 - 38)	30 (121 - 8)
03 June	23392 (29849 - 17948)	50398 (66358 - 41033)	36 (47 - 21)	169 (231 - 136)	67 (78 - 43)
10 June	946 (11948 - 13)	2944 (21693 - 118)	14 (89 - 3)	38 (235 - 20)	9 (59 - 4)
21 June	1502 (2249 - 637)	8399 (24737 - 211)	25 (63 - 4)	70 (121 - 9)	25 (68 - 7)
08 July	506 (2930 - 47)	1586 (17579 - 0)	6 (41 - 1)	21 (60 - 15)	4 (21 - 1)
15 July	885 (2138 - 383)	8758 (27140 - 88)	4 (22 - 1)	11 (61 - 0)	3 (15 - 2)
29 July	2809 (4138 - 1755)	8191 (25119 - 216)	20 (66 - 4)	71 (111 - 28)	32 (66 - 12)
08 August	4815 (6475 - 2785)	15681 (26418 - 7987)	17 (25 - 5)	113 (124 - 101)	45 (51 - 24)
12 August	1524 (5916 - 954)	5886 (25498 - 117)	7 (22 - 1)	29 (99 - 11)	9 (45 - 3)
19 August	1673 (3282 - 877)	3179 (17619 - 0)	45 (77 - 12)	24 (51 - 9)	22 (60 - 6)
10 September	1514 (5346 - 392)	405 (23745 - 0)	26 (62 - 8)	58 (208 - 7)	26 (79 - 8)
20 September	4796 (8436 - 2930)	14426 (20693 - 6959)	52 (84 - 13)	91 (116 - 70)	37 (49 - 26)
08 October	8722 (30033 - 1874)	7404 (27543 - 152)	49 (114 - 12)	123 (224 - 29)	50 (101 - 14)
23 October	30401 (38913 - 2949)	14436 (44716 - 3067)	32 (57 - 16)	96 (139 - 31)	30 (49 - 2)
Median	1673	7473	26	70	26
Mean	6101	10038	31	74	27
SD	8874	12172	20	47	18

Table 13 Summary of EMCs and range of variation of influent particle size fractions

Rainfall-runoff event	Sediment [mg/L]	Settleable [mg/L]	SSC [mg/L]	TSS [mg/L]	VSSC/SSC [%]
20 March	718.1 (3136.8 - 18.1)	50.8 (177.2 - 6.6)	262.1 (606.7 -22.0)	27.5 (37.5 - 16.0)	46.4 (53.9 - 37.5)
16 May	847.7 (1980.7 - 14.5)	137.8 (305.7 - 11.3)	413.4 (1319.6 -20.0)	65.4 (160.5 - 19.0)	43.9 (83.1 -19.9)
03 June	1835.5 (6032.0 - 1.2)	159.0 (594.7 - 4.8)	1492.4 (4886.4 -31.7)	55.4 (110.1 - 26.4)	60.2 (84.5 -47.9)
10 June	819.4 (2127.0 - 8.9)	95.5 (437.8 -10.1)	359.3 (1570.6 -23.8)	87.7 (532.0 - 14.5)	53.7 (97.6 - 29.4)
21 June	296.1 (499.0 - 3.0)	43.5 (72.5 - 3.2)	731.9 (1271.5 -12.4)	59.8 (87.7 - 7.8)	60.9 (78.8 - 41.8)
08 July	102.0 (633.6 - 7.1)	22.1 (147.9 - 5.1)	111.2 (988.4 - 7.0)	15.3 (77.3 - 5.8)	34.0 (62.3 - 17.1)
15 July	57.5 (548.9 - 3.5)	16.0 (84.0 - 5.8)	86.3 (803.4 - 8.5)	15.8 (40.6 - 3.2)	29.9 (49.4 - 12.1)
29 July	302.1 (627.2 - 11.1)	202.3 (918.8 - 4.6)	1207.7 (4955.5 -19.0)	46.9 (96.3 - 10.2)	50.6 (60.1 - 24.2)
08 August	422.2 (1405.9 - 25.5)	21.2 (117.8 - 5.2)	1022.7 (10450.0 -30.2)	84.6 (162.2 - 14.6)	42.2 (49.5 - 8.4)
12 August	292.6 (1162.9 - 19.7)	28.5 (55.0 - 5.9)	336.9 (2987.5 -18.9)	28.5 (90.0 - 8.1)	46.5 (59.6 - 5.2)
19 August	401.7 (1463.4 - 22.9)	133.4 (346.1 - 12.0)	509.3 (1736.9 -29.8)	60.7 (104.6 - 17.1)	43.9 (65.4 - 18.2)
10 September	230.0 (773.3 - 16.0)	53.1 (101.6 - 5.7)	334.5 (541.3 -20.4)	46.0 (144.2 - 12.8)	53.7 (73.2 - 33.5)
20 September	163.7 (813.1 - 25.3)	78.1 (171.0 -10.8)	571.2 (2325.7 -49.5)	95.7 (163.3 - 20.4)	47.2 (71.9 - 26.0)
08 October	144.0 (404.7 - 10.1)	109.4 (246.0 - 5.7)	287.0 (1450.6 -67.2)	68.6 (180.0 - 10.0)	54.8 (72.6 - 40.7)
23 October	159.1 (676.6 - 4.9)	26.6 (97.8 - 4.3)	947.9 (14262.9 -22.8)	79.8 (149.7 - 19.7)	54.3 (83.7 - 4.0)
Median	296.1	53.1	413.4	59.8	47.2
Mean	452.8	78.5	578.3	55.8	48.1
SD	458.5	58.4	416.8	25.7	8.7

Table 14 Summary of EMCs and range of variation of effluent PM fractions

Rainfall-runoff event	Sediment [mg/L]	Settleable [mg/L]	SSC [mg/L]	TSS [mg/L]	VSSC/SSC [%]
20 March	23.3 (36.9 - 4.2)	35.1 (112.1 - 0.3)	72.2 (171.0 - 6.7)	30.9 (60.2 - 7.5)	65.4 (82.8 - 52.4)
16 May	41.6 (92.3 - 8.8)	63.0 (147.8 - 1.1)	100.0 (158.7 - 8.4)	43.9 (70.5 - 4.5)	63.9 (236.0 - 30.4)
03 June	3.6 (9.4 - 1.0)	12.7 (23.4 - 2.2)	54.3 (141.3 - 19.5)	31.1 (41.1 - 21.1)	57.5 (68.2 - 39.3)
10 June	8.7 (41.0 - 1.7)	20.6 (57.5 - 7.0)	63.1 (223.6 - 12.8)	22.1 (72.2 - 7.0)	28.3 (73.0 - 7.6)
21 June	8.1 (14.2 - 2.3)	11.0 (16.2 - 2.4)	39.0 (101.0 - 5.7)	29.9 (63.2 - 5.2)	49.1 (66.7 - 34.6)
08 July	14.7 (46.9 - 2.4)	7.7 (34.6 - 2.5)	26.4 (64.9 - 3.2)	6.7 (35.4 - 1.6)	50.4 (62.9 - 38.1)
15 July	4.6 (24.3 - 1.1)	6.8 (17.9 - 4.3)	10.8 (60.6 - 1.6)	5.4 (26.8 - 1.6)	36.8 (81.5 - 13.8)
29 July	7.7 (17.4 - 2.3)	10.6 (41.0 - 2.6)	33.2 (171.2 - 6.3)	16.6 (56.0 - 4.8)	73.6 (100.0 - 41.0)
08 August	9.1 (14.9 - 1.8)	4.2 (9.3 - 1.8)	23.6 (32.3 - 11.1)	18.8 (31.3 - 3.0)	71.1 (81.5 - 65.8)
12 August	17.7 (37.4 - 0.3)	5.4 (12.2 - 4.0)	9.6 (26.3 - 2.0)	8.5 (18.6 - 3.8)	62.7 (105.3 - 46.0)
19 August	10.8 (41.1 - 1.6)	17.5 (35.3 - 3.7)	51.8 (138.5 - 7.2)	33.1 (53.5 - 10.2)	59.1 (84.9 - 45.5)
10 September	7.7 (14.5 - 2.9)	11.1 (28.7 - 4.1)	38.7 (93.2 - 7.5)	21.4 (59.6 - 3.3)	63.1 (80.0 - 51.7)
20 September	10.0 (17.9 - 3.4)	15.6 (25.6 - 2.8)	63.6 (111.1 - 15.9)	51.6 (89.3 - 13.0)	64.4 (74.9 - 59.1)
08 October	9.2 (15.6 - 2.3)	20.5 (45.8 - 3.3)	64.3 (162.1 - 10.3)	35.4 (78.3 - 9.4)	81.9 (119.5 - 55.3)
23 October	7.8 (22.9 - 1.7)	8.1 (17.0 - 2.0)	34.7 (54.6 - 12.3)	31.4 (50.0 - 6.7)	77.8 (112.6 - 0.1)
Median	9.1	11.1	39.0	29.9	63.1
Mean	12.3	16.7	45.7	25.8	60.3
SD	9.5	15.0	24.6	13.3	14.5

Table 15 Influent and effluent event mean PM indices of d₁₅, d₅₀ and d₈₅ and range of variation within each monitored storm event

Rainfall -Runoff Event	Influent PSD (µm)			Effluent PSD (µm)		
	d ₁₅	d ₅₀	d ₈₅	d ₁₅	d ₅₀	d ₈₅
20 March	42.7 (21.9 - 112.6)	135.9 (58.5 - 270.1)	937.6 (191.7 - 1116.4)	9.9 (3.5 - 11.0)	30.7 (22.6 - 74.7)	63.6 (53.1 - 142.4)
16 May	48.5 (8.3 - 96.4)	166.4 (31.7 - 345.1)	635.3 (137.8 - 1012.7)	9.6 (4.6 - 29.3)	27.4 (14.7 - 82.3)	64.9 (39.9 - 190.9)
03 June	44.0 (1.9 - 58.1)	151.6 (8.7 - 217.2)	777.8 (38.1 - 903.1)	8.3 (2.9 - 14.6)	34.6 (11.0 - 56.0)	105.8 (50.0 - 161.1)
10 June	101.8 (4.5 - 211.9)	332.9 (21.9 - 486.4)	673.0 (96.9 - 907.7)	3.7 (1.0 - 15.7)	27.1 (3.3 - 44.7)	83.8 (13.0 - 107.0)
21 June	38.2 (3.3 - 44.4)	250.4 (30.9 - 294.2)	956.1 (118.3 - 995.7)	3.1 (1.1 - 4.1)	15.9 (2.7 - 16.7)	52.3 (6.3 - 49.6)
08 July	36.9 (2.1 - 120.3)	102.3 (11.6 - 369.9)	285.1 (50.6 - 876.5)	3.6 (1.5 - 17.5)	28.6 (2.4 - 74.8)	81.4 (3.8 - 130.8)
15 July	37.0 (5.1 - 92.5)	105.4 (27.9 - 236.7)	218.9 (88.8 - 391.6)	9.0 (2.5 - 15.7)	35.3 (13.7 - 55.9)	97.1 (53.4 - 259.7)
29 July	38.2 (7.5 - 72.5)	252.8 (107.7 - 398.3)	797.7 (446.0 - 960.0)	5.8 (2.3 - 15.3)	29.0 (9.6 - 37.0)	87.3 (66.4 - 141.5)
08 August	43.3 (2.2 - 200.4)	246.2 (15.8 - 423.6)	668.1 (45.3 - 748.8)	2.9 (1.4 - 11.9)	16.9 (7.0 - 73.0)	93.3 (26.1 - 226.2)
12 August	54.4 (7.9 - 81.1)	238.6 (83.3 - 268.2)	640.8 (345.6 - 719.4)	4.1 (0.9 - 6.0)	26.7 (2.6 - 34.7)	92.2 (5.1 - 129.5)
19 August	21.1 (10.8 - 57.3)	150.2 (89.7 - 524.8)	613.6 (488.3 - 1258.8)	5.0 (1.2 - 6.0)	23.6 (3.4 - 25.4)	69.8 (8.4 - 77.5)
10 September	20.8 (2.4 - 27.1)	98.7 (11.5 - 156.0)	462.7 (99.8 - 570.6)	6.8 (1.4 - 15.2)	28.5 (5.6 - 47.2)	94.9 (14.9 - 118.8)
20 September	10.8 (4.4 - 26.9)	78.6 (18.9 - 121.4)	411.1 (101.8 - 484.1)	4.4 (2.1 - 12.5)	20.1 (8.8 - 49.7)	77.3 (40.0 - 112.3)
08 October	14.0 (1.9 - 39.4)	80.6 (6.9 - 141.2)	358.7 (19.1 - 520.7)	3.7 (1.8 - 6.9)	17.1 (7.3 - 49.8)	69.9 (19.8 - 171.9)
23 October	6.7 (2.4 - 43.8)	36.0 (12.9 - 263.0)	252.8 (51.9 - 700.7)	3.3 (1.6 - 17.8)	17.7 (7.3 - 37.2)	66.4 (23.0 - 82.9)

Table 16 Summary of EMCs and range of variation of influent dissolved, particulate bound and total phosphorus

Rainfall- runoff events	TDP [µg/L]	Sediment TP [µg/L]	Settleable TP [µg/L]	Suspended TP [µg/L]	TP [µg/L]
20 March	789 (1428- 510)	1860 (7778 - 171)	533 (1782 - 122)	497 (1203 - 151)	3673 (12191 - 966)
16 May	517 (1523- 302)	1693 (2999 - 742)	1371 (2994 - 115)	794 (2223 - 267)	4375 (6988 - 1964)
03 June	1352 (1767- 734)	2418 (7564 - 139)	1534 (5764 - 52)	1187 (2083 - 722)	6491 (17178 - 1675)
10 June	942 (4488- 270)	2008 (5440 - 134)	940 (5772 - 69)	1143 (6039 - 310)	5032 (17224 - 872)
21 June	245 (396 - 216)	828 (1281 - 147)	465 (750 - 68)	455 (574 - 235)	1994 (2814 - 795)
08 July	222 (553 - 144)	598 (3423 - 121)	67 (1171 - 409)	1319 (2053 - 473)	2206 (7200 - 1646)
15 July	476 (1822- 216)	296 (841 - 36)	193 (523 - 80)	802 (1973 - 232)	1767 (4514 - 685)
29 July	2663 (4896- 1071)	1188 (2868 - 59)	1003 (2787 - 182)	1341 (2726 - 477)	6196 (11743 - 2594)
08 August	579 (939 - 483)	1510 (4562 - 65)	29 (283 - 0)	1089 (1908 - 687)	3206 (7563 - 1495)
12 August	1022 (4533- 397)	1499 (4840 - 126)	729 (3776 - 250)	494 (1231 - 164)	3744 (10738 - 1242)
19 August	410 (986 - 338)	1231 (2480 - 747)	1271 (1717 - 143)	1367 (3917 - 322)	4278 (8866 - 1820)
10 September	754 (4394- 523)	822 (2709 - 125)	558 (1249 - 303)	1093 (3964 - 374)	3228 (10215 - 1292)
20 September	623 (955 - 472)	519 (2029 - 135)	557 (1459 - 104)	625 (1279 - 146)	2324 (5721 - 995)
08 October	996 (4417- 567)	392 (598 - 58)	677 (1696 - 53)	790 (1495 - 414)	2855 (7751 - 1244)
23 October	468 (1078- 191)	520 (1392 - 36)	254 (975 - 81)	788 (1609 - 259)	2030 (5012 - 664)
Median	623	1188	558	802	3228
Mean	804	1159	679	919	3560
SD	601	656	466	321	1489

Table 17 Summary of EMCs and range of variation of effluent dissolved, particulate bound and total phosphorus

Rainfall- runoff events	TDP [µg/L]	Sediment TP [µg/L]	Settleable TP [µg/L]	Suspended TP [µg/L]	TP [µg/L]
20 March	144 (202 - 111)	185 (270 - 80)	429 (1379 - 0)	304 (373 - 225)	1063 (2135 - 424)
16 May	135 (461 - 49)	429 (935 - 88)	774 (1838 - 0)	851 (1298 - 200)	2189 (4155 - 200)
03 June	67 (87 - 50)	44 (93 - 21)	136 (265 - 9)	489 (607 - 364)	736 (947 - 480)
10 June	227 (393 - 54)	85 (294 - 52)	266 (701 - 63)	325 (462 - 191)	903 (1597 - 402)
21 June	126 (147 - 89)	89 (139 - 35)	126 (193 - 21)	292 (377 - 205)	633 (788 - 363)
08 July	146 (221 - 98)	102 (180 - 35)	0 (0 - 0)	1257 (1731 - 647)	1505 (2006 - 895)
15 July	187 (301 - 51)	59 (138 - 11)	90 (271 - 55)	681 (1008 - 289)	1017 (1665 - 605)
29 July	497 (733 - 274)	97 (226 - 35)	279 (578 - 104)	1199 (1908 - 458)	2072 (3118 - 1012)
08 August	105 (146 - 36)	93 (145 - 7)	4 (21 - 0)	776 (1148 - 594)	977 (1413 - 810)
12 August	357 (654 - 137)	187 (505 - 2)	124 (625 - 18)	427 (857 - 153)	1096 (1981 - 416)
19 August	360 (539 - 245)	99 (437 - 7)	244 (485 - 63)	890 (1740 - 330)	1594 (2677 - 763)
10 September	299 (424 - 113)	76 (147 - 40)	32 (410 - 0)	443 (1093 - 141)	850 (1904 - 455)
20 September	255 (424 - 174)	89 (157 - 20)	104 (250 - 0)	429 (577 - 199)	878 (1234 - 469)
08 October	208 (514 - 110)	92 (224 - 32)	134 (289 - 0)	705 (1245 - 145)	1139 (2147 - 490)
23 October	87 (349 - 26)	106 (321 - 41)	15 (170 - 0)	462 (773 - 266)	671 (1155 - 406)
Median	187	93	126	489	1017
Mean	213	122	184	635	1155
SD	121	93	202	309	478

Table 18 Summary of event mean value and range of variation of the dissolved fraction (f_d) and partition coefficient (k_d) of phosphorus for influent and effluent runoff

Rainfall-runoff event	f_d (-)		k_d (L/Kg)	
	Influent	Effluent	Influent	Effluent
20 March	0.43 (0.53 - 0.12)	0.25 (0.31 - 0.05)	11945 (17302 - 2250)	112430 (185165 - 53535)
16 May	0.21 (0.35 - 0.07)	0.13 (0.40 - 0.05)	18303 (46637 - 5761)	176615 (388364 - 34195)
03 June	0.38 (0.56 - 0.10)	0.11 (0.16 - 0.05)	11038 (39268 - 1295)	220225 (293917 - 165411)
10 June	0.32 (0.58 - 0.07)	0.23 (0.35 - 0.07)	13834 (30197 - 1049)	97984 (313113 - 31535)
21 June	0.25 (0.43 - 0.08)	0.23 (0.29 - 0.13)	43146 (87658 - 14036)	136479 (226795 - 69002)
8 July	0.10 (0.16 - 0.07)	0.10 (0.16 - 0.06)	137208 (381011 - 10911)	417623 (1278214 - 83021)
15 July	0.24 (0.40 - 0.10)	0.20 (0.40 - 0.06)	57524 (191197 - 2449)	308904 (986519 - 67440)
29 July	0.49 (0.65 - 0.32)	0.23 (0.35 - 0.11)	9021 (35778 - 852)	141626 (310153 - 58322)
8 August	0.27 (0.48 - 0.11)	0.10 (0.15 - 0.03)	10986 (22629 - 4670)	623604 (3029953 - 182996)
12 August	0.36 (0.59 - 0.22)	0.30 (0.48 - 0.17)	14808 (62247 - 1469)	137661 (255936 - 35079)
19 August	0.18 (0.30 - 0.07)	0.27 (0.40 - 0.11)	20963 (83778 - 4176)	72798 (111047 - 35624)
10 September	0.36 (0.61 - 0.15)	0.33 (0.54 - 0.13)	11978 (23622 - 2620)	73812 (125642 - 24692)
20 September	0.38 (0.60 - 0.17)	0.29 (0.37 - 0.21)	11593 (19568 - 4391)	45576 (85094 - 21673)
8 October	0.44 (0.63 - 0.23)	0.21 (0.35 - 0.09)	10138 (42048 - 1622)	84926 (187614 - 22818)
23 October	0.27 (0.55 - 0.09)	0.15 (0.49 - 0.03)	25417 (92993 - 3950)	222488 (549038 - 47926)
Median	0.32	0.23	13834	137661
Mean	0.31	0.21	27193	191517
SD	0.11	0.08	33362	155297

Table 19 Summary of EMCs and range of variation of influent nitrate, nitrite, ammonia and dissolved, particulate bound and total nitrogen.

Parameters	NO ₃ ⁻ -N [µg/L]	NH ₃ -N [µg/L]	TDN [µg/L]	Sediment TN [µg/L]	Settleable TN [µg/L]	Suspended TN [µg/L]	TN [µg/L]	NO ₂ ⁻ -N [µg/L]
20 March	2326 (4771 - 1135)	326 (762 - 65)	3087 (4219 - 2123)	N/A	N/A	N/A	N/A	N/A
16 May	680 (3799 - 109)	81 (794 - 19)	3193 (13316 - 1362)	913 (2116 - 30)	653 (2338 - 49)	717 (3667 - 46)	5476 (19450 - 1487)	N/A
03 June	2033 (2534 - 341)	188 (285 - 22)	3955 (4853 - 1529)	5608 (19532 - 5)	689 (2086 - 2)	715 (971 - 324)	10967 (27442 - 2041)	N/A
10 June	643 (800 - 0)	251 (987 - 17)	4001 (10098 - 1276)	2566 (7879 - 53)	477 (2463 - 33)	1074 (1808 - 250)	8119 (22055 - 2851)	N/A
21 June	1119 (1770 - 752)	133 (173 - 20)	3993 (5098 - 2799)	1034 (1911 - 39)	232 (345 - 18)	614 (1293 - 144)	5873 (8554 - 3357)	N/A
08 July	2663 (15088 - 310)	22 (80 - 5)	4469 (32885 - 801)	172 (1077 - 21)	65 (316 - 15)	1011 (3462 - 128)	5704 (33419 - 1358)	N/A
15 July	612 (1195 - 243)	48 (97 - 8)	968 (2821 - 64)	120 (528 - 10)	53 (274 - 12)	246 (545 - 48)	1386 (3847 - 342)	N/A
29 July	558 (819 - 310)	58 (80 - 2)	2577 (4909 - 1121)	998 (2056 - 14)	1129 (5090 - 18)	1538 (2318 - 455)	5481 (13974 - 2032)	N/A
08 August	1070 (1272 - 785)	105 (145 - 0)	2150 (4790 - 944)	816 (3083 - 27)	89 (529 - 6)	2000 (4344 - 1090)	5054 (12747 - 2530)	N/A
12 August	363 (1140 - 175)	15 (147 - 5)	937 (6078 - 240)	672 (2106 - 72)	160 (422 - 16)	461 (1078 - 60)	2231 (8498 - 1165)	N/A
19 August	671 (774 - 332)	41 (83 - 9)	1886 (3683 - 868)	1263 (4999 - 37)	644 (956 - 2)	197 (419 - 12)	3989 (9208 - 1032)	1.6 (2.0-1.2)
10 September	560 (875 - 450)	4 (203 - 0)	1063 (4719 - 561)	740 (2212 - 55)	254 (482 - 26)	195 (3138 - 14)	2252 (8704 - 853)	1.3 (9.1-0.1)
20 September	961 (2018 - 379)	70 (188 - 16)	1560 (336 - 745)	383 (1655 - 90)	341 (756 - 56)	832 (1294 - 272)	3117 (6759 - 1690)	1.3 (1.9-0.2)
08 October	644 (967 - 71)	32 (51 - 19)	988 (4362 - 740)	468 (710 - 52)	450 (893 - 59)	1268 (4668 - 102)	3174 (10131 - 1263)	1.6 (2.4-0.1)
23 October	731 (1085 - 42)	184 (554 - 91)	1660 (5581 - 988)	496 (2054 - 73)	127 (512 - 26)	157 (494 - 26)	2440 (8641 - 1208)	3.4 (13.5-1.8)
Mean	1042	104	2433	1201	329	788	4703	1.9
Median	680	70	2150	778	298	716	4522	1.6
SD	710	95	1267	1414	225	550	2623	0.9

Table 20 Summary of EMCs and range of variation of effluent nitrate, nitrite, ammonia and dissolved, particulate bound and total nitrogen.

Parameters	NO ₃ ⁻ -N [µg/L]	NH ₃ -N [µg/L]	TDN [µg/L]	Sediment TN [µg/L]	Settleable TN [µg/L]	Suspended TN [µg/L]	TN [µg/L]	NO ₂ ⁻ -N [µg/L]
20 March	9385 (22697 - 2052)	296 (396 - 108)	5557 (7104 - 3142)	N/A	N/A	N/A	N/A	N/A
16 May	2434 (27533 - 0)	66 (1421 - 0)	4738 (84580 - 1420)	95 (203 - 25)	228 (524 - 2)	2238 (21339 - 448)	6737 (106324 - 2217)	N/A
03 June	782 (1557 - 170)	29 (57 - 3)	8533 (27132 - 1794)	45 (104 - 9)	162 (318 - 17)	786 (1838 - 147)	9474 (29314 - 2037)	N/A
10 June	802 (1140 - 581)	162 (470 - 0)	4785 (14207 - 2195)	66 (206 - 18)	236 (579 - 76)	916 (1791 - 223)	5969 (16659 - 3814)	N/A
21 June	866 (1128 - 509)	186 (286 - 102)	3689 (4322 - 2483)	25 (37 - 10)	82 (124 - 25)	555 (1149 - 230)	4345 (5632 - 3101)	N/A
08 July	945 (8761 - 243)	27 (477 - 2)	1048 (12436 - 192)	25 (68 - 4)	25 (146 - 3)	1237 (3910 - 16)	2326 (15118 - 392)	N/A
15 July	488 (1615 - 66)	59 (516 - 21)	816 (2628 - 256)	21 (100 - 6)	22 (83 - 9)	870 (1683 - 224)	1707 (4051 - 1175)	N/A
29 July	752 (1770 - 199)	72 (477 - 0)	2820 (5879 - 1152)	38 (67 - 11)	59 (260 - 9)	1590 (6182 - 91)	4477 (11131 - 1477)	N/A
08 August	1791 (3783 - 199)	149 (427 - 11)	4385 (5385 - 2657)	58 (109 - 4)	22 (45 - 8)	661 (1416 - 64)	5101 (6062 - 3419)	N/A
12 August	873 (1075 - 241)	8 (175 - 0)	1103 (2545 - 449)	82 (146 - 2)	175 (256 - 8)	329 (479 - 63)	1666 (2891 - 707)	N/A
19 August	885 (1615 - 553)	319 (1142 - 3)	5539 (7844 - 629)	75 (192 - 7)	142 (303 - 8)	416 (689 - 63)	6114 (8491 - 709)	0.7 (1.4 - 0.1)
10 September	545 (835 - 50)	104 (1698 - 15)	1605 (6454 - 638)	51 (120 - 16)	48 (236 - 8)	207 (485 - 102)	1927 (6818 - 990)	2.0 (8.1 - 0.9)
20 September	804 (1954 - 52)	575 (2226 - 15)	1943 (4288 - 852)	67 (102 - 30)	561 (1155 - 63)	1016 (1934 - 465)	3579 (6711 - 2109)	1.8 (3.4 - 1.2)
08 October	866 (2241 - 118)	92 (1416 - 24)	1432 (5077 - 357)	67 (16 - 33)	189 (331 - 64)	1023 (1709 - 128)	2669 (5852 - 1244)	28.1 (176.7 - 0.0)
23 October	292 (896 - 118)	268 (2281 - 67)	1844 (4419 - 610)	85 (228 - 19)	53 (83 - 2)	1151 (2413 - 110)	3107 (5019 - 981)	1.3 (1.8 - 1.0)
Mean	1497	161	3316	66	143	926	4219	6.8
Median	866	104	2820	62	112	893	3962	1.8
SD	2242	151	2227	50	143	527	2263	12.0

Table 21 Summary of event mean value and range of variation of the dissolved fraction (f_d) and partition coefficient (k_d) of nitrogen for influent and effluent runoff

Rainfall-runoff event	f_d				k_d			
	(-)				(L/Kg)			
20 March 08	N/A				N/A			
16 May 08	0.59				2649			
	0.80	-	0.03	0.88 - 0.17	6081	-	442	238432 - 2473
03 June 08	0.62				5986			
	0.86	-	0.18	0.94 - 0.74	16075	-	783	16929 - 2774
10 June 08	0.61				8499			
	0.86	-	0.28	0.95 - 0.53	49136	-	922	58026 - 1736
21 June 08	0.78				5949			
	0.94	-	0.60	0.92 - 0.77	13267	-	1863	31758 - 4352
8 July 2008	0.70				27959			
	0.98	-	0.28	0.95 - 0.12	169741	-	130	1067652 - 4334
15 July 2008	0.68				56967			
	0.88	-	0.19	0.83 - 0.22	712830	-	1459	641361 - 21113
29 July 2008	0.54				11823			
	0.76	-	0.36	0.94 - 0.43	26303	-	3070	66217 - 4706
8 August 2008	0.42				15762			
	0.55	-	0.33	0.97 - 0.74	42068	-	1862	88485 - 3634
12 August 2008	0.51				16096			
	0.87	-	0.21	0.89 - 0.49	48369	-	1347	118023 - 12878
19 August 2008	0.60				4107			
	0.90	-	0.40	0.94 - 0.63	6441	-	1387	49217 - 1925
10 September 2008	0.57				12122			
	0.88	-	0.35	0.95 - 0.64	69455	-	3235	54756 - 2605
20 September 2008	0.51				17175			
	0.71	-	0.41	0.49 - 0.33	43929	-	1962	160060 - 36370
8 October 2008	0.35				32524			
	0.71	-	0.16	0.78 - 0.24	128927	-	5838	323000 - 12518
23 October 2008	0.74				2862			
	0.86	-	0.60	0.94 - 0.31	7872	-	593	39586 - 974
Mean	0.59				15749			
Median	0.60				11973			
SD	0.12				14877			

Table 22 Summary of EMCs and range of variation of influent metals

Rainfall-runoff event	Sodium [µg/L]	Magnesium [µg/L]	Calcium [µg/L]	Copper [µg/L]	Zinc [µg/L]	Lead [µg/L]
20 March	4720 (12790- 1210)	1973 (3677 - 974)	13206 (23392- 7310)	10 (29 - 0)	59 (106 - 30)	19 (3677-973)
16 May	NA	1793 (9992 - 809)	13860 (64310- 7209)	31 (105- 15)	40 (230 - 17)	15 (29 - 8)
03 June	1711 (2545 - 1135)	4646 (7238 - 3286)	28191 (43911- 20447)	32 (55 - 17)	86 (149 - 53)	16 (22 - 8)
10 June	649 (2895 - 134)	1372 (6867 - 624)	9123 (38306- 4527)	47 (181- 14)	40 (175 - 20)	20 (30 - 10)
21 June	649 (1360 - 287)	1683 (3267 - 776)	12982 (24666- 6792)	11 (23 - 6)	33 (64 - 16)	18 (26 - 9)
08 July	2167 (6300 - 65)	421 (5280 - 255)	3910 (24903- 1301)	5 (36 - 1)	17 (229 - 7)	20 (33 - 8)
15 July	424 (5065 - 112)	338 (2605 - 219)	2932 (21046- 1837)	3 (23 - 1)	36 (143 - 21)	46 (33 - 8)
29 July	1527 (3655 - 476)	2503 (4434 - 1103)	17271 (31840- 8321)	32 (107- 5)	104 (232 - 38)	100 (117 - 81)
08 August	1198 (4180 - 424)	2524 (3980 - 2082)	20419 (26915- 17584)	24 (101- 9)	108 (237 - 75)	101 (150 - 74)
12 August	551 (4560 - 281)	1068 (7863 - 554)	7488 (41722- 5075)	9 (52 - 5)	37 (357 - 25)	20 (34 - 13)
19 August	2838 (4075 - 1820)	855 (1987 - 586)	7486 (12689- 5570)	25 (41 - 15)	22 (40 - 17)	7 (13 - 5)
10 September	1668 (7960 - 682)	1773 (9136 - 1098)	10590 (43518- 7480)	14 (81 - 9)	37 (498 - 19)	2 (4 - 1)
20 September	2736 (5705 - 443)	2644 (4002 - 1879)	17617 (25103- 12977)	47 (93 - 29)	67 (140 - 34)	48 (73 - 30)
08 October	1534 (4140 - 649)	2381 (6715 - 1213)	16223 (34113- 9440)	44 (127- 19)	67 (248 - 29)	45 (71 - 23)
23 October	24198 (94600- 6715)	3517 (8881 - 1639)	21779 (45596- 11786)	40 (114- 19)	63 (164 - 26)	3 (4 - 2)
Median	1601	1793	13206	25	40	20
Mean	3326	1966	13538	25	54	32
SD	6116	1146	6943	16	28	31

Table 23 Summary of EMCs and range of variation of effluent metals

Rainfall-runoff event	Sodium [µg/L]	Magnesium [µg/L]	Calcium [µg/L]	Copper [µg/L]	Zinc [µg/L]	Lead [µg/L]
20 March	6043 (11171-1351)	4377 (10340-1031)	19513 (40893 - 7034)	2 (2 - 0)	121 (266 - 34)	21 (24 - 14)
16 May	NA	3188 (40647-1014)	20242 (179164- 8238)	16 (31 - 9)	31 (83 - 15)	18 (28 - 13)
03 June	1700 (2025 - 1270)	7911 (13817-4866)	53805 (87034 -35026)	9 (11 - 6)	53 (68 - 34)	10 (14 - 6)
10 June	445 (1610 - 164)	3327 (11622- 859)	9096 (77200 - 5129)	17 (39 - 9)	25 (60 - 12)	23 (36 - 12)
21 June	544 (986 - 357)	779 (5280 - 255)	29188 (99127 - 7971)	8 (12 - 4)	21 (35 - 13)	20 (27 - 9)
08 July	2608 (7665 - 323)	313 (3390 - 34)	6970 (42919 - 2609)	6 (28 - 2)	25 (101 - 11)	17 (30 - 7)
15 July	2630 (12400- 48)	727 (7038 - 347)	5818 (48863 - 2851)	3 (8 - 1)	45 (80 - 32)	16 (29 - 7)
29 July	1036 (1525 - 483)	2740 (8960 -1125)	19064 (54836 - 8183)	15 (25 - 8)	80 (179 - 36)	106 (138 - 88)
08 August	1395 (3900 - 77)	8082 (14993-3891)	51045 (82845 -30980)	14 (20 - 5)	130 (200 - 51)	104 (115 - 87)
12 August	500 (1910 - 258)	1179 (9679 - 33)	8278 (57842 - 369)	7 (12 - 2)	38 (118 - 9)	24 (36 - 14)
19 August	2587 (4025 -2140)	3427 (10066- 815)	24773 (65537 - 7894)	16 (40 - 13)	62 (125 - 31)	10 (12 - 5)
10 September	1565 (2860 - 714)	3257 (14972-2094)	25927 (96844 -18696)	31 (41 - 16)	54 (91 - 42)	4 (8 - 3)
20 September	1358 (1835 - 881)	5619 (16315-2382)	44216 (110208-21534)	39 (57 - 28)	80 (120 - 55)	31 (59 - 18)
08 October	2016 (5475 - 610)	3773 (12534-1458)	30380 (93172 -11286)	29 (45 - 14)	83 (157 - 30)	48 (58 - 26)
23 October	9423 (29700- 897)	4385 (11801-2062)	32906 (78870 -15122)	18 (24 - 8)	58 (89 - 22)	3 (6 - 1)
Median	1633	3327	24773	15	54	20
Mean	2418	3539	25415	15	60	30
SD	2463	2360	15349	11	33	32

Table 24 Summary of mean concentration values and range of variation of quality characteristics of stored runoff into the filter system during inter event retention periods (Physical-Chemical characteristics)

Inter-event retention period	HRT [hours]	pH [s.u.]	Redox [mV]	Salinity [ppt]	Temperature [°C]	Conductivity [µS/cm]	TDS [mg/L]	Alkalinity [mg/L as CaCO ₃]	Turbidity [NTU]
20 March 08	324	7.09 (7.27-6.88)	87.2 (384.1 ~ 23.7)	0.17 (0.20-0.06)	19.0 (21.8 - 13.4)	348 (408 - 131)	226 (265-85)	97 (158 - 28)	3.0 (12.8-1.2)
16 May 08	384	6.86 (7.29-6.62)	-100.9 (253.3 ~ -282.0)	0.19 (0.32-0.08)	26.1 (27.6 - 24.4)	402 (668 - 169)	262 (435-110)	125 (252 - 32)	10.3 (48.1-2.4)
03 June 08	114	6.87 (7.10-6.73)	-111.0 (237.5 ~ -232.4)	0.18 (0.20-0.10)	26.9 (29.1 - 21.1)	374 (475 - 228)	183 (233-112)	124 (185 - 64)	20.4 (60.1-7.2)
10 June 08	217	6.60 (7.30-6.29)	-175.3 (175.0 ~ -227.0)	0.16 (0.29-0.06)	26.1 (28.3 - 23.8)	341 (607 - 117)	222 (395-76)	152 (287 - 10)	22.3 (61.2-8.5)
21 June 08	366	6.46 (6.82-6.27)	-189.7 (155.0 ~ -230.0)	0.17 (0.28-0.07)	25.8 (27.5 - 24.3)	341 (570 - 138)	222 (371-90)	163 (298 - 26)	27.5 (49.9-8.1)
08 July 08	138	6.71 (7.15-6.41)	-158.3 (287.8 ~ -243.0)	0.10 (0.14-0.05)	26.8 (28.4 - 24.9)	209 (292 - 106)	136 (190-69)	103 (132 - 70)	10.6 (15.9-5.2)
15 July 08	142	6.62 (7.18-6.31)	-158.7 (270.3 ~ -248.0)	0.10 (0.15-0.04)	27.0 (28.6 - 25.7)	213 (318 - 91)	138 (207-59)	99 (156 - 24)	9.7 (13.0-3.5)
29 July 08	138	6.40 (7.00-6.18)	-192.5 (81.3 ~ -235.0)	0.16 (0.24-0.07)	26.7 (29.8 - 25.6)	338 (487 - 151)	220 (317-98)	165 (312 - 52)	14.6 (19.3-10.1)
08 August 08	89	6.47 (6.65-6.37)	-189.0 (105.5 ~ -232.3)	0.14 (0.18-0.09)	27.8 (29.7 - 26.4)	288 (363 - 187)	188 (236-122)	133 (204 - 62)	19.8 (29.4-13.8)
12 August 08	143	6.39 (7.21-6.08)	-200.5 (245.0 ~ -262.3)	0.21 (0.36-0.05)	25.6 (27.0 - 24.9)	440 (741 - 106)	287 (482-69)	171 (326 - 40)	8.9 (21.9-5.8)
19 August 08	385	6.39 (7.02-6.27)	-195.7 (258.0 ~ -257.3)	0.22 (0.26-0.06)	26.2 (28.3 - 24.5)	448 (532 - 117)	291 (346-76)	225 (356 - 60)	8.7 (12.9-5.6)
10 September 08	213	6.42 (7.02-6.27)	-196.6 (258.0 ~ -253.3)	0.21 (0.25-0.12)	27.0 (28.0 - 26.2)	429 (526 - 256)	279 (342-166)	193 (326 - 69)	15.5 (62.5-1.6)
20 September 08	192	6.60 (6.76-6.53)	-234.7 (-214.0 ~ -243.5)	0.20 (0.23-0.15)	24.3 (27.4 - 21.0)	408 (471 - 316)	266 (306-206)	186 (260 - 78)	16.3 (25.4-8.1)
08 October 08	265	6.74 (7.17-6.55)	-209.5 (213.0 ~ -255.0)	0.17 (0.22-0.06)	24.0 (27.8 - 22.0)	364 (464 - 120)	236 (302-77)	163 (260 - 30)	12.6 (18.2-4.2)
23 October 08	195	6.81 (6.99-6.68)	-204.6 (198.8 ~ -252.0)	0.17 (0.21-0.10)	18.2 (23.5 - 10.2)	363 (444 - 206)	236 (289-134)	139 (210 - 50)	17.0 (26.7-9.3)

Table 25 Summary of mean concentration values and range of variation of quality characteristics of stored runoff into the filter system during inter event retention periods (Ions)

Inter-event retention period	NH ₃ -N [µg/L]	TDP [µg/L]	NO ₃ ⁻ -N [µg/L]	SO ₄ ²⁻ [µg/L]	Cl ⁻ [mg/L]	NO ₂ ⁻ -N [µg/L]	COD [µg/L]	TDN [µg/L]	DOC [mg/L]
20 March 08	323 (846 - 15)	281 (394-194)	9282 (21318 - 1045)	12761 (24615-5308)	20 (32 - 6)	N/A	20 (45 - 3)	14628 (23952 - 5689)	9.7 (14.5-7.7)
16 May 08	983 (2795 - 0)	620 (972-234)	2854 (4500 - 500)	36496 (49346-15769)	20 (28 - 13)	N/A	50 (73 - 40)	10067 (12395 - 6527)	N/A
03 June 08	375 (1167 - 11)	373 (577-128)	909 (1455 - 227)	36766 (39692-27962)	19 (29 - 9)	N/A	148 (168 - 133)	3290 (4638 - 2511)	51.6 (63.0-46.6)
10 June 08	314 (666 - 2)	574 (705-389)	2092 (6903 - 0)	187 (1269-0)	30 (50 - 15)	N/A	148 (275 - 50)	6764 (15902 - 2626)	36.5 (68.7-15.0)
21 June 08	495 (2465 - 5)	654 (1785-168)	236 (545 - 45)	1021 (4654-77)	38 (54 - 13)	N/A	89 (138 - 33)	2561 (3526 - 1218)	21.8 (41.3-3.5)
8 July 08	880 (1490 - 381)	521 (905-200)	1558 (2455 - 773)	2029 (2500-1731)	33 (61 - 11)	N/A	17 (45 - 3)	2738 (3205 - 2500)	26.5 (71.0-7.7)
15 July 08	259 (484 - 15)	775 (1252-359)	939 (1773 - 45)	372 (1607-0)	27 (41 - 10)	N/A	44 (78 - 8)	2601 (3205 - 1923)	168.3 (390.9-34.0)
29 July 08	728 (1615 - 40)	821 (1822-45)	459 (2136 - 0)	714 (2107-0)	28 (43 - 13)	N/A	250 (505 - 55)	3905 (5255 - 2194)	19.0 (49.8-7.8)
8 August 08	998 (1720 - 15)	1502 (2052-497)	409 (1000 - 0)	452 (1393-0)	25 (42 - 14)	N/A	128 (140 - 113)	1843 (2395 - 1138)	19.2 (26.1-11.0)
12 August 08	997 (2614 - 2)	3586 (5517-1745)	821 (2136 - 0)	759 (3607-0)	16 (38 - 6)	N/A	77 (163 - 18)	2545 (3593 - 2036)	64.8 (142.0-5.9)
19 August 08	1487 (4956 - 9)	3160 (5314-562)	415 (2091 - 0)	484 (2393-0)	16 (24 - 7)	0.1 (1.1 - 0.0)	136 (205 - 5)	3235 (5818 - 1818)	21.7 (47.7-1.9)
10 September 08	1707 (4990 - 176)	2398 (3895-572)	286 (2000 - 0)	141 (714-0)	12 (33 - 2)	0.1 (1.1 - 0.0)	151 (303 - 40)	3064 (5629 - 1617)	22.7 (46.2-9.0)
20 September 08	957 (2084 - 253)	1497 (2010-790)	374 (2182 - 0)	27 (357-0)	27 (42 - 12)	0.5 (2.3 - 0.0)	197 (313 - 23)	2418 (3010 - 1735)	21.2 (31.4-11.4)
8 October 08	600 (1839 - 29)	1319 (1936-576)	677 (1840 - 47)	263 (2036-0)	8 (13 - 1)	1.1 (2.7 - 0.1)	63 (78 - 48)	2201 (2857 - 1531)	18.6 (33.2-9.8)
23 October 08	297 (735 - 29)	998 (1774-257)	139 (991 - 0)	46 (422-0)	25 (32 - 19)	1.6 (7.7 - 0.1)	207 (368 - 15)	1929 (2449 - 1582)	14.1 (24.1-6.4)



Figure 1 University of Florida Reitz Union paved surface parking facility in Gainesville, FL. Particular of the monitored inlet.

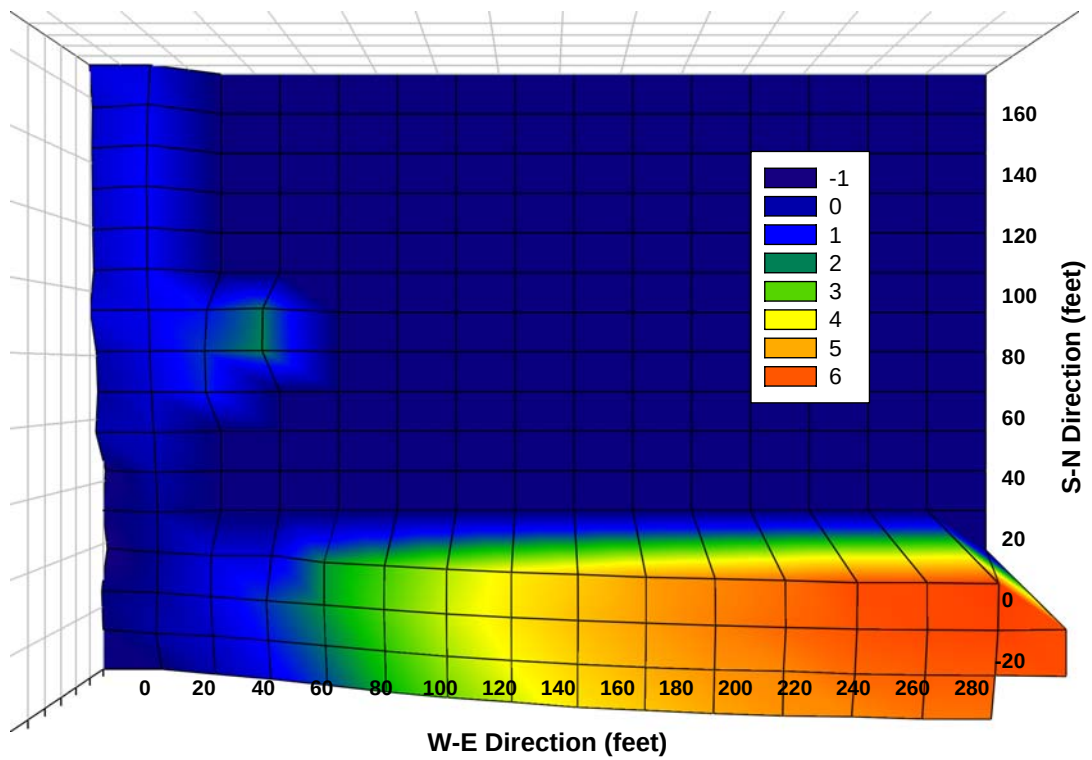


Figure 2 Contour lines showing the monitored area relative elevations

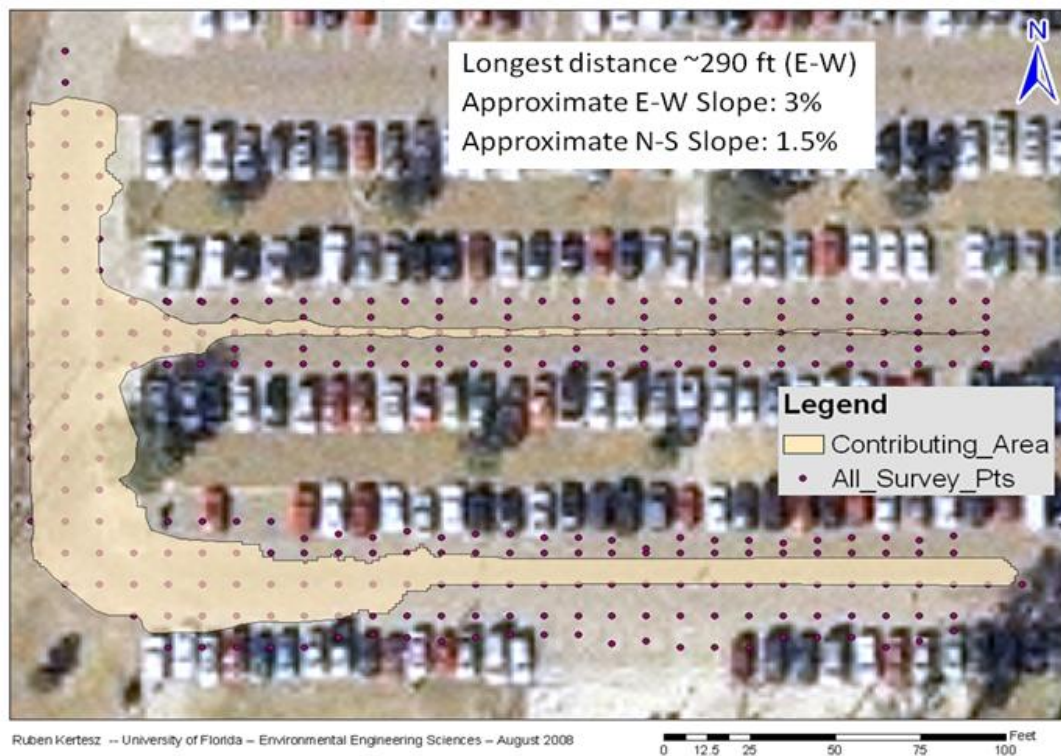


Figure 3 Catchment area

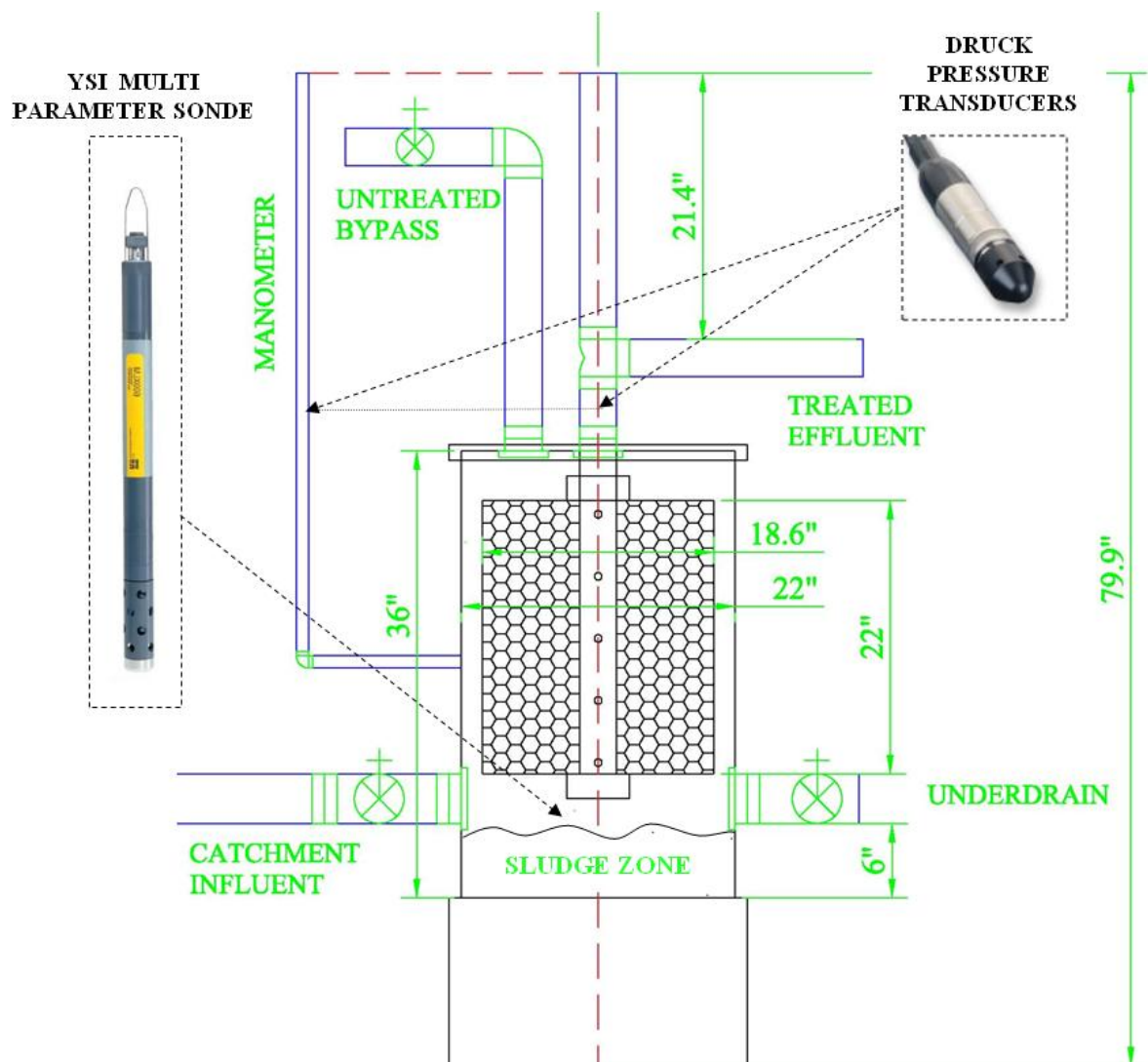


Figure 4 Experimental treatment system

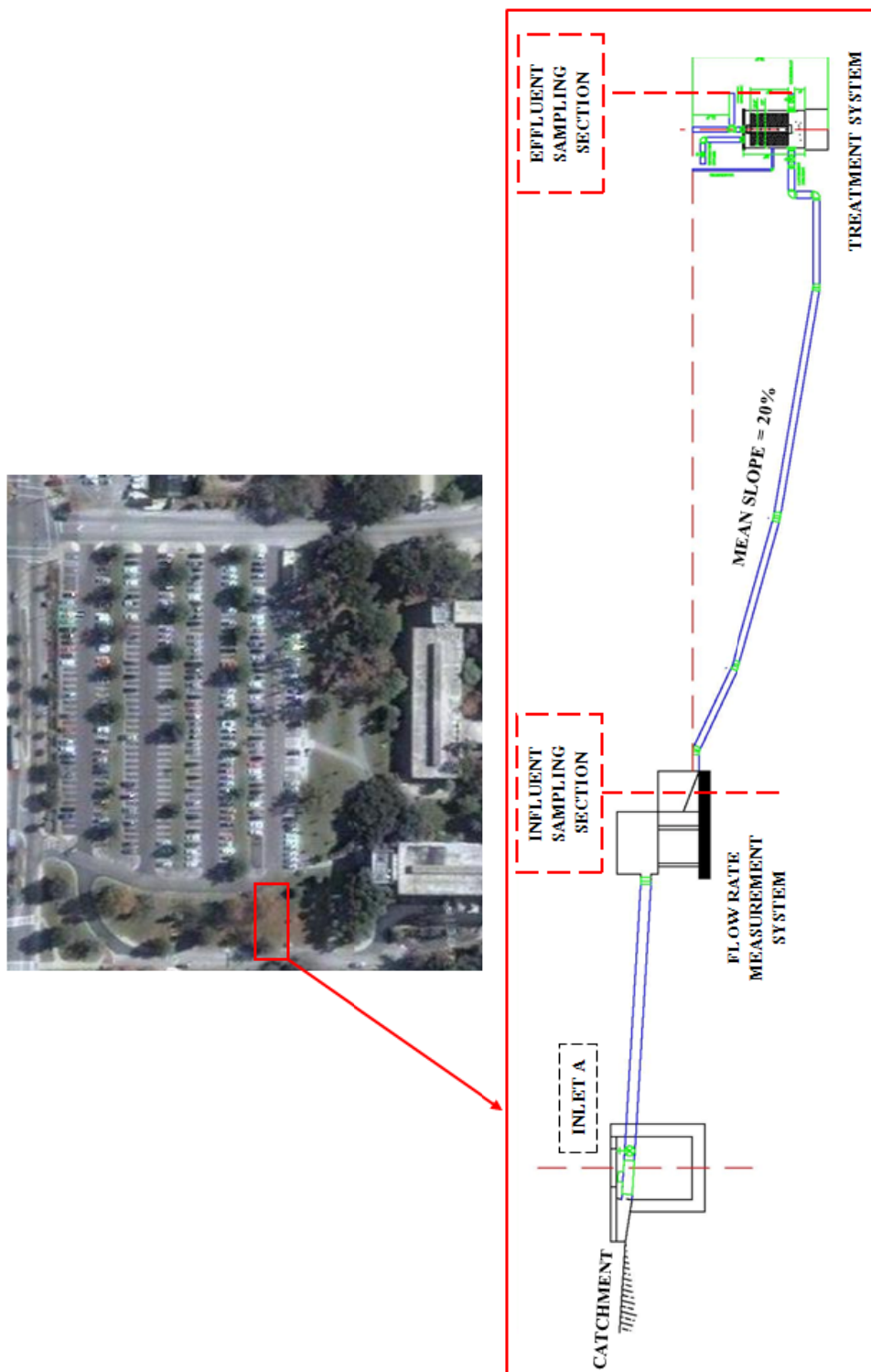


Figure 5 Monitoring system location and design

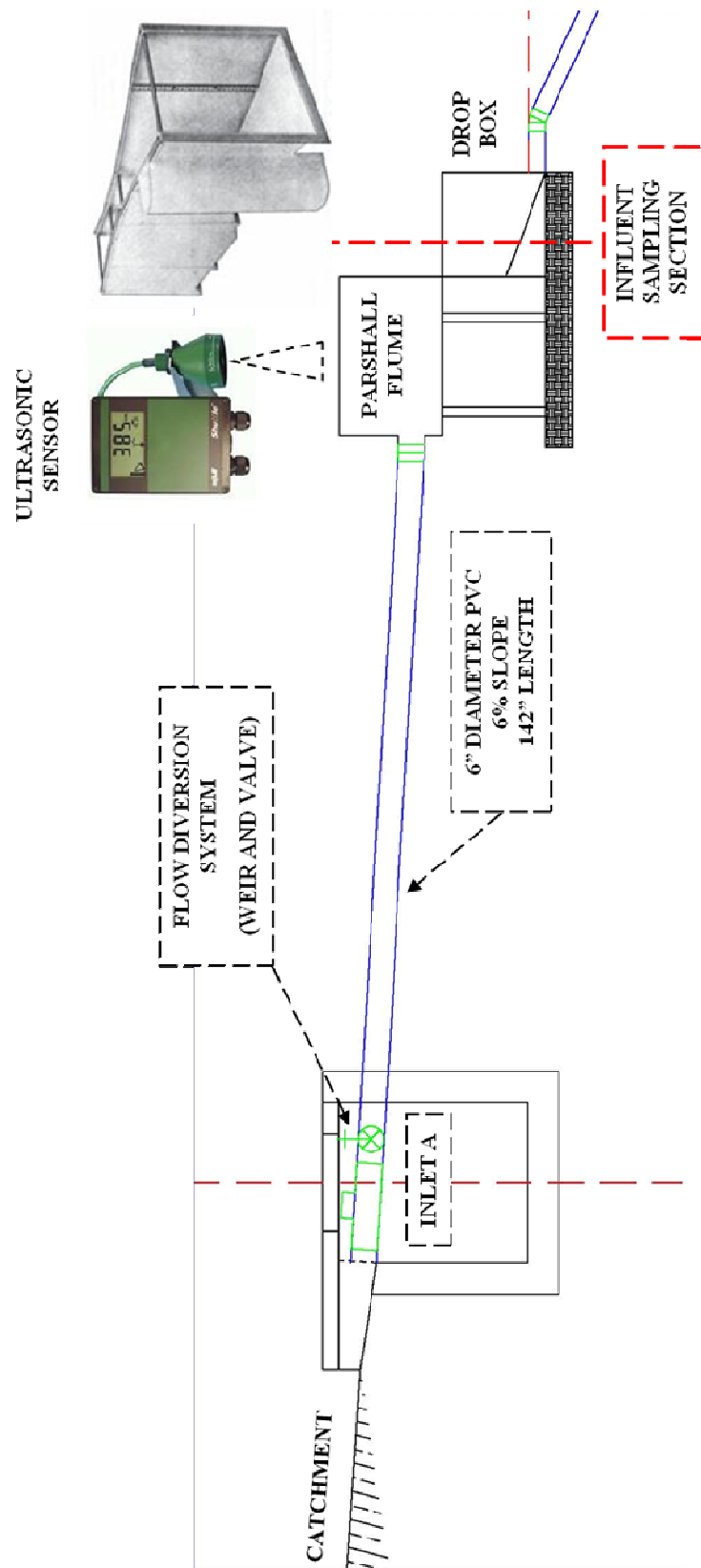


Figure 6 Monitoring system design. Detail of the influent sampling section and inlet A.



Figure 7 Monitoring system as installed. The flow rate measurement system: Parshall flume and drop box.

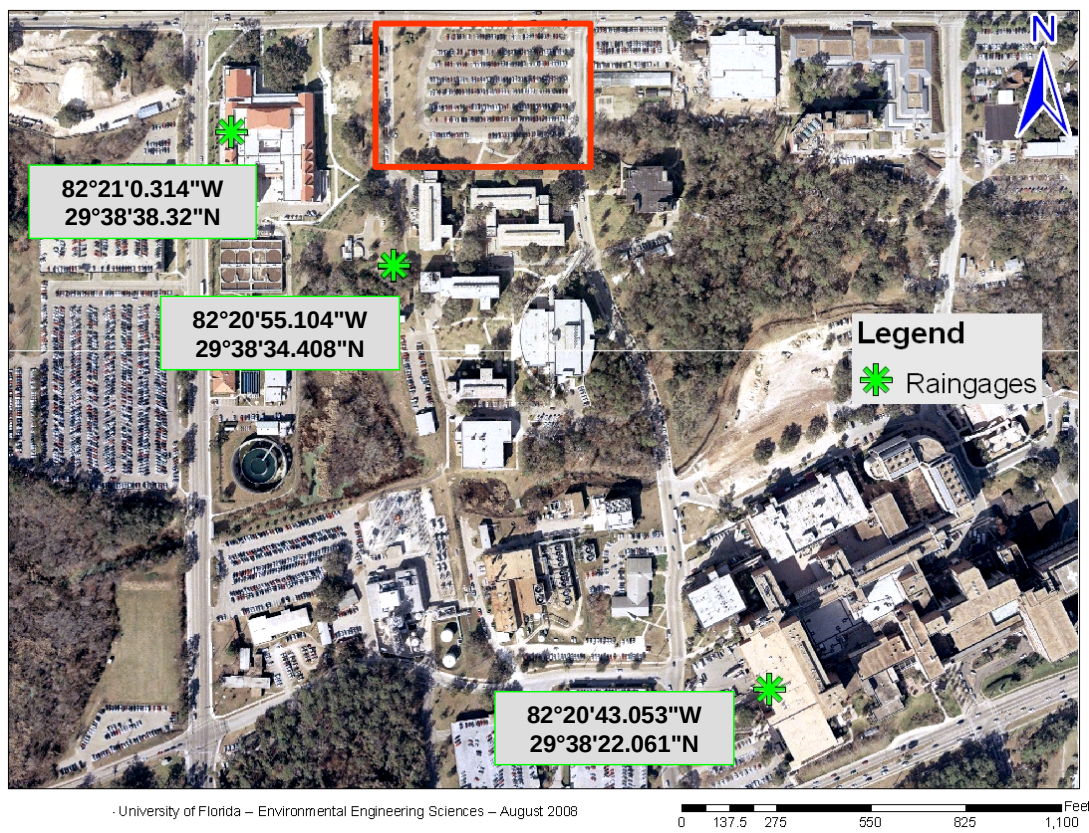


Figure 8 Rain gauges in the area of interest



Figure 9 Parshall Flume calibration set-up

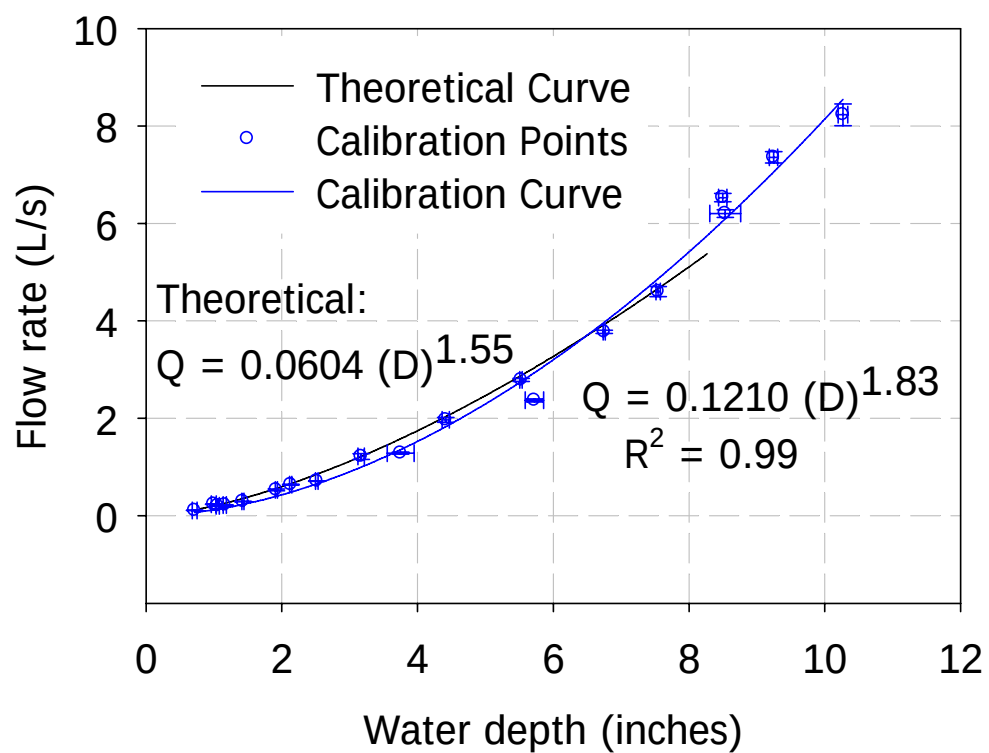


Figure 10 Comparison between the Parshall flume theoretical curve and the calibration one



Figure 11 Hydraulic conductivity set-up and testing for engineered soil media

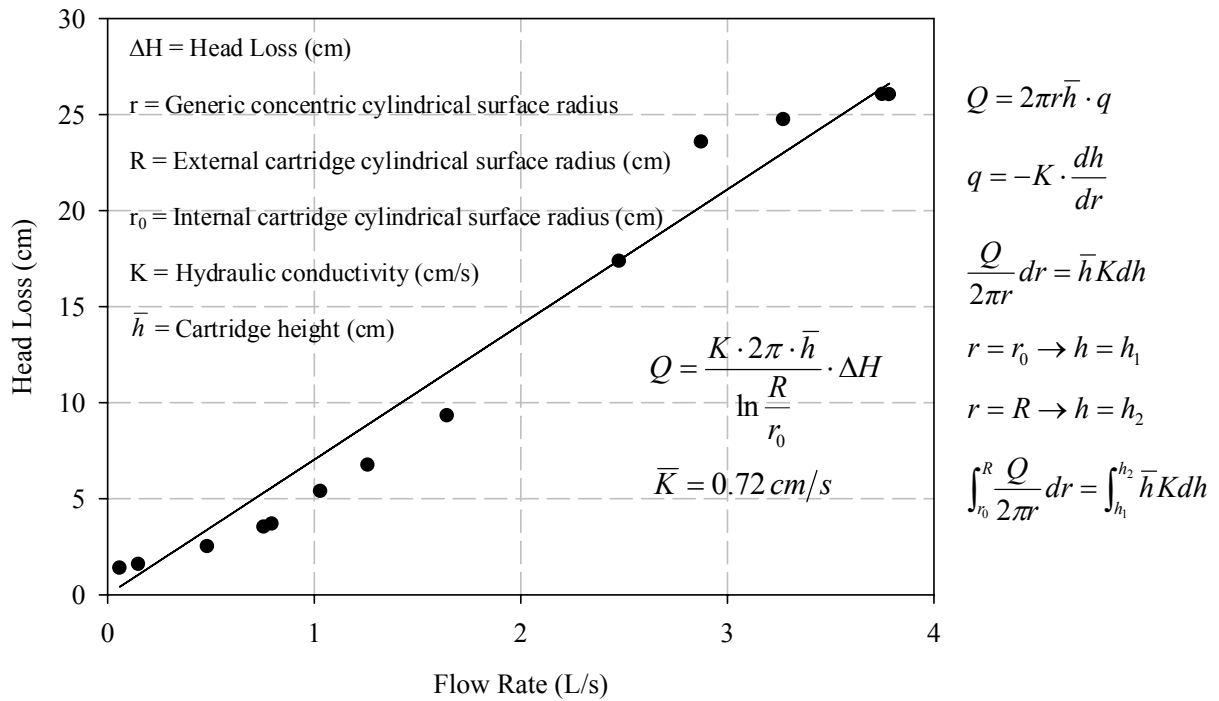


Figure 12 Hydraulic Conductivity Test experimental data and interpolating curve

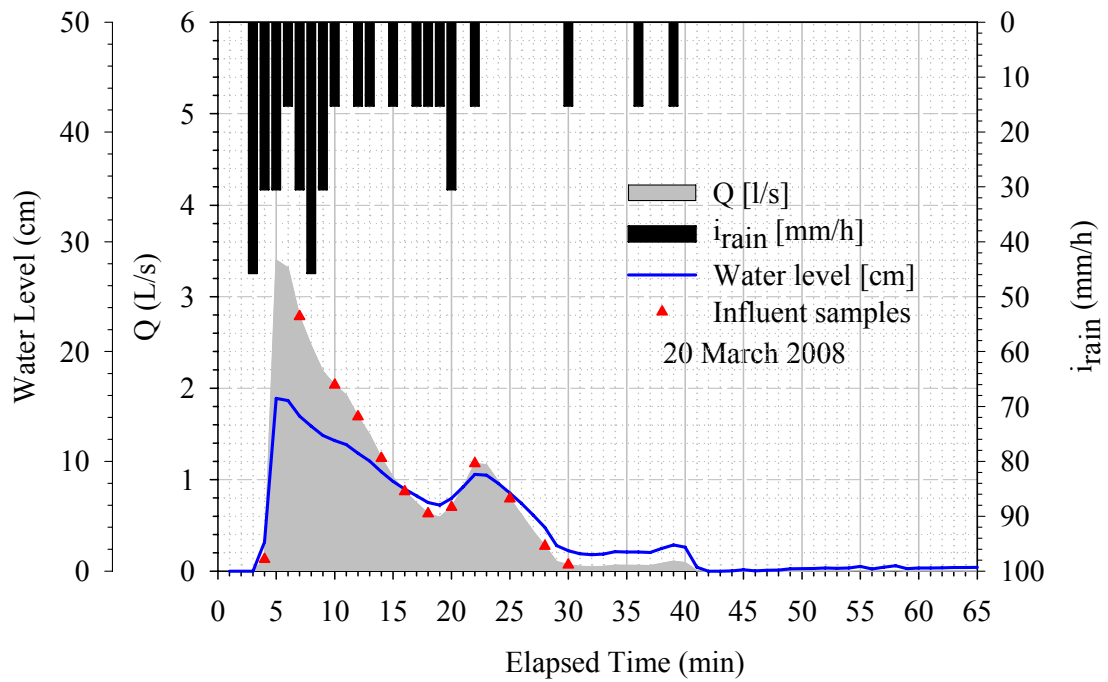


Figure 13 Hyetograph, hydrograph, water level in the Parshall flume and influent sampling time for the 20 March 2008 event

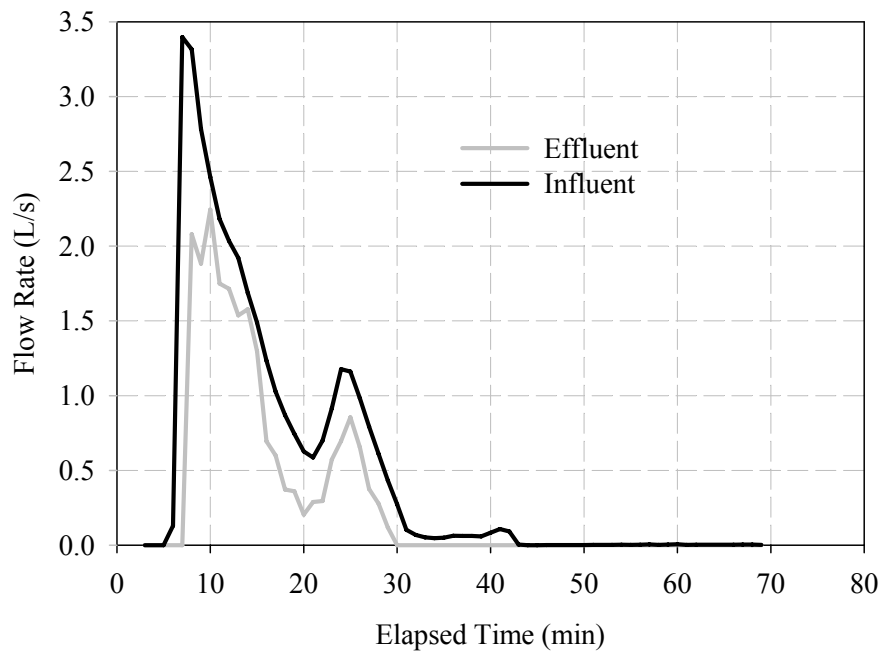


Figure 14 Influent and Effluent Flow rate for 20 March 2008 event

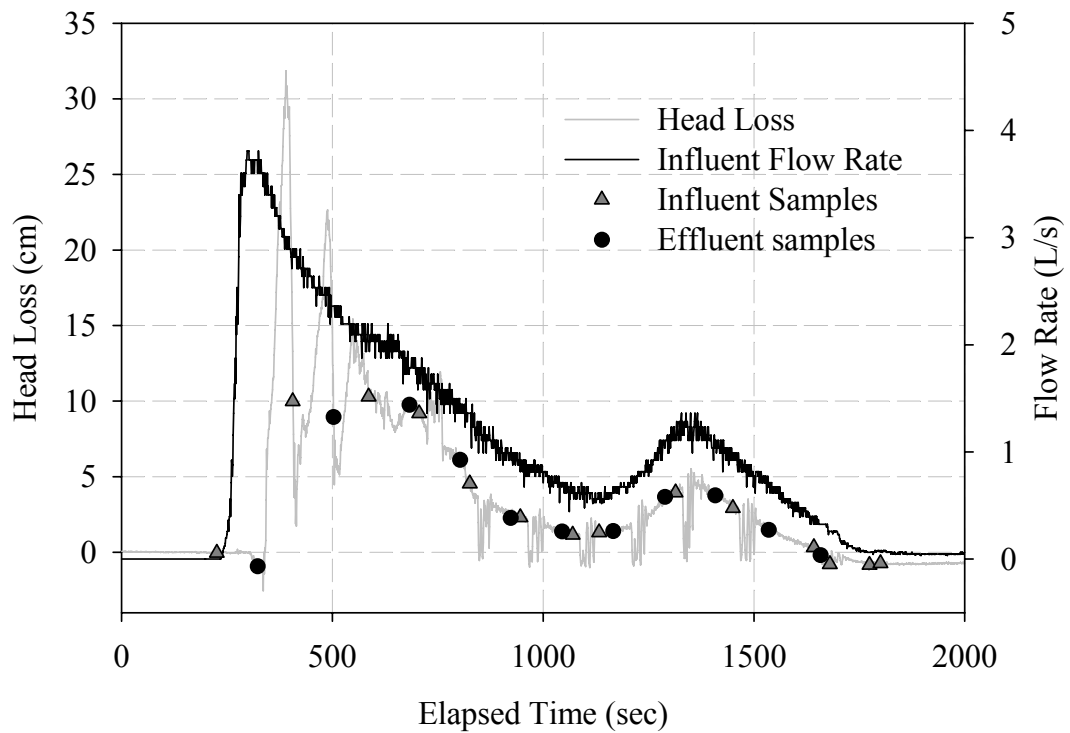


Figure 15 Head Loss, Influent Flow rate and influent and effluent sampling starting time

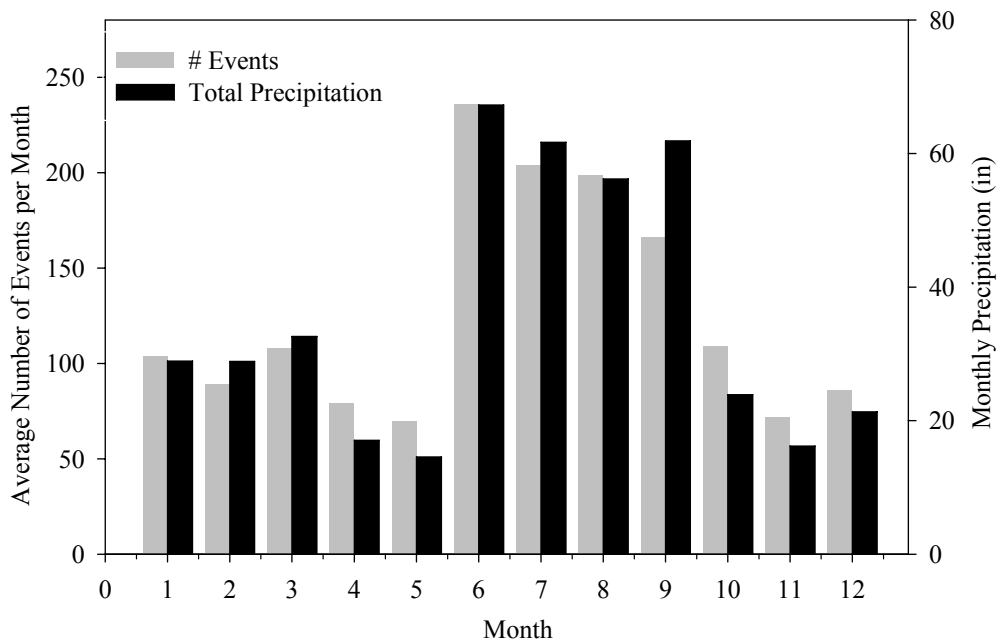


Figure 16 Total precipitation and total number of events for each month between August 1999 and July 2008 in Gainesville, FL (Gainesville Regional Airport station)

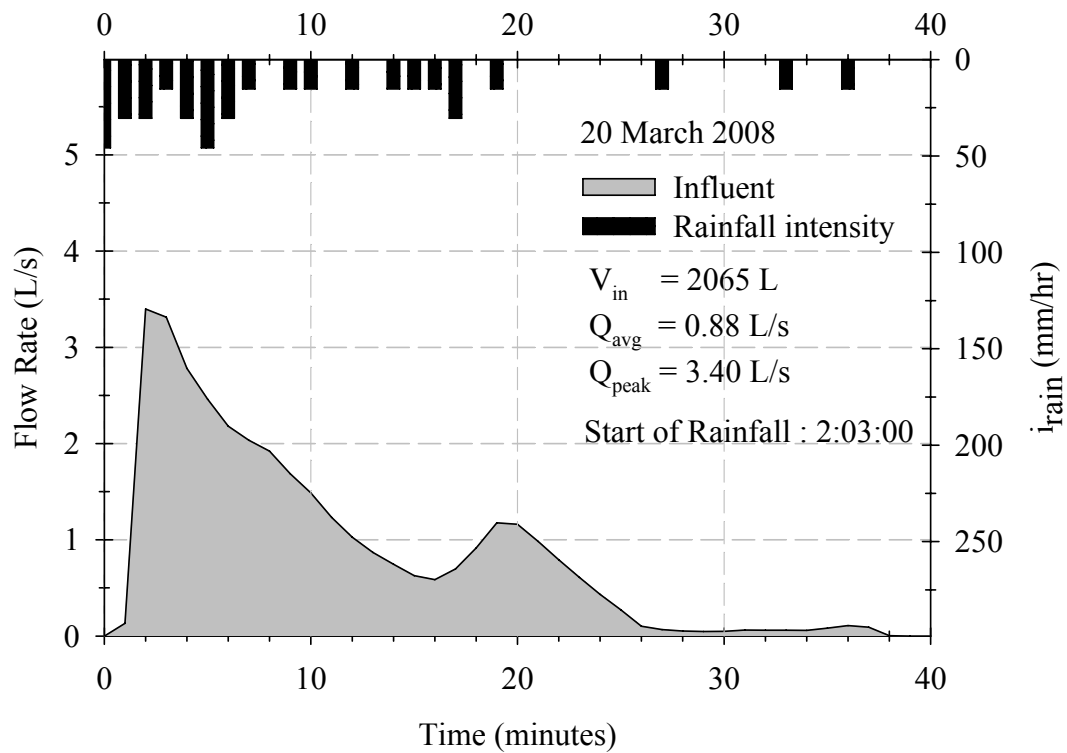


Figure 17 Hyetograph and hydrograph for the 20 March 2008

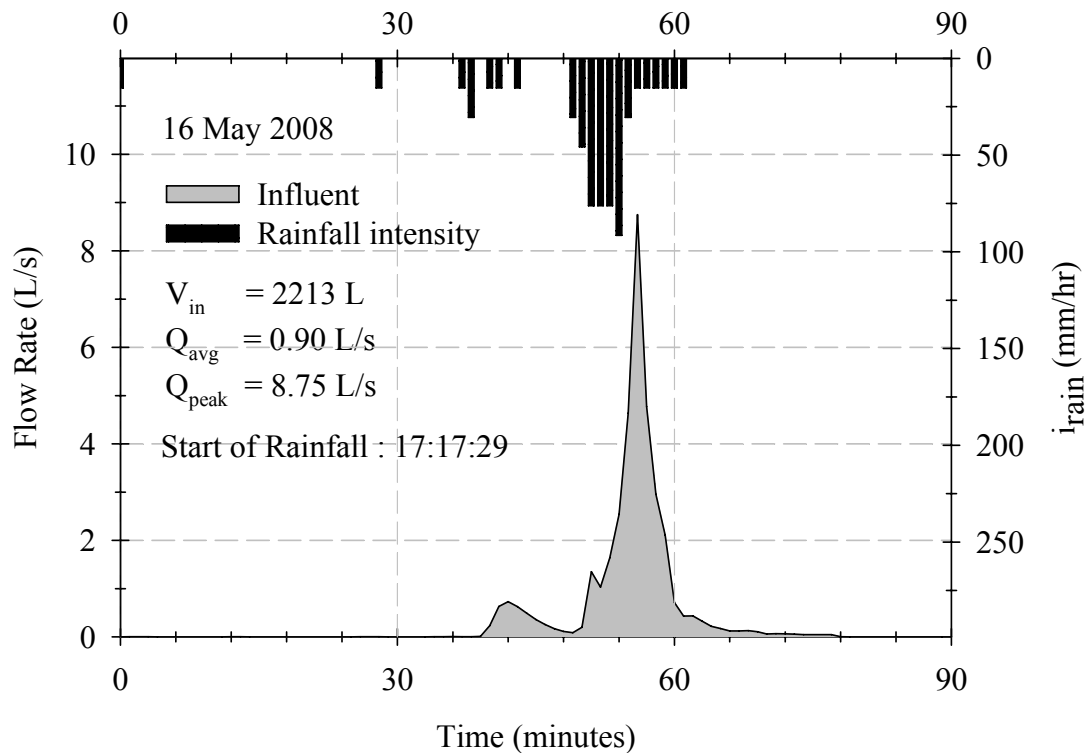


Figure 18 Hyetograph and hydrograph for the 16 May 2008

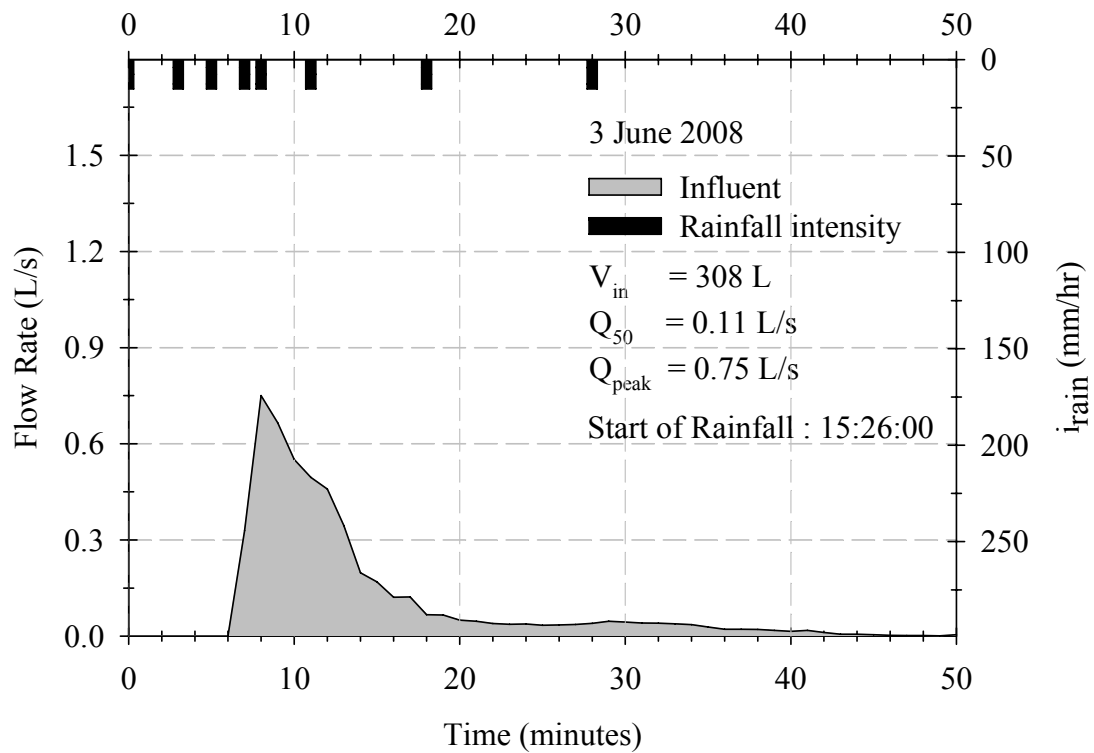


Figure 19 Hyetograph and hydrograph for the 03 June 2008

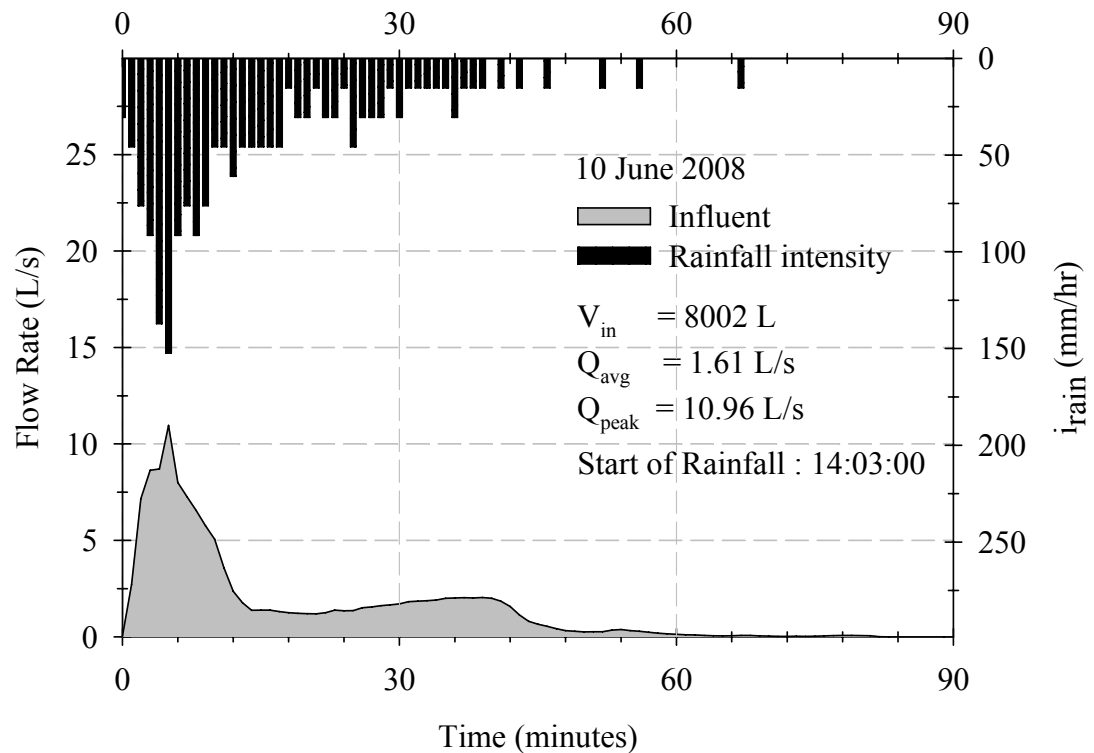


Figure 20 Hyetograph and hydrograph for the 10 June 2008

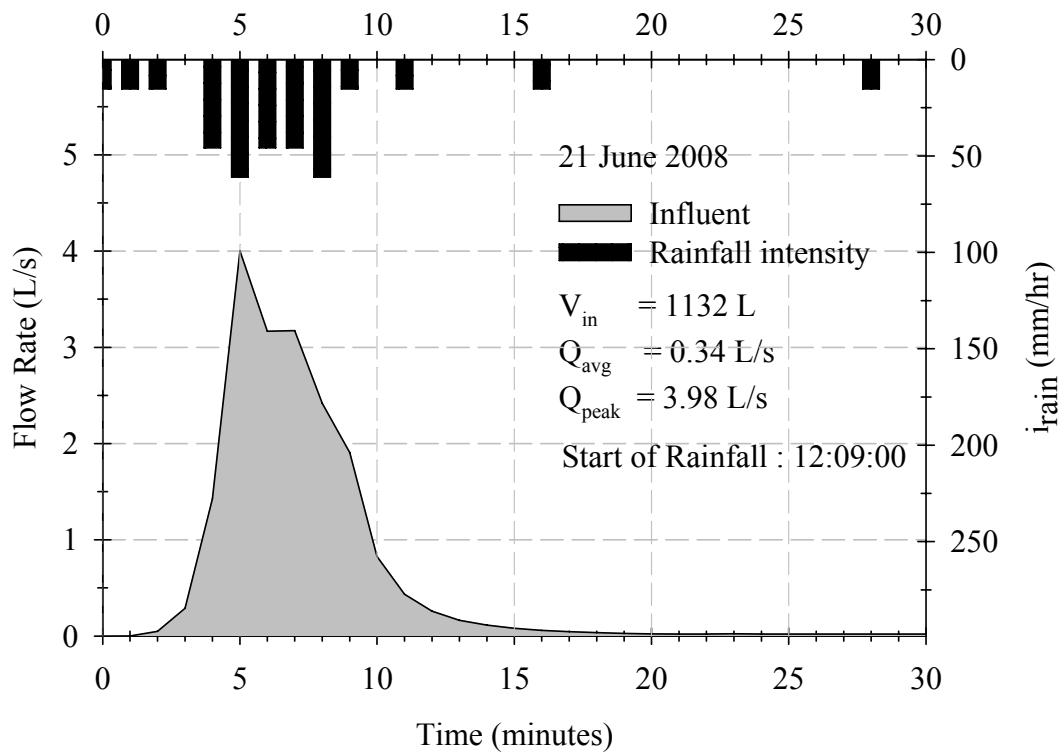


Figure 21 Hyetograph and hydrograph for the 21 June 2008

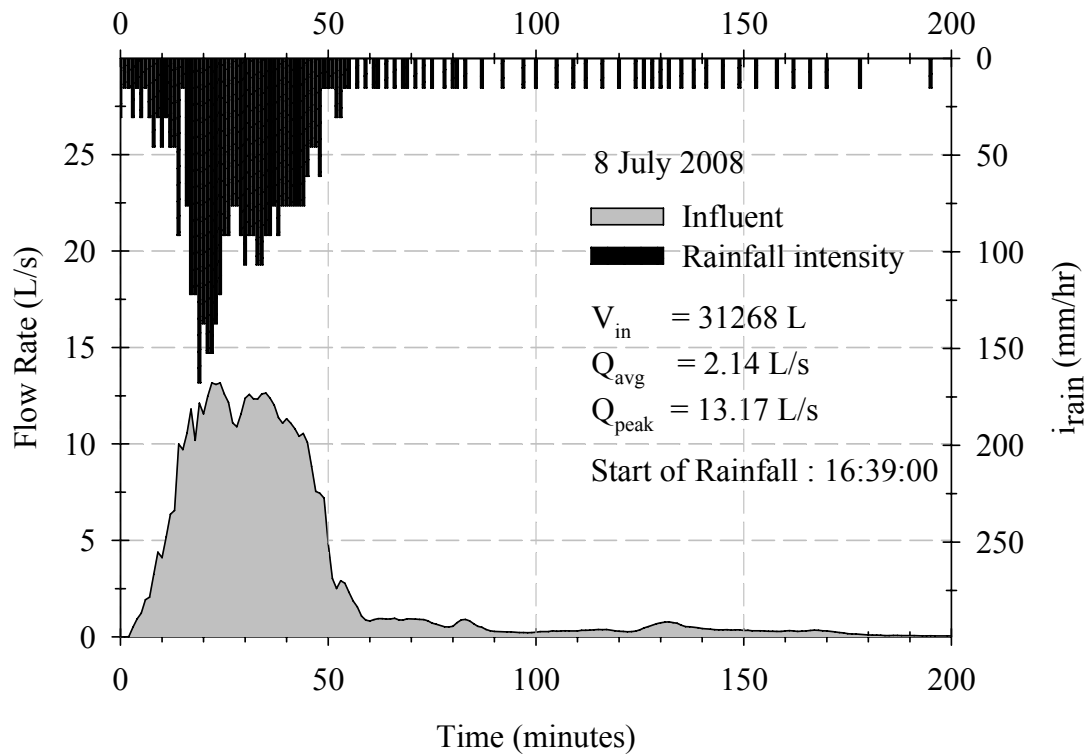


Figure 22 Hyetograph and hydrograph for the 08 July 2008

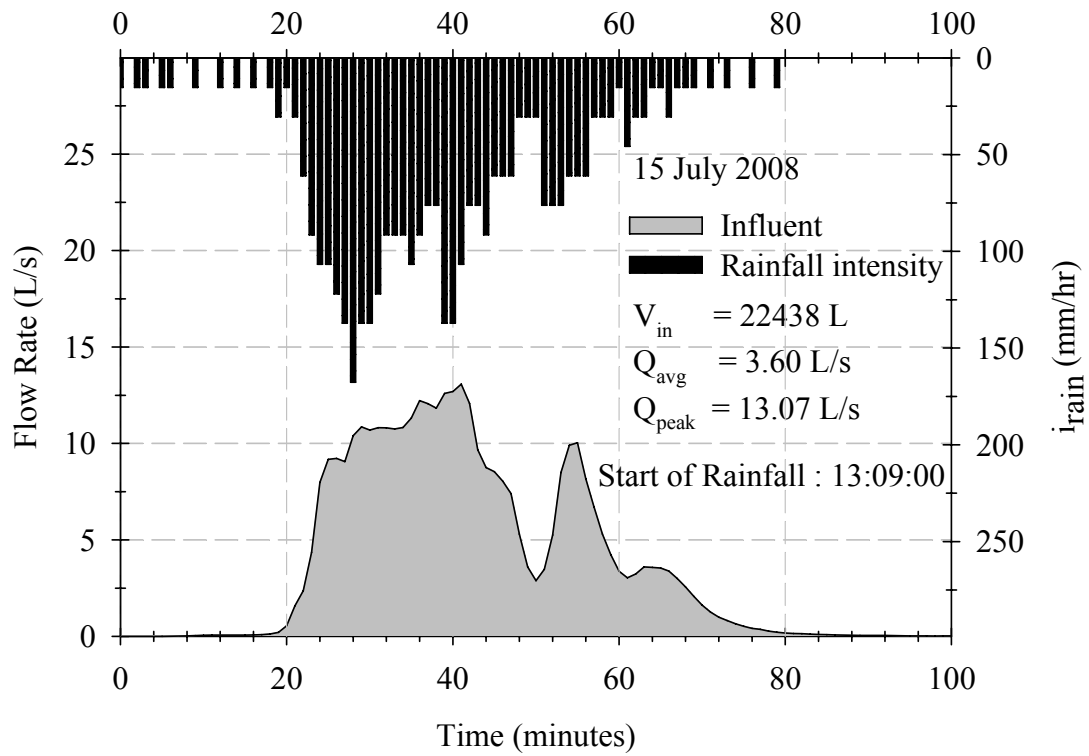


Figure 23 Hyetograph and hydrograph for the 15 July 2008

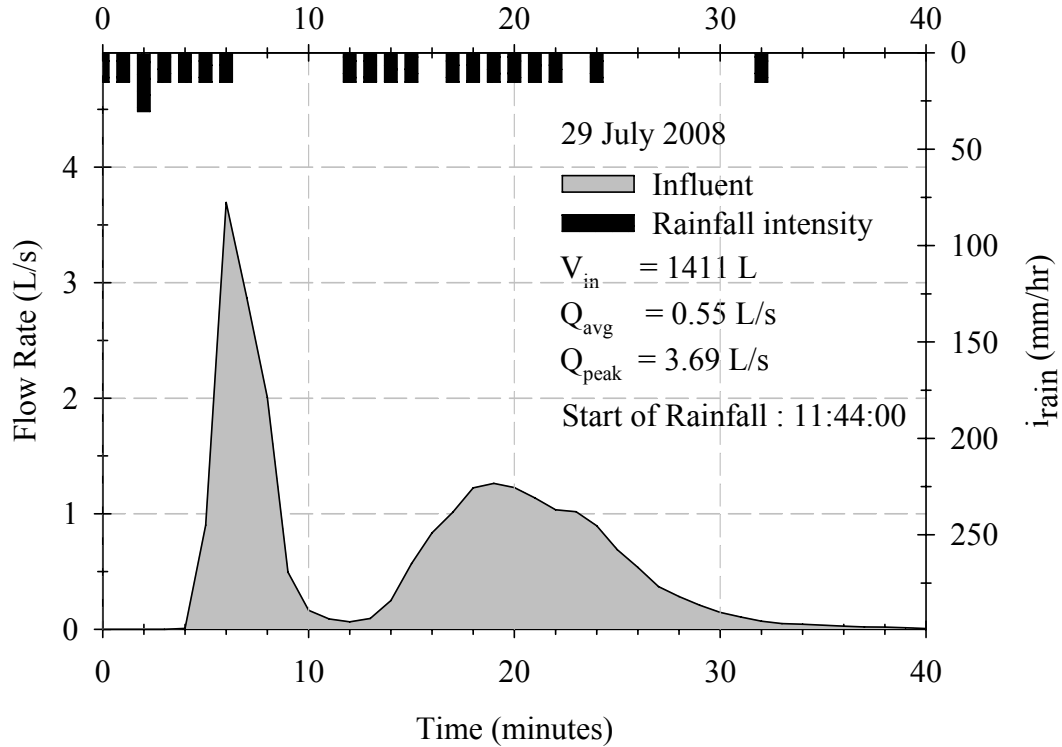


Figure 24 Hyetograph and hydrograph for the 29 July 2008

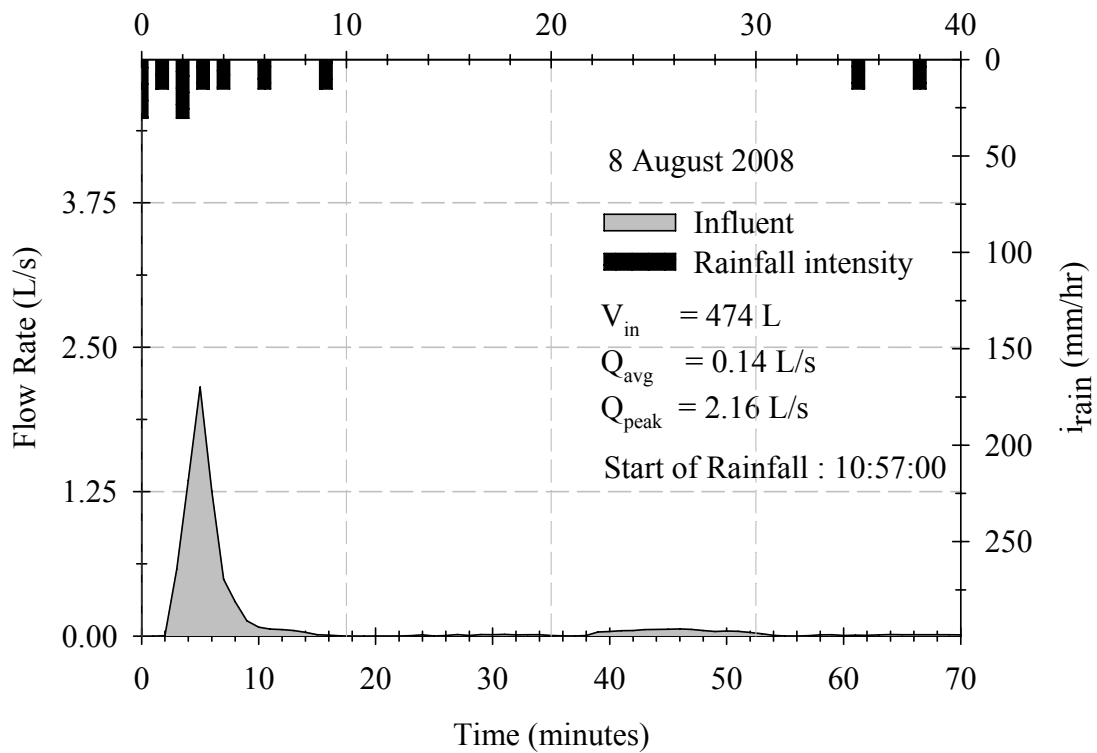


Figure 25 Hyetograph and hydrograph for the 08 August 2008

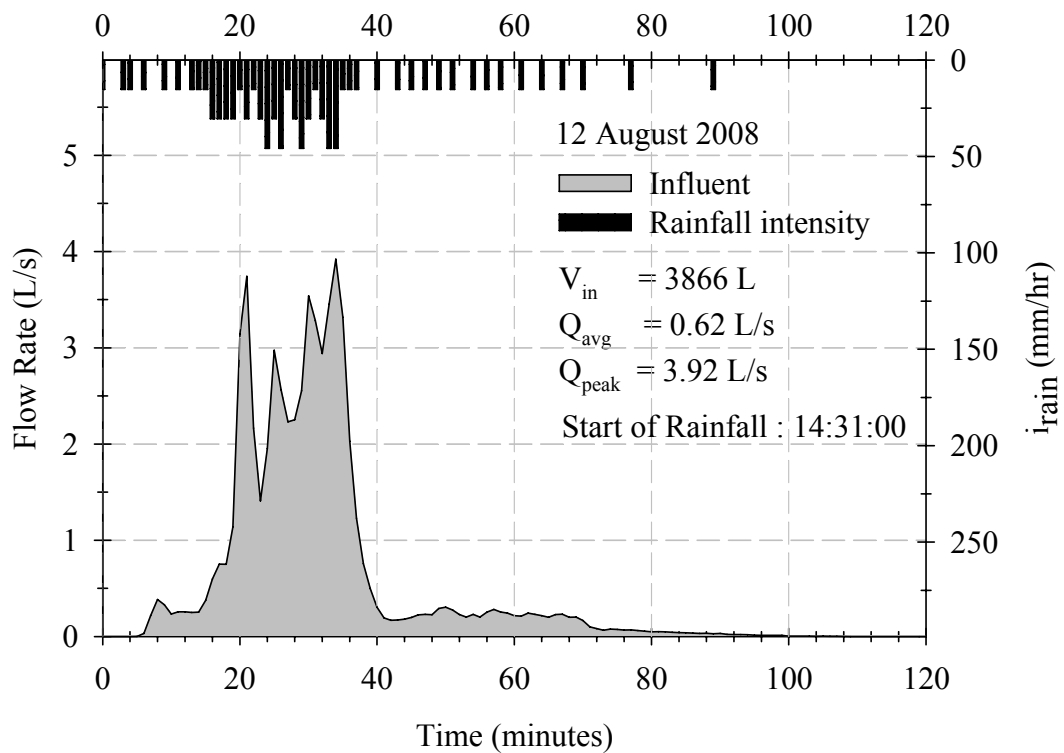


Figure 26 Hyetograph and hydrograph for the 12 August 2008

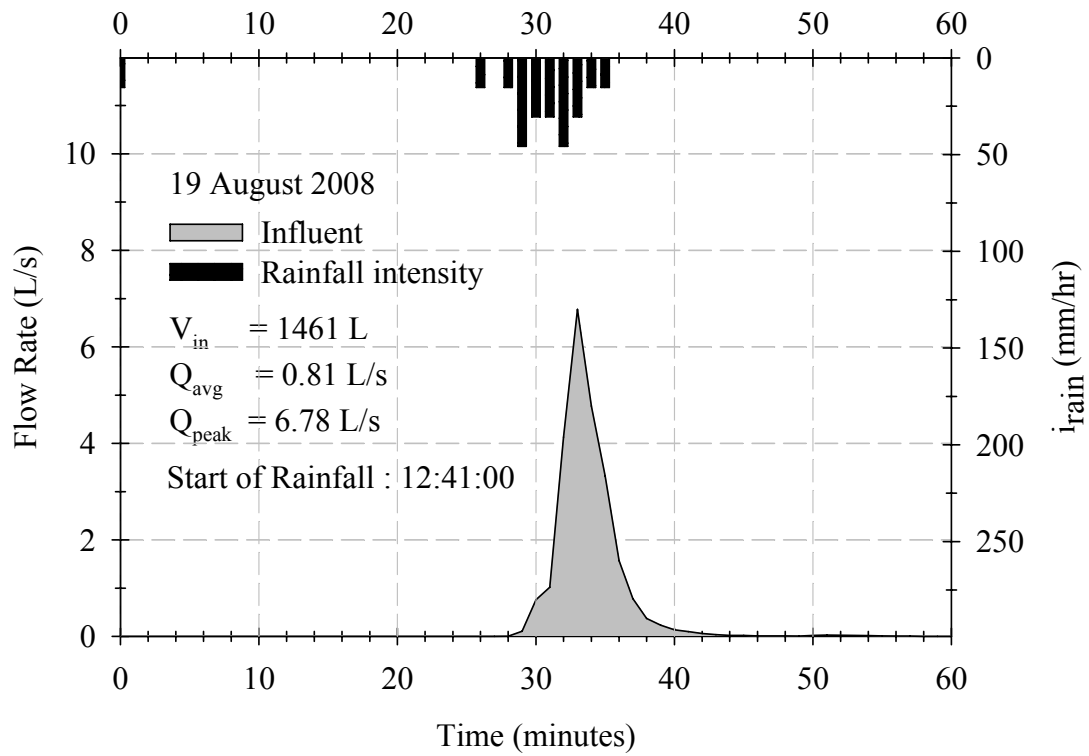


Figure 27 Hyetograph and hydrograph for the 19 August 2008

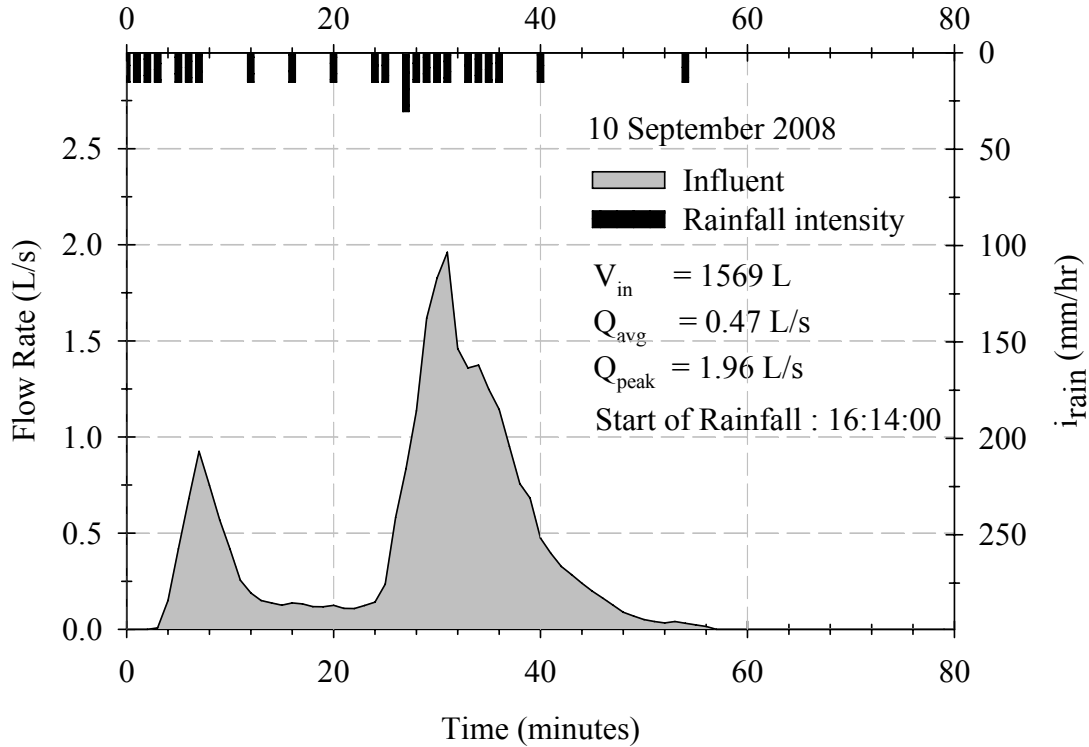


Figure 28 Hyetograph and hydrograph for the 10 September 2008

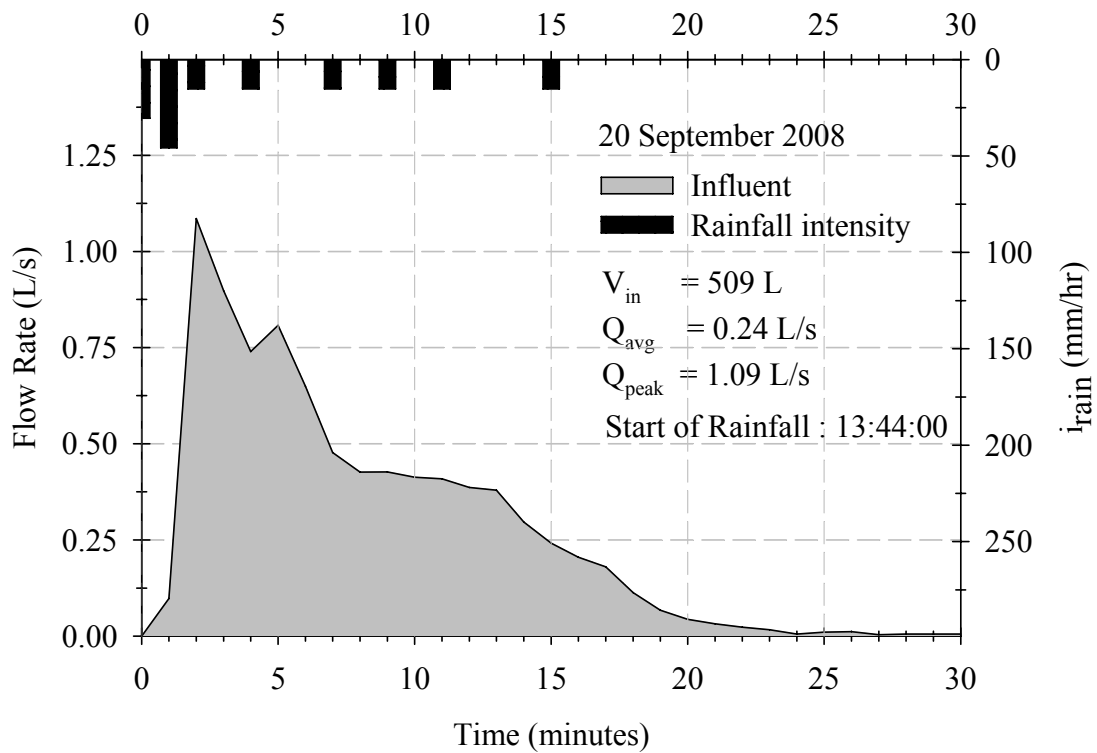


Figure 29 Hyetograph and hydrograph for the 20 September 2008

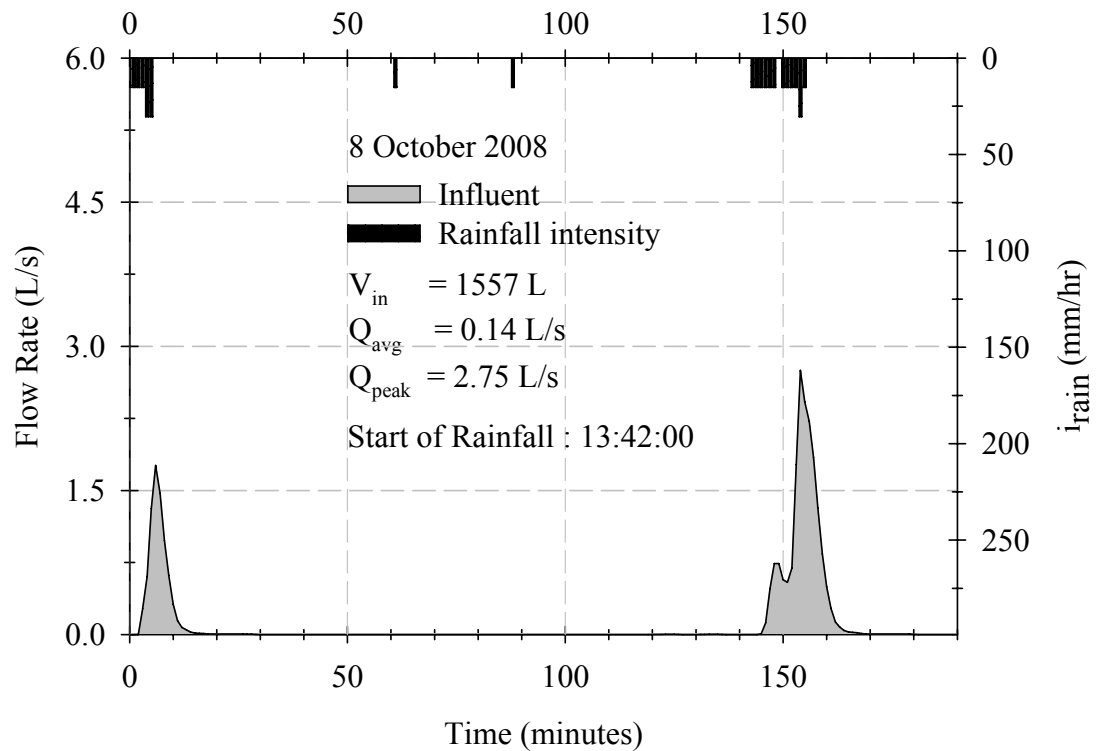


Figure 30 Hyetograph and hydrograph for the 08 October 2008

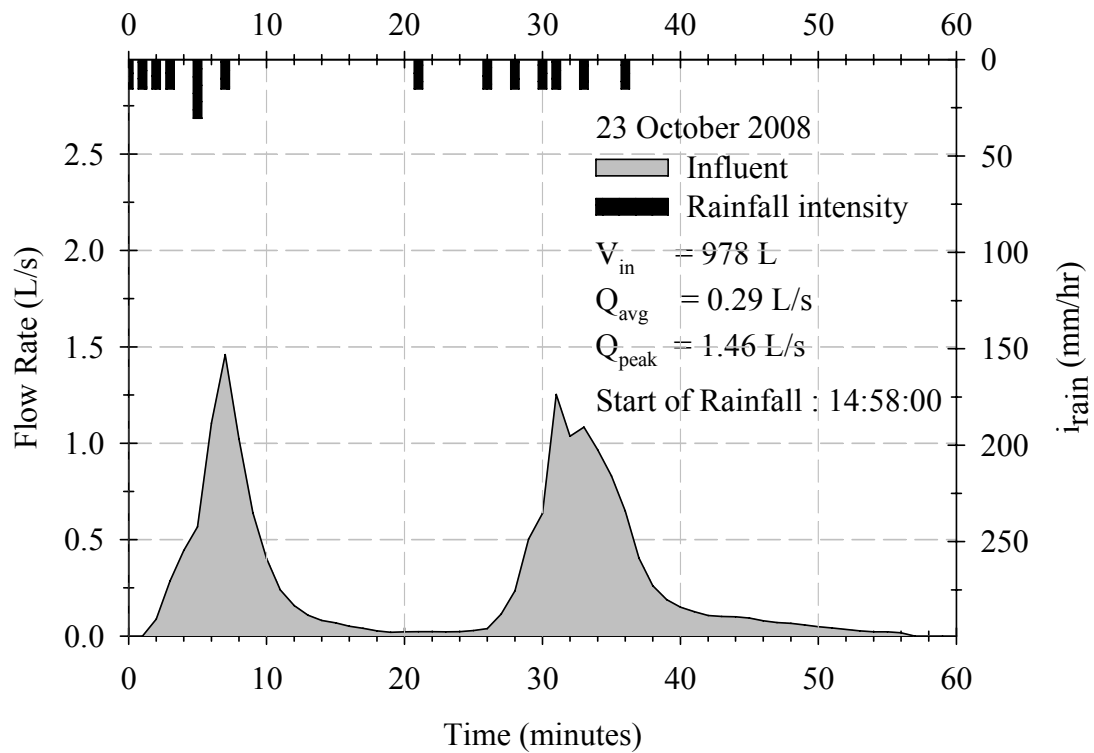


Figure 31 Hyetograph and hydrograph for the 23 October 2008

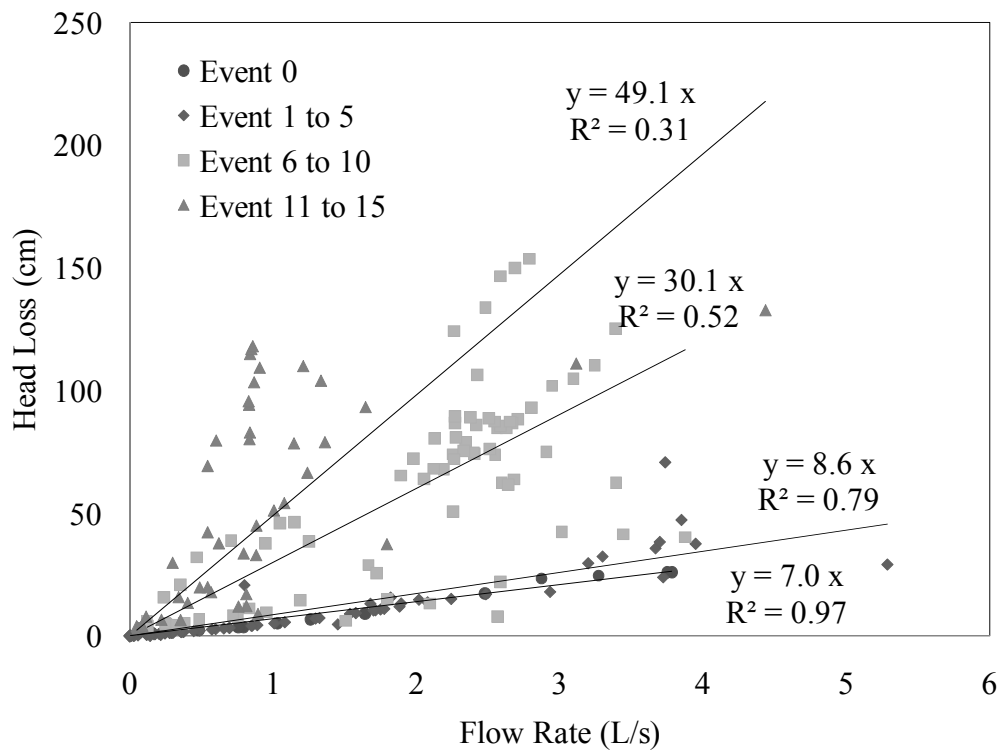


Figure 32 Head Loss – Flow Rate behavior during the whole monitoring program

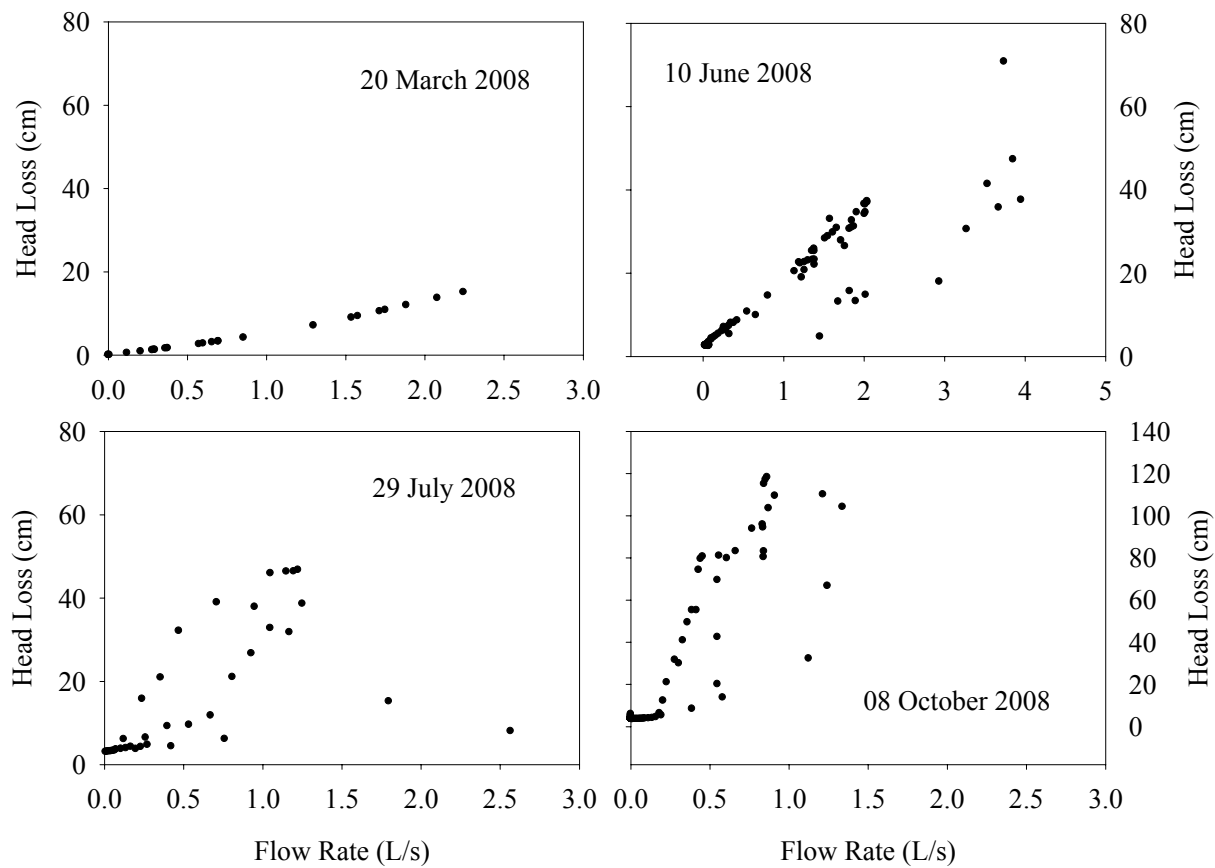


Figure 33 Detailed Head Loss – Flow Rate curves for 4 events

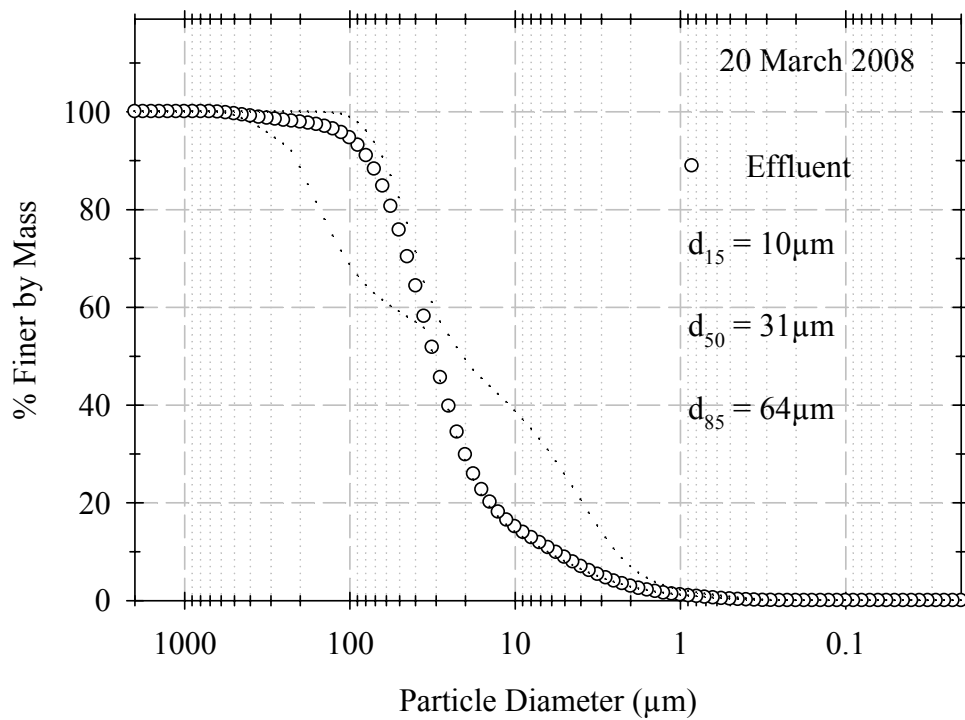
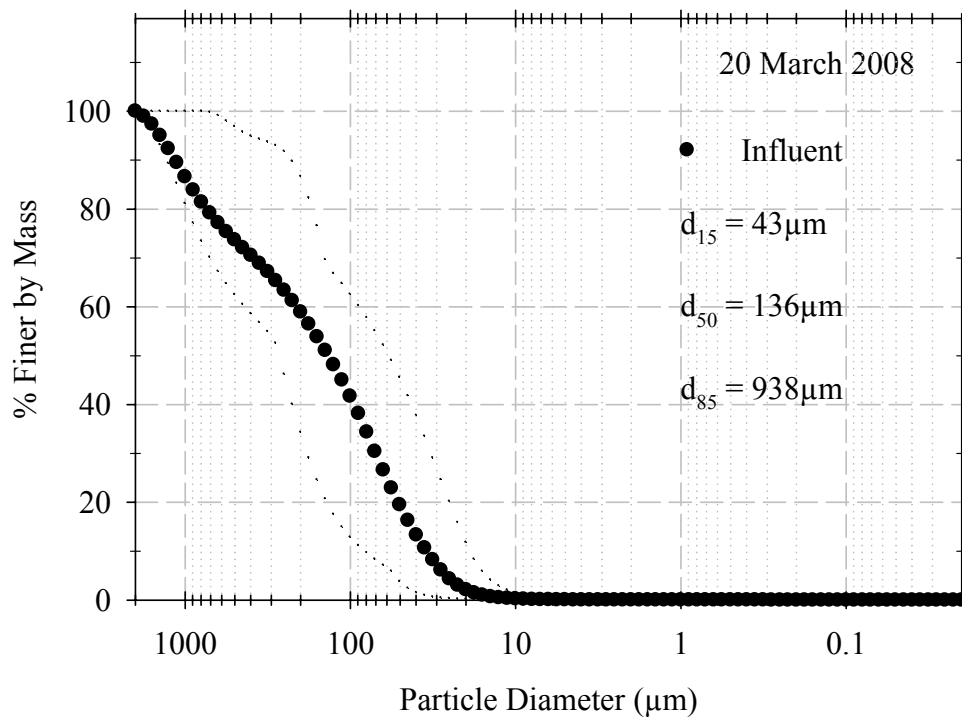


Figure 34 Mean and range of influent and effluent PSD of the 20 March 2008 rainfall event

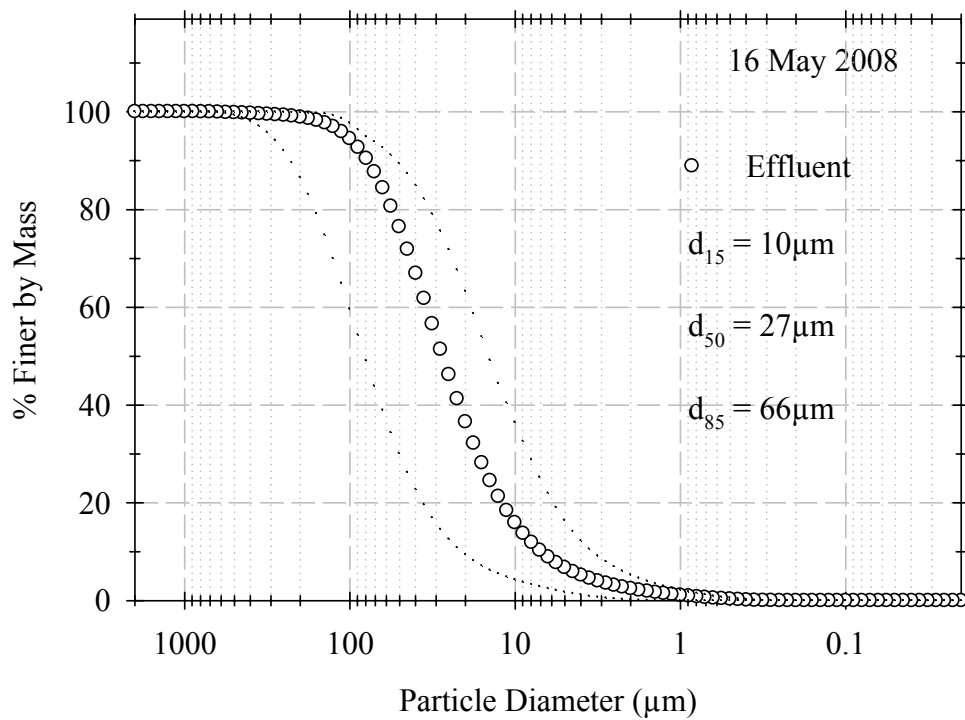
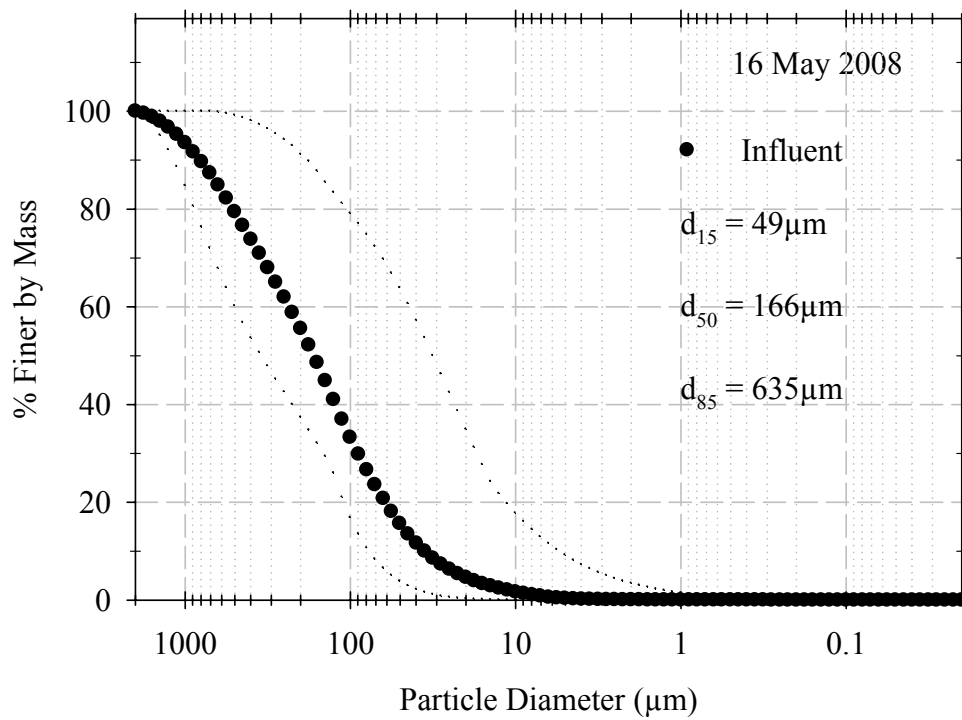


Figure 35 Mean and range of influent and effluent PSD of the 16 May 2008 rainfall event

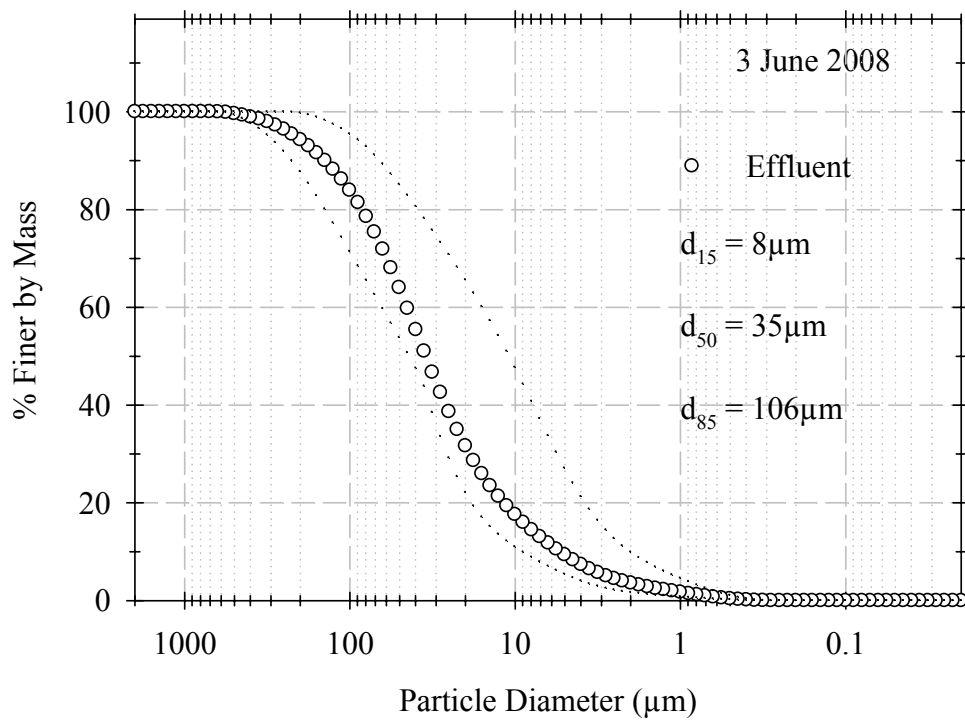
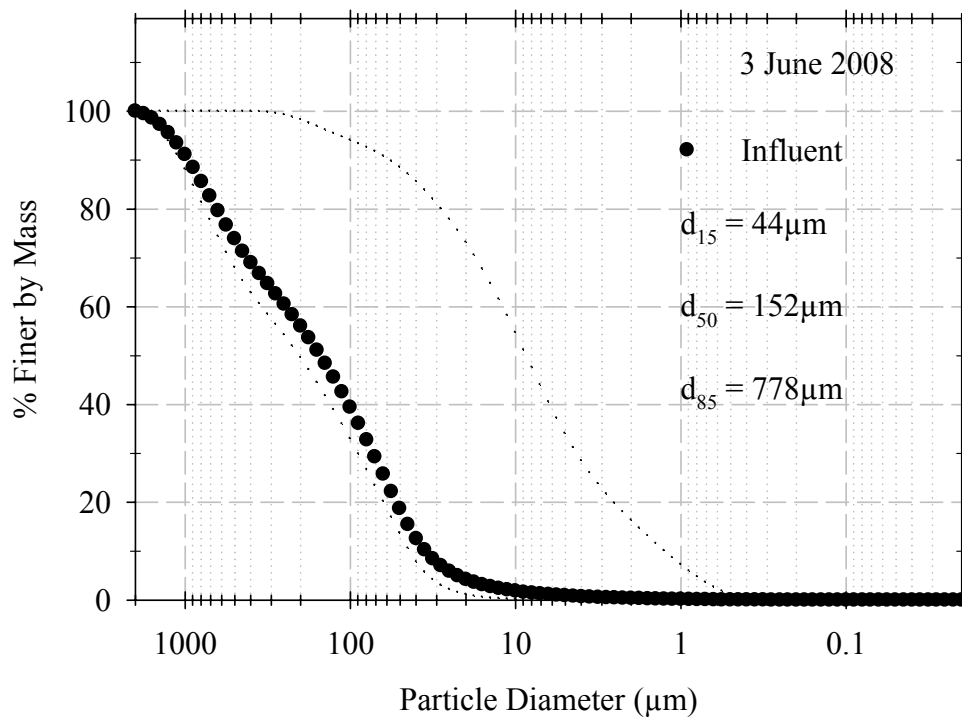


Figure 36 Mean and range of influent and effluent PSD of the 3 June 2008 rainfall event

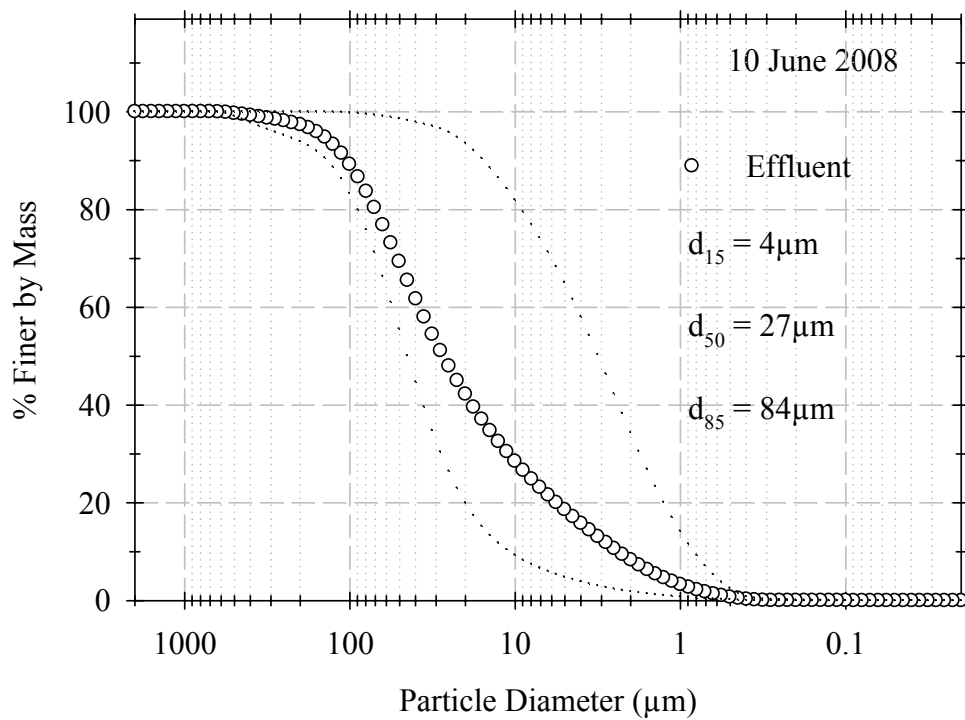
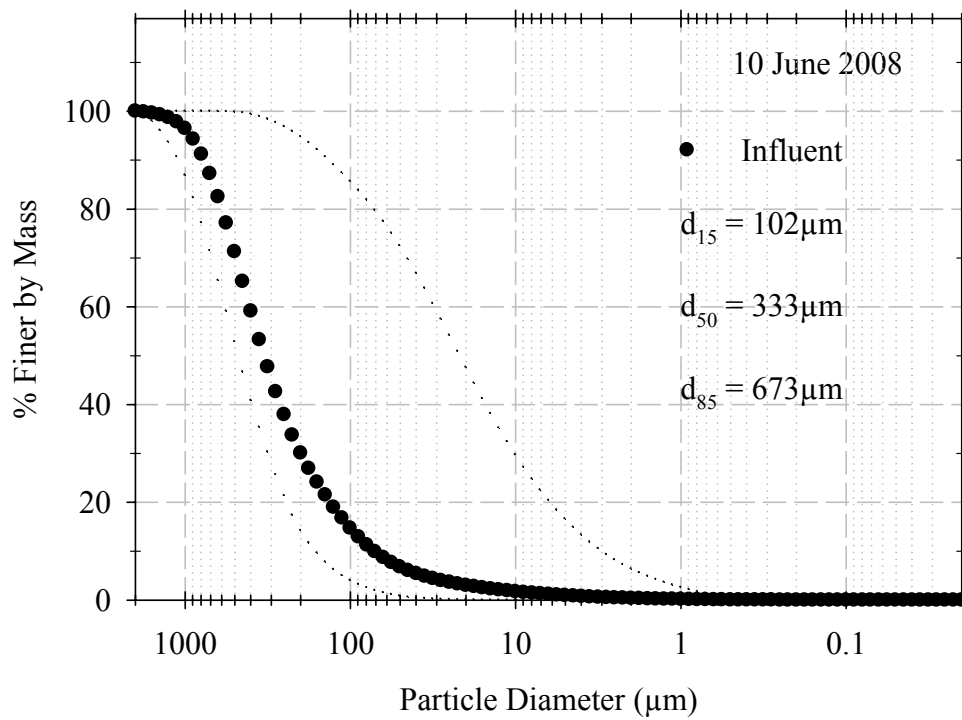


Figure 37 Mean and range of influent and effluent PSD of the 10 June 2008 rainfall event

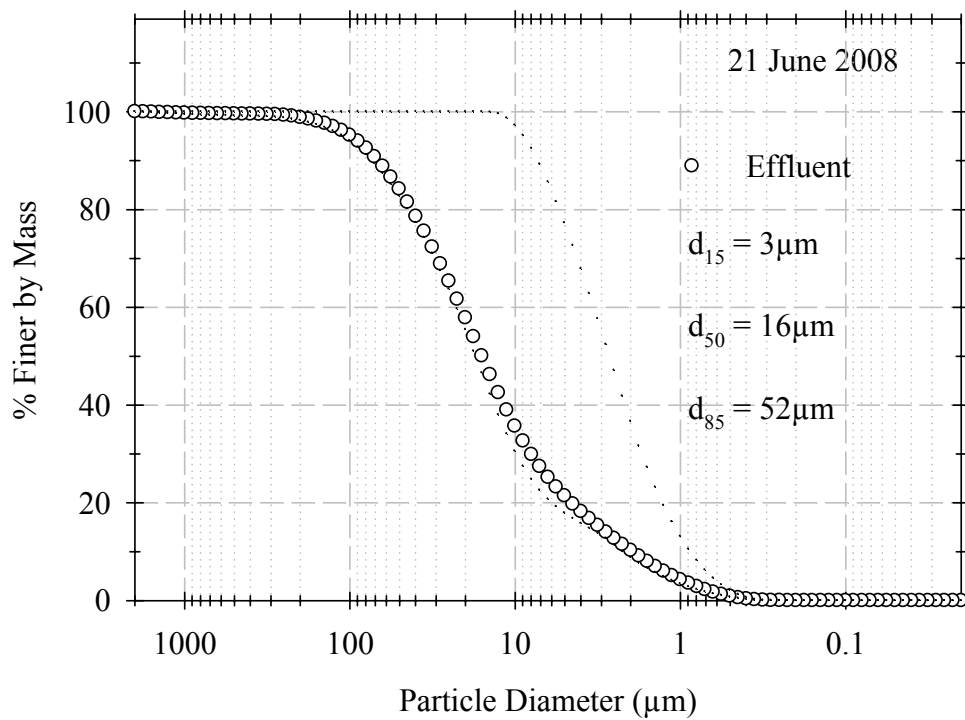
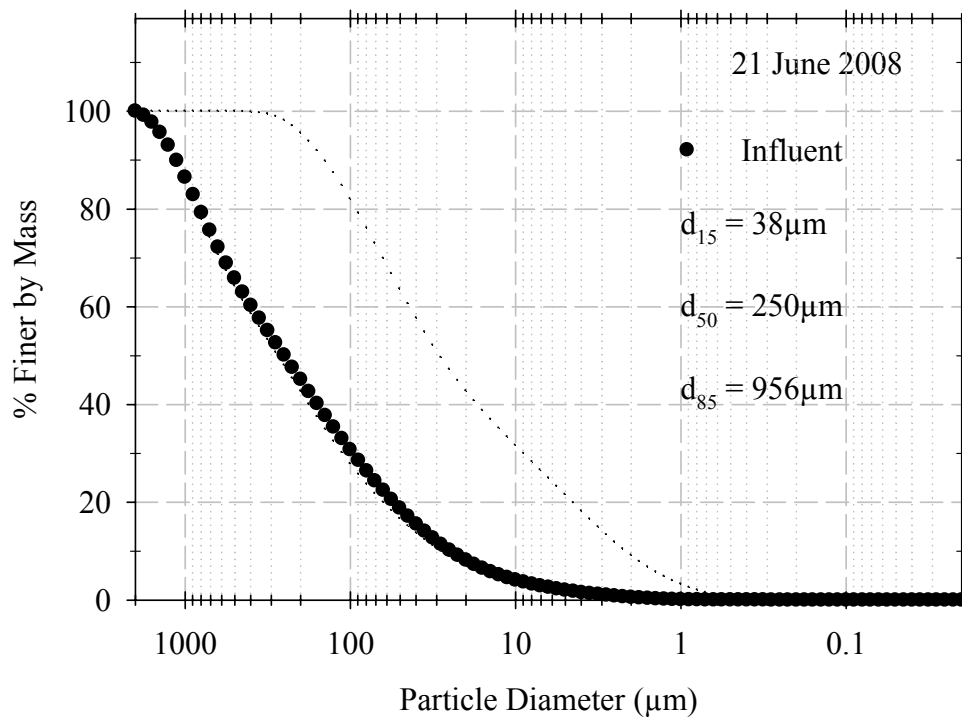


Figure 38 Mean and range of influent and effluent PSD of the 21 June 2008 rainfall event

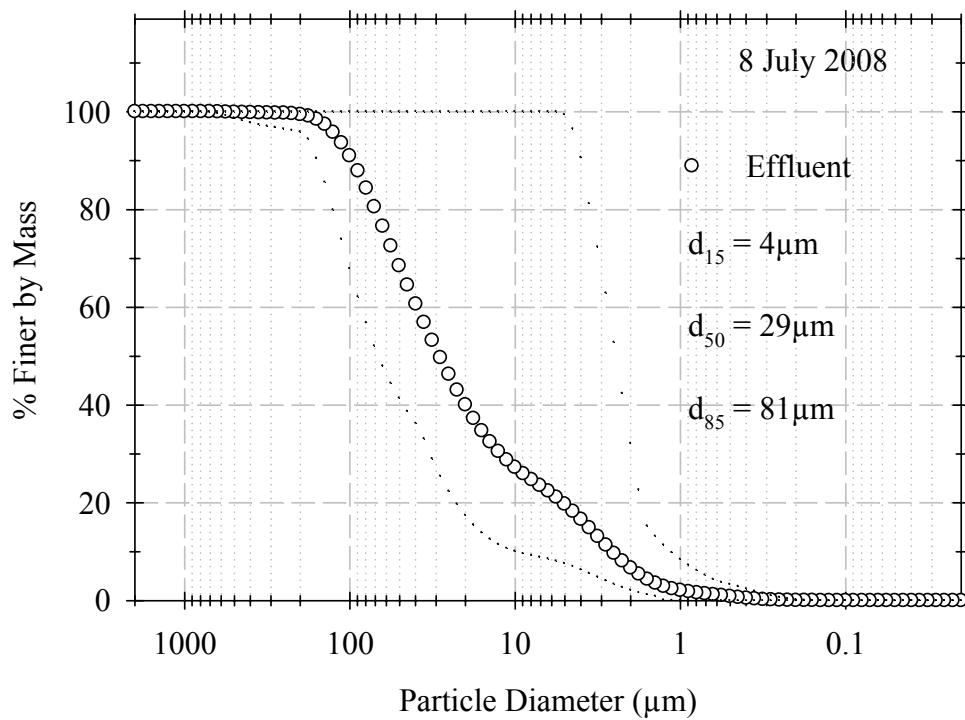
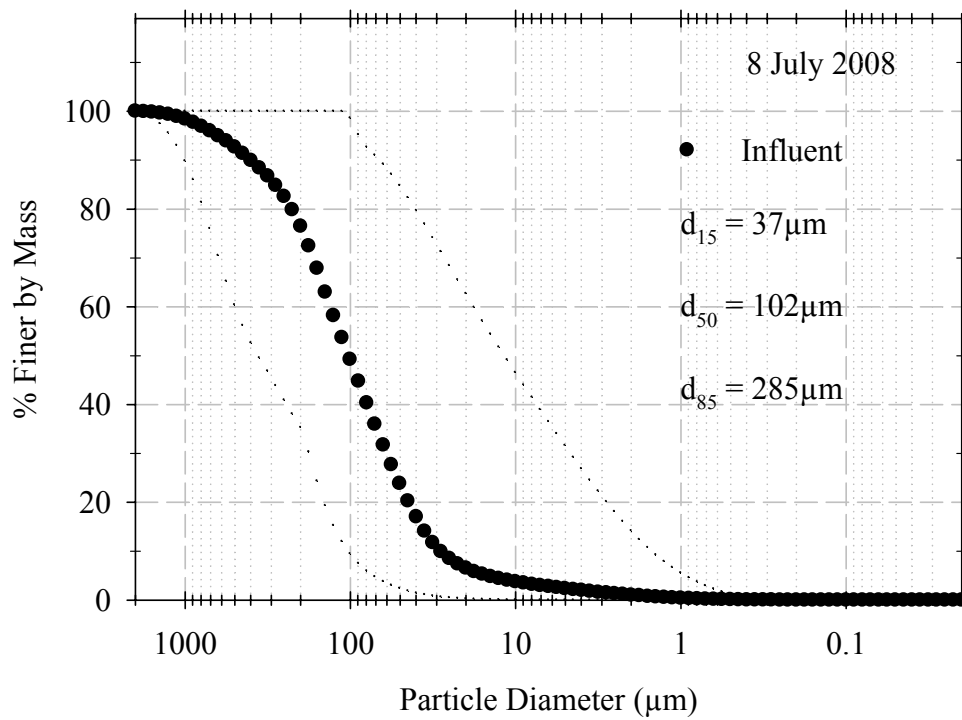


Figure 39 Mean and range of influent and effluent PSD of the 8 July 2008 rainfall event

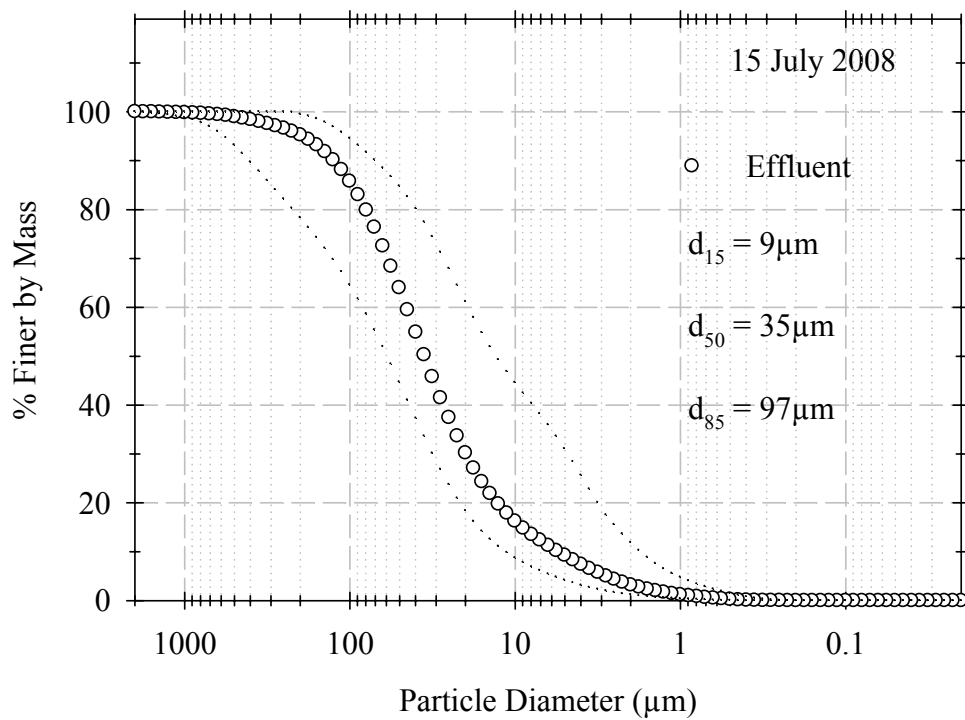
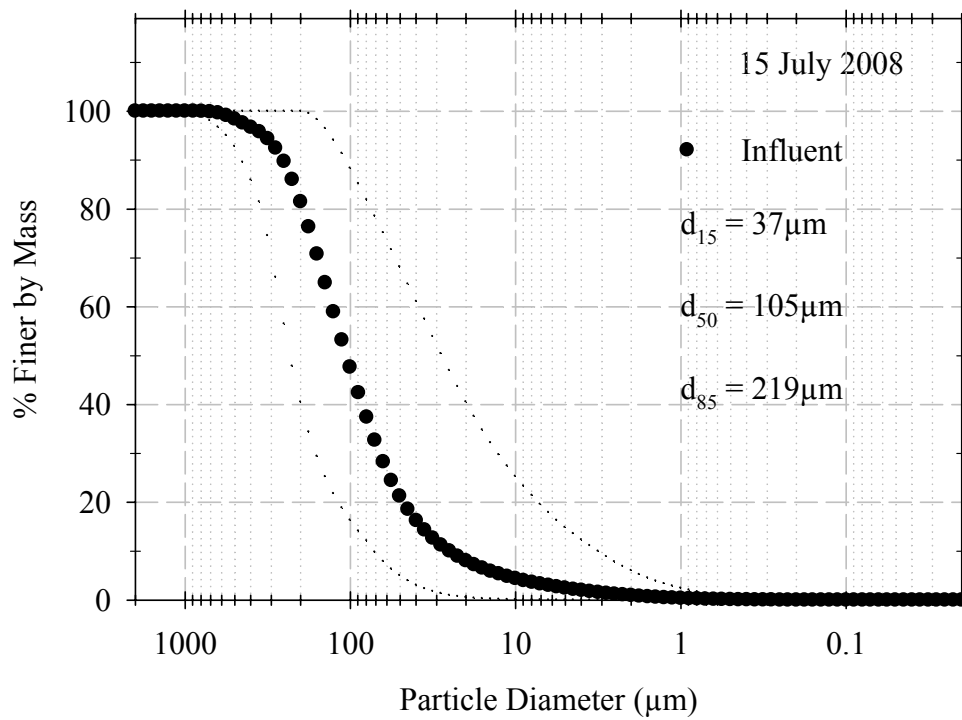


Figure 40 Mean and range of influent and effluent PSD of the 15 July 2008 rainfall event

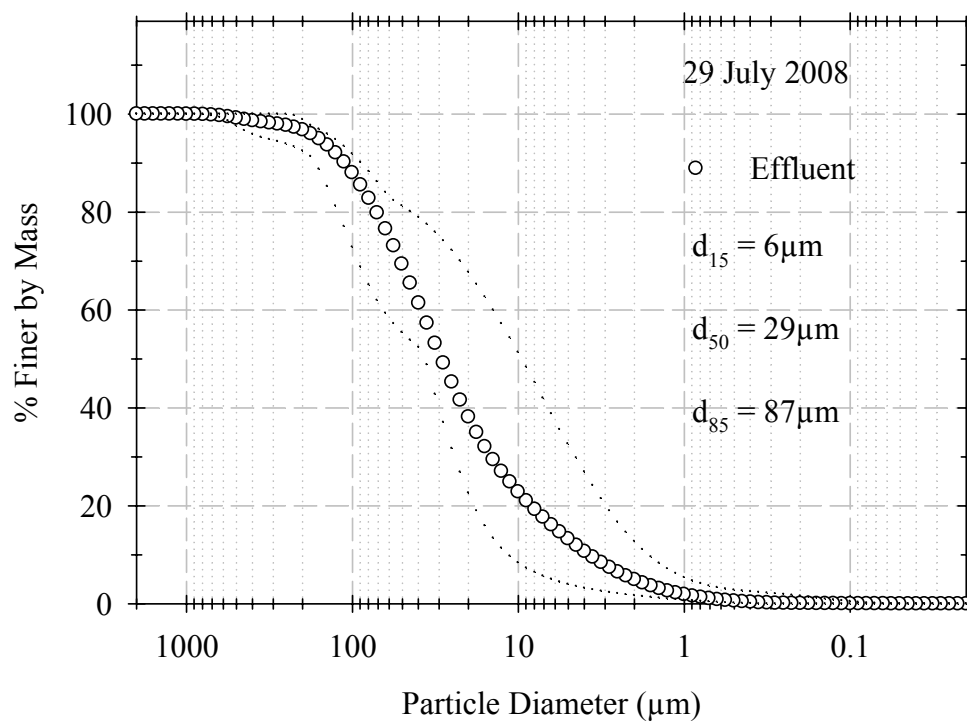
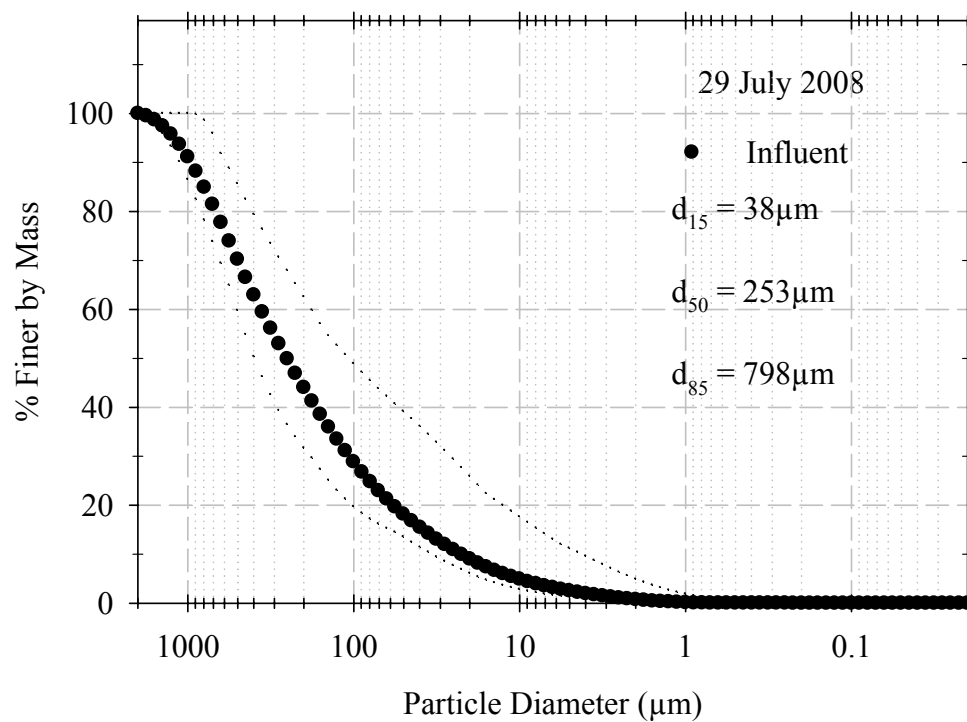


Figure 41 Mean and range of influent and effluent PSD of the 29 July 2008 rainfall event

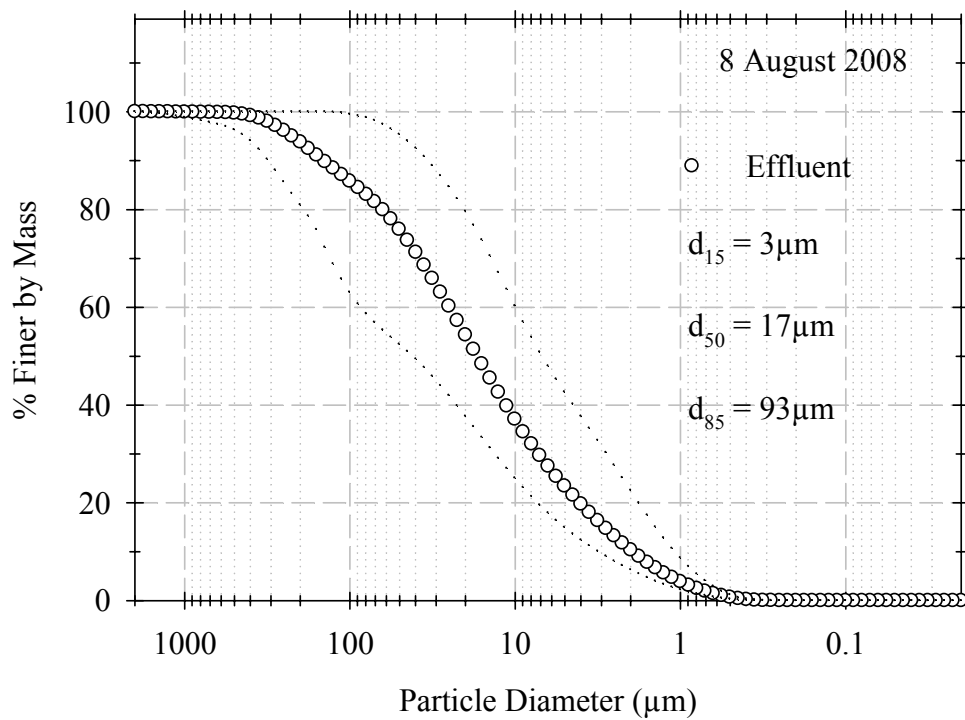
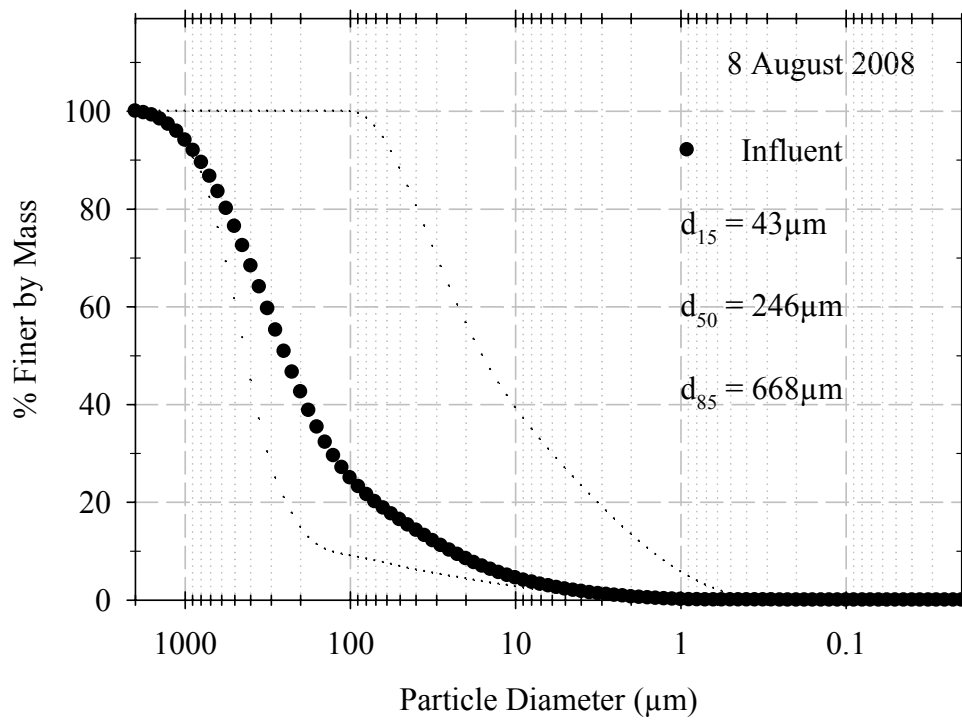


Figure 42 Mean and range of influent and effluent PSD of the 8 August 2008 rainfall event

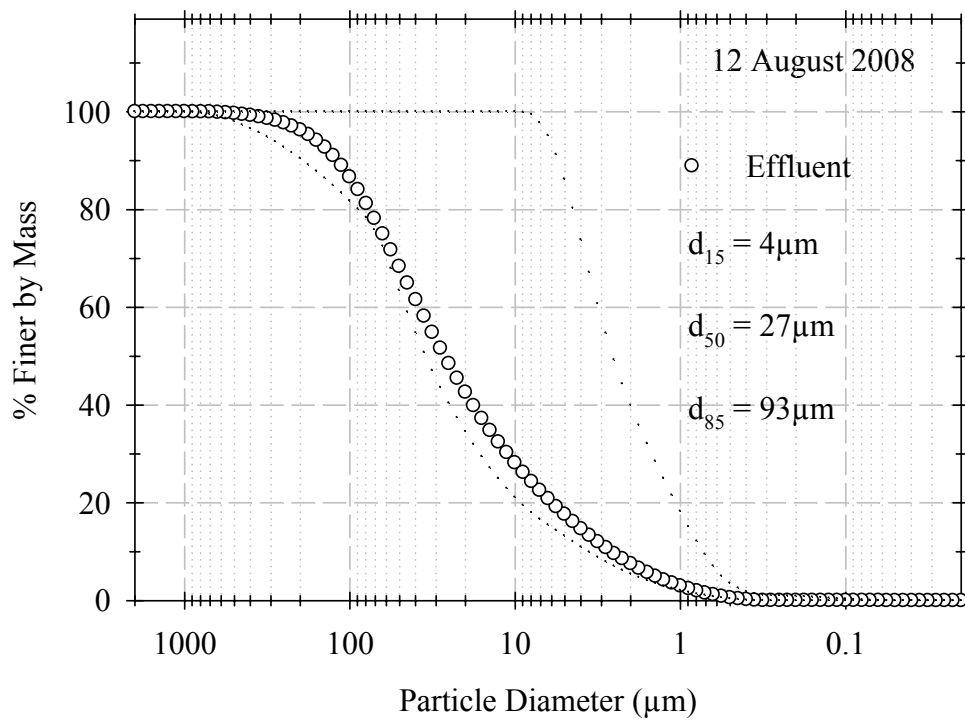
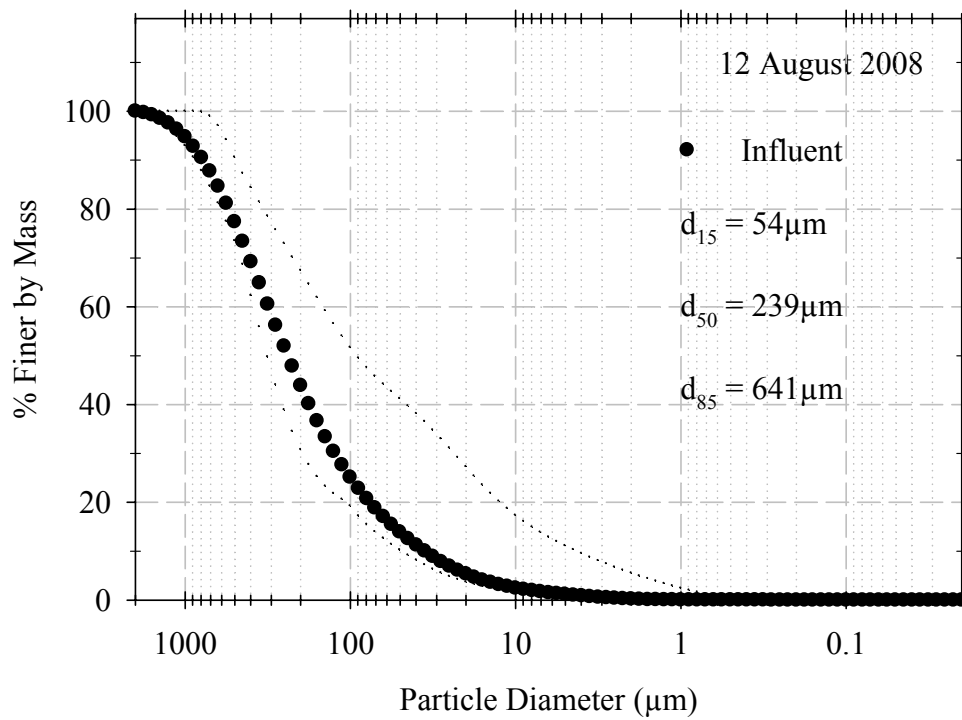


Figure 43 Mean and range of influent and effluent PSD of the 12 August 2008 rainfall event

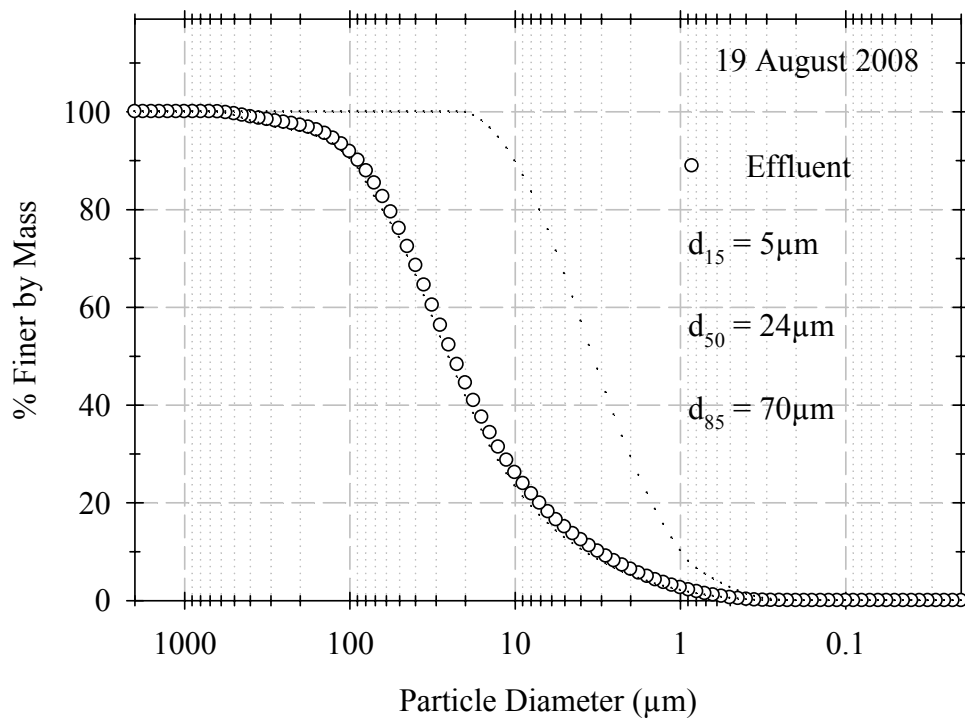
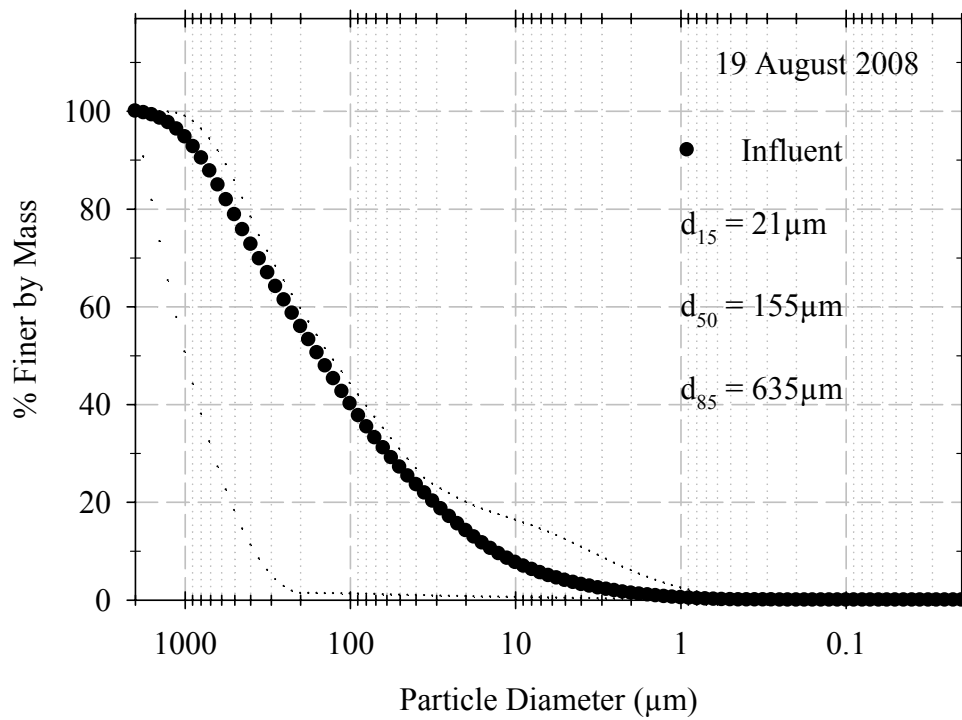


Figure 44 Mean and range of influent and effluent PSD of the 19 August 2008 rainfall event

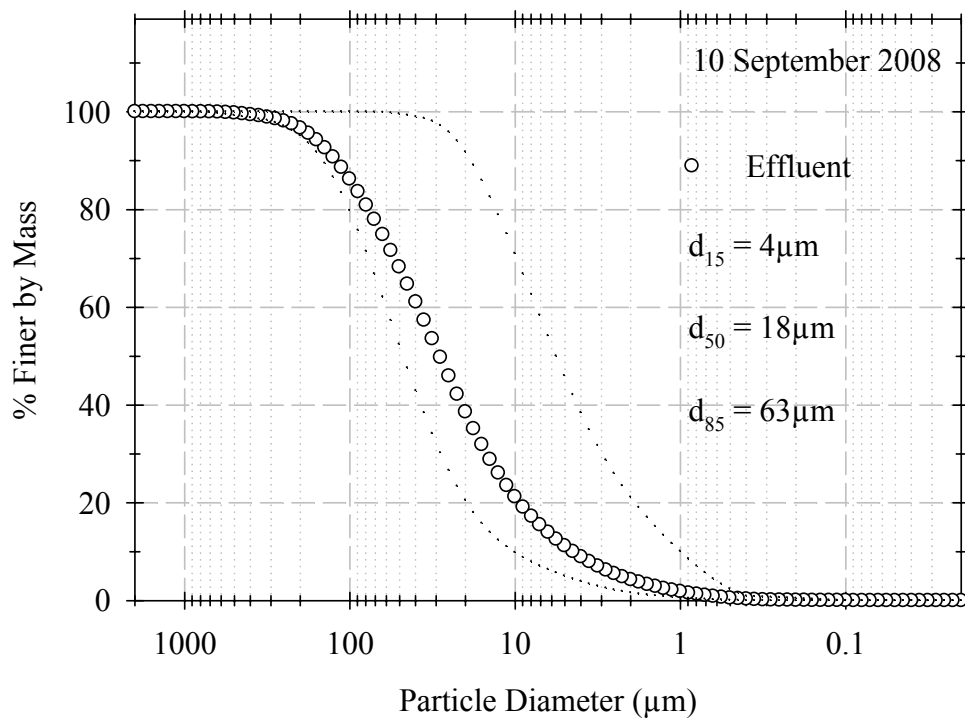
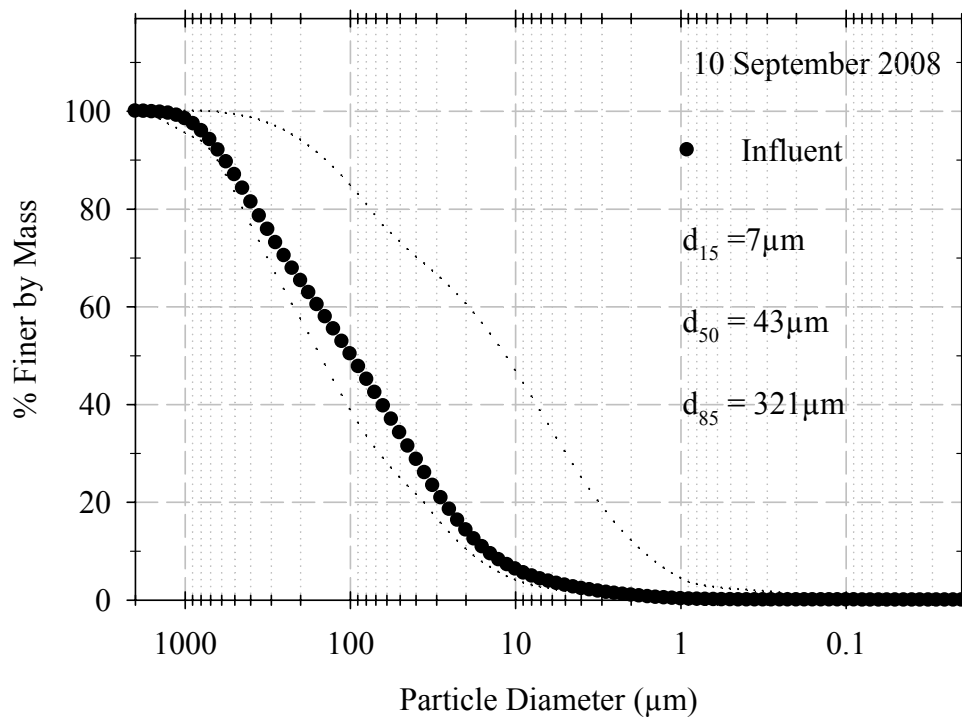


Figure 45 Mean and range of influent and effluent PSD of the 10 September 2008 rainfall event

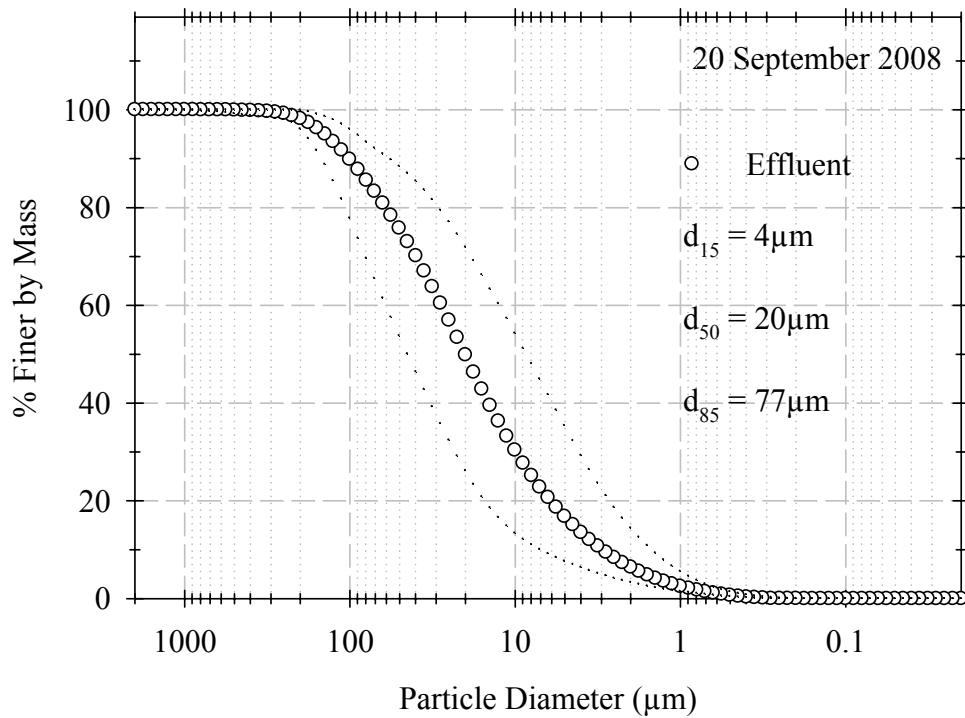
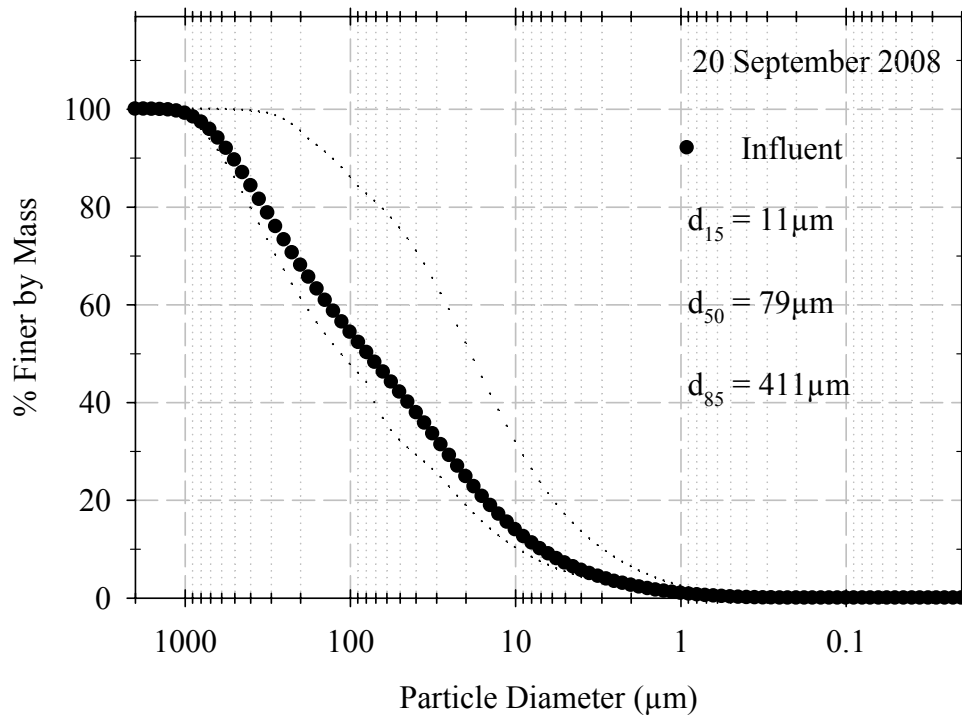


Figure 46 Mean and range of influent and effluent PSD of the 20 September 2008 rainfall event

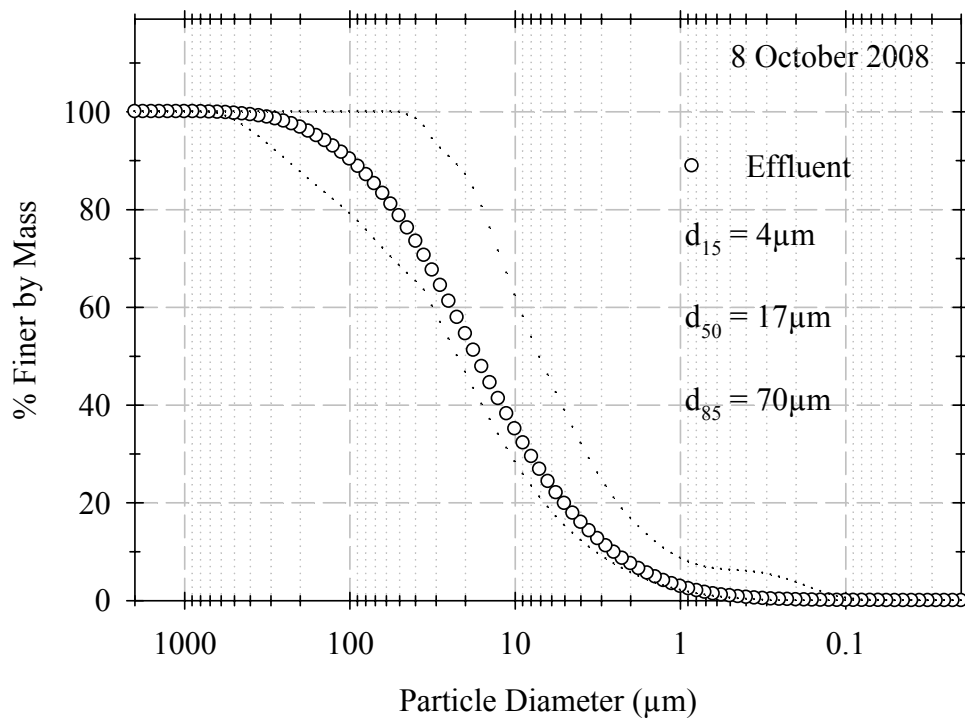
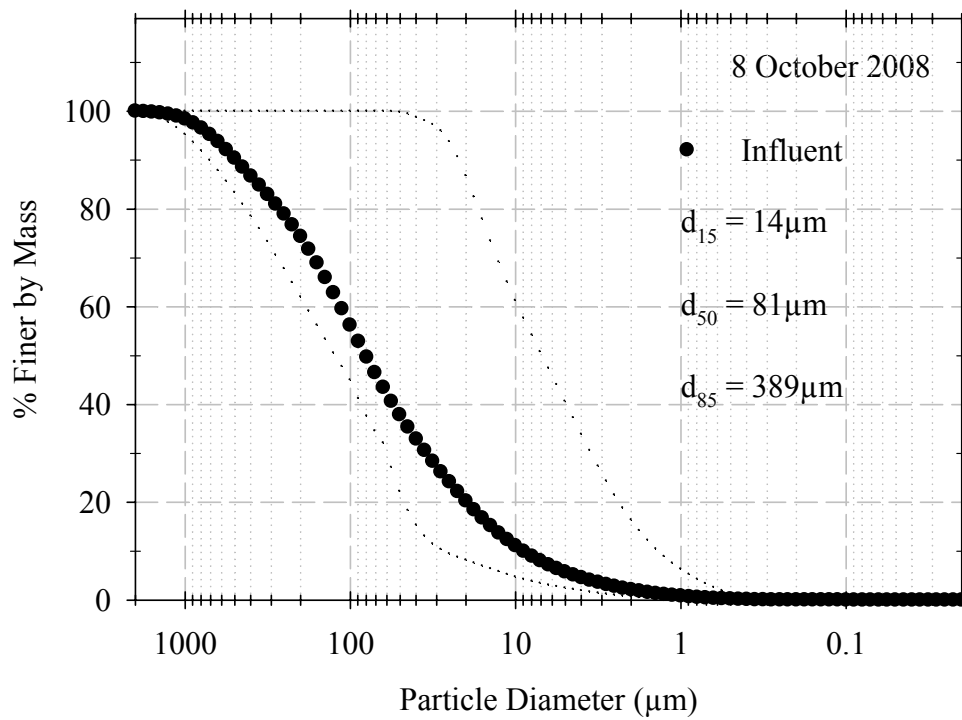


Figure 47 Mean and range of influent and effluent PSD of the 8 October 2008 rainfall event

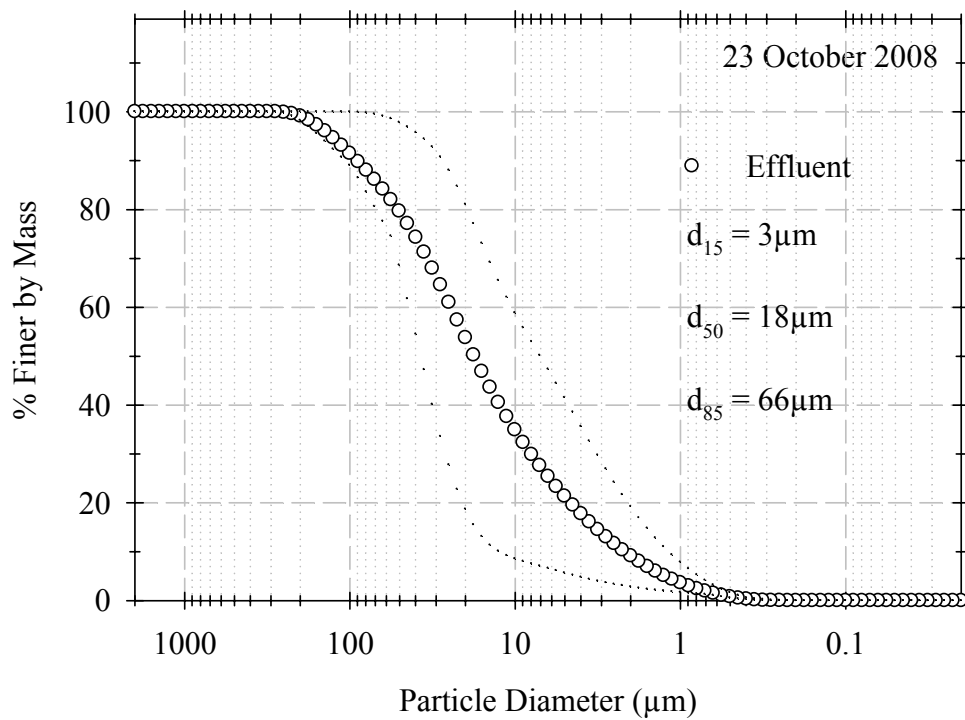
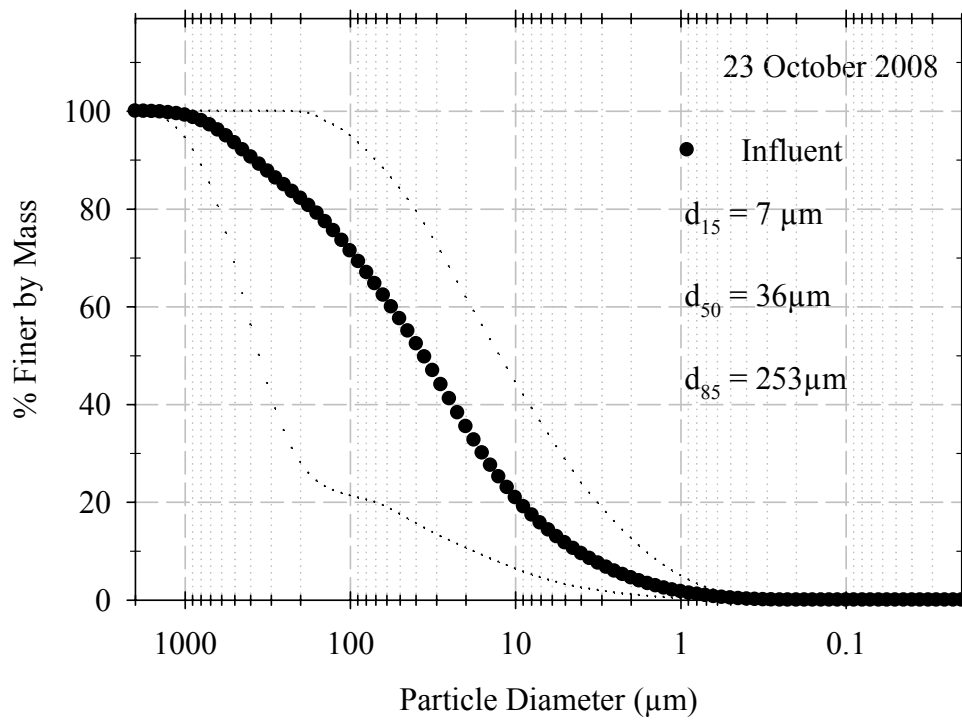


Figure 48 Mean and range of influent and effluent PSD of the 23 October 2008 rainfall event.

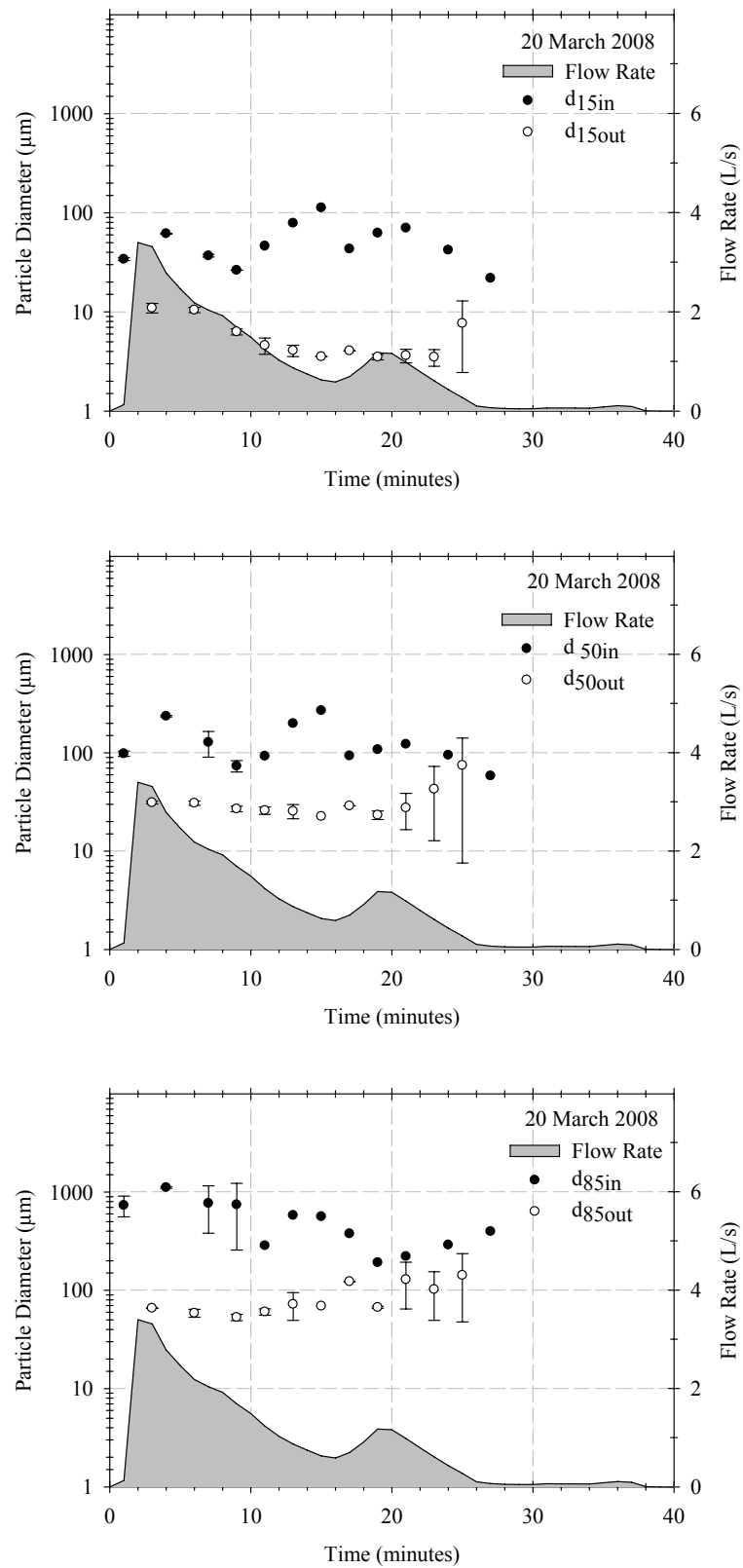


Figure 49 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 20 March 2008 event

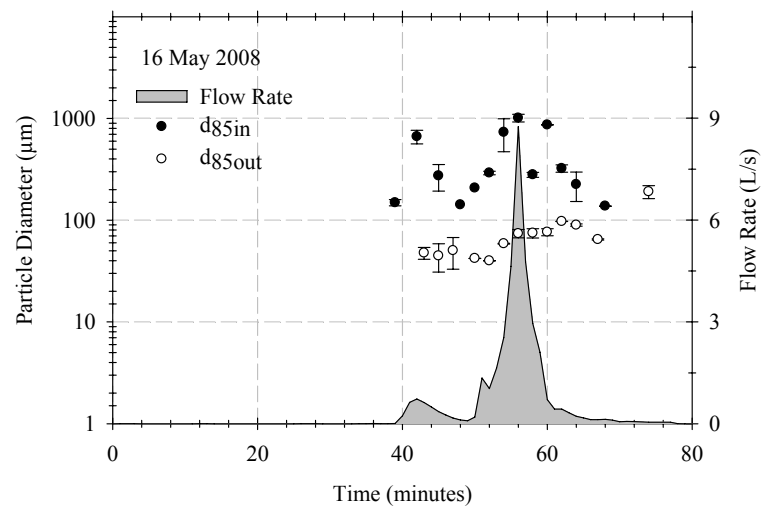
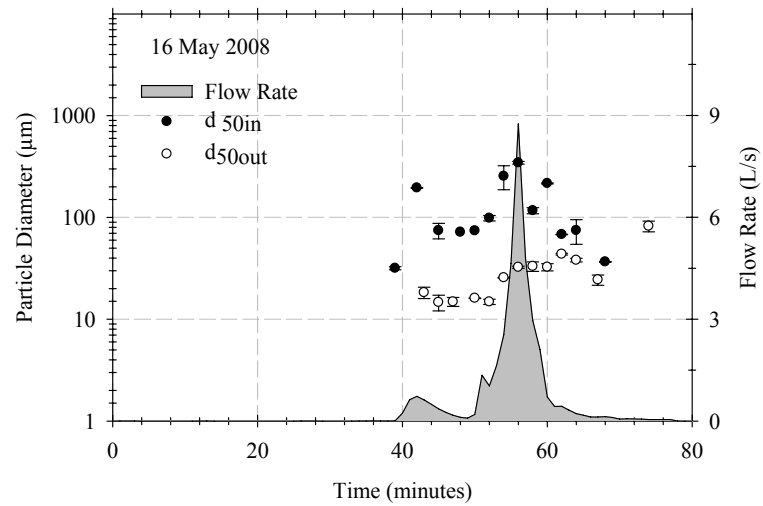
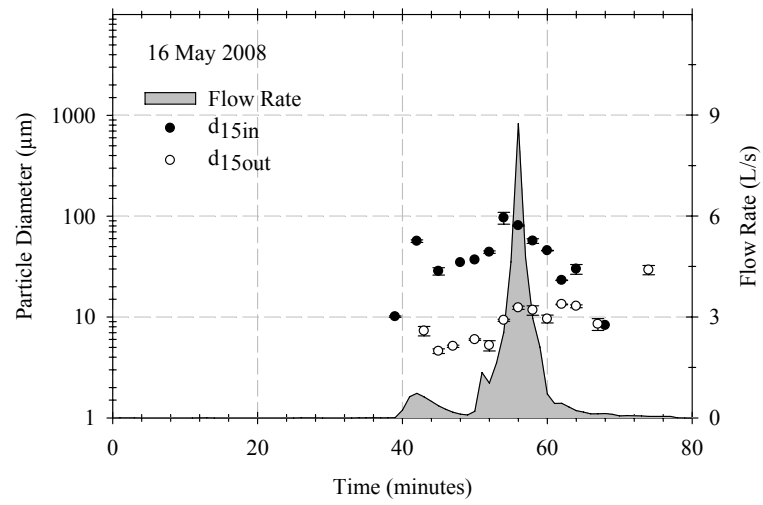


Figure 50 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 16 May 2008 event

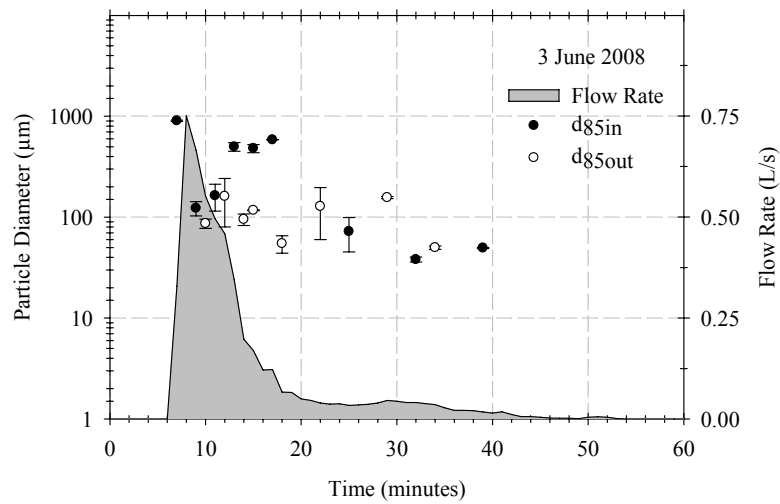
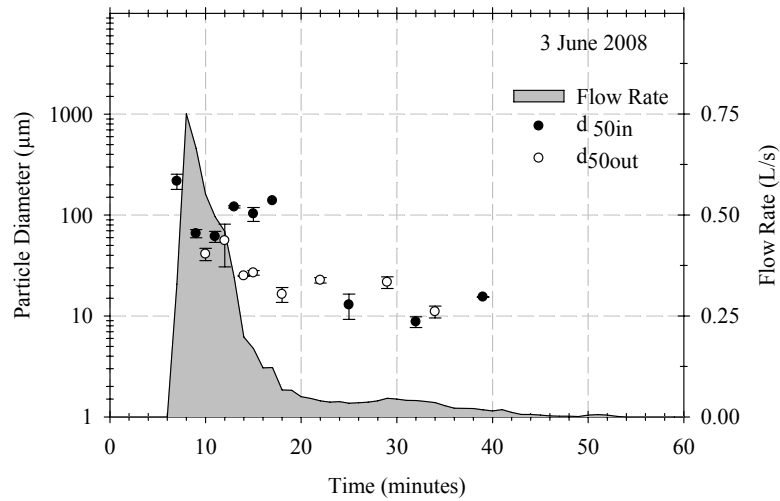
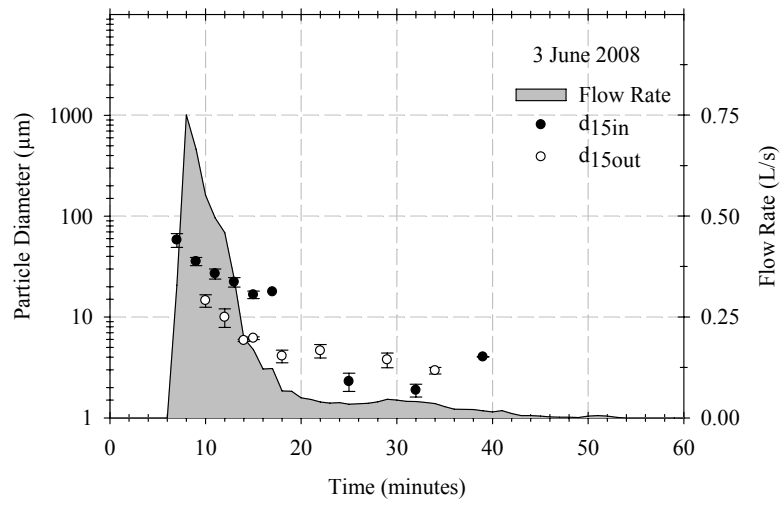


Figure 51 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 3 June 2008 event

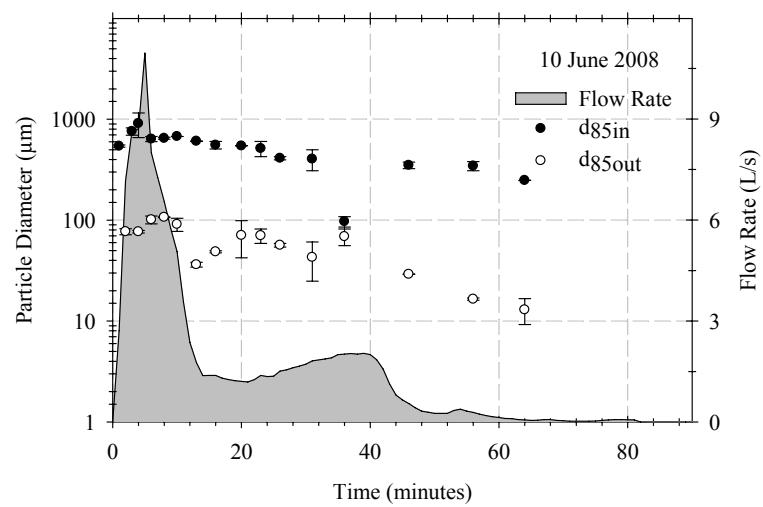
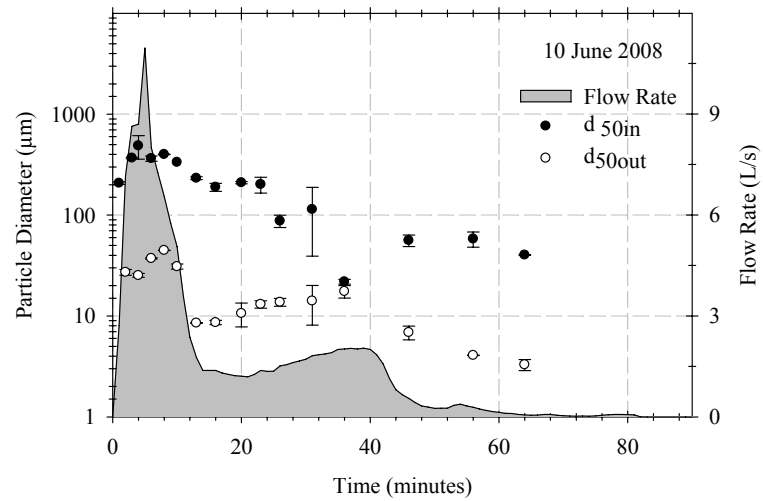
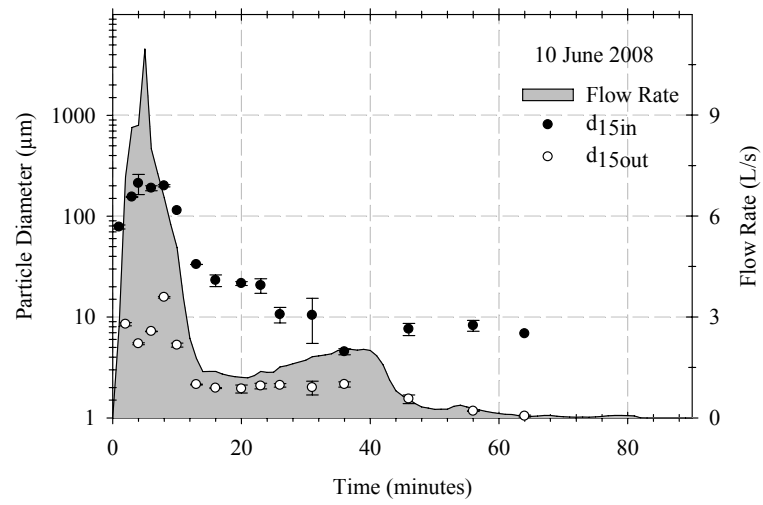


Figure 52 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 10 June 2008 event

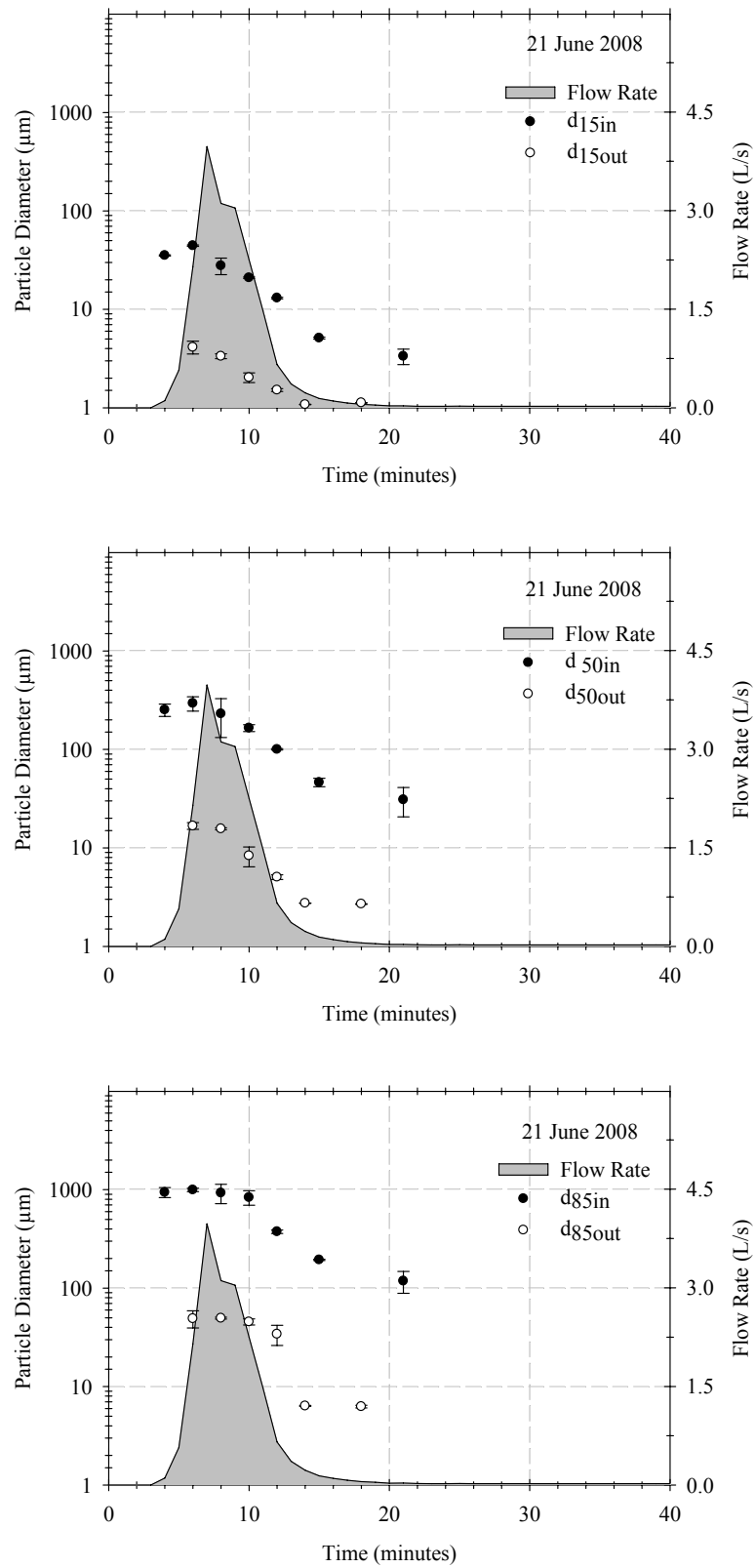


Figure 53 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 21 June 2008 event

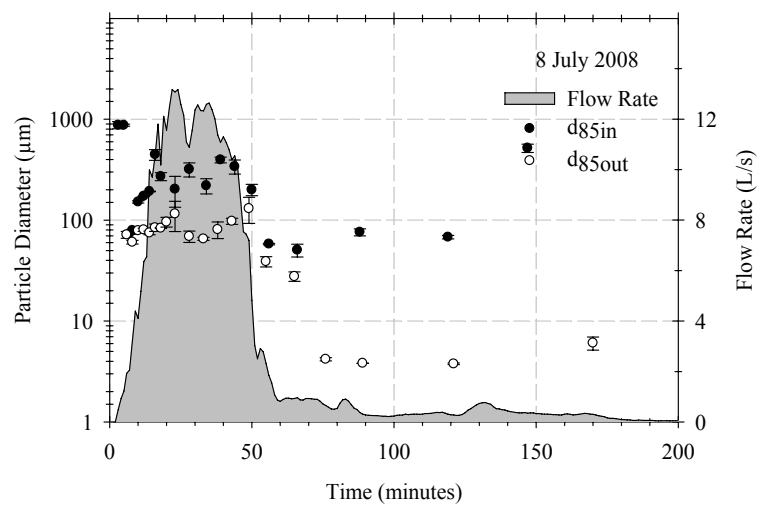
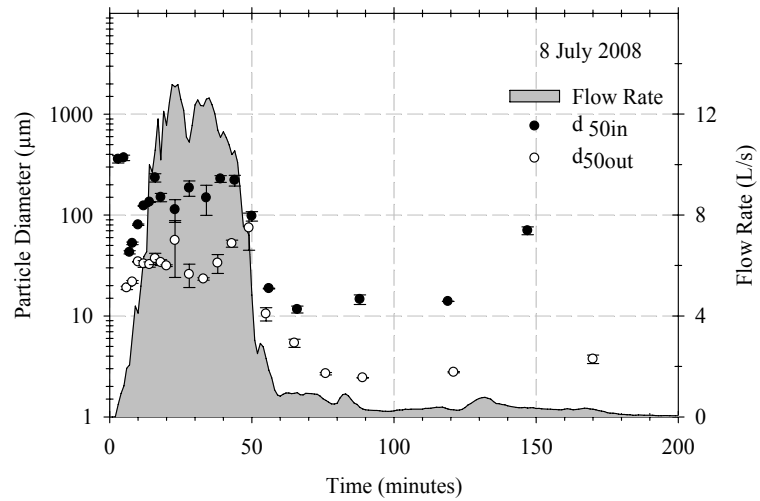
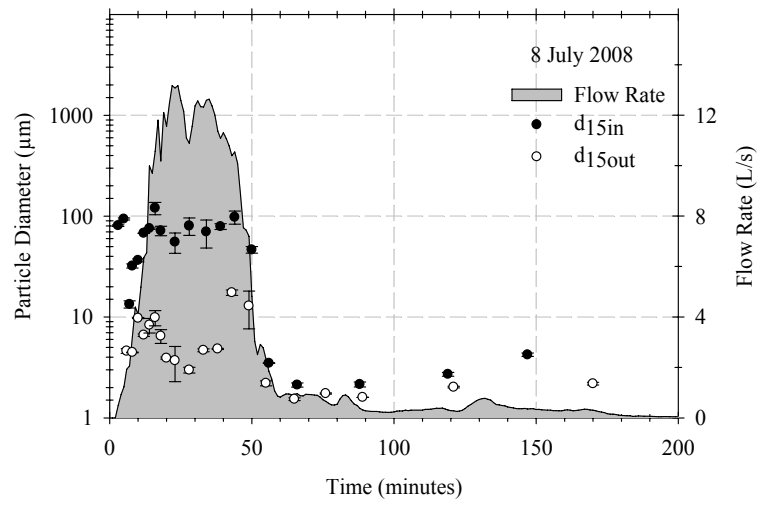


Figure 54 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 8 July 2008 event

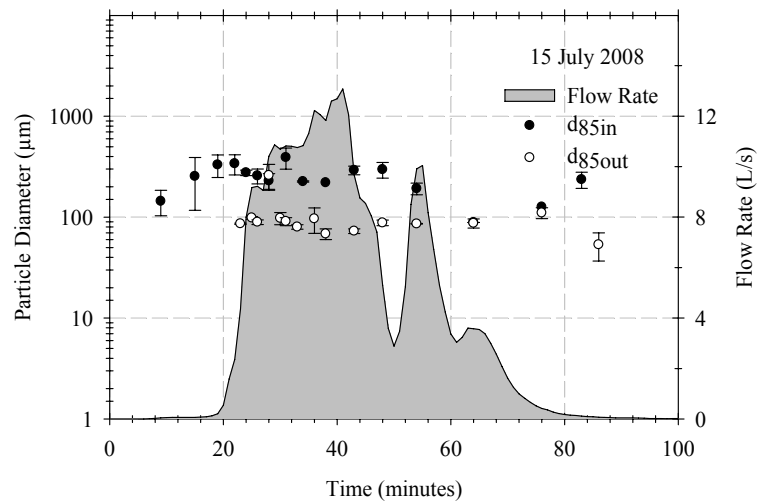
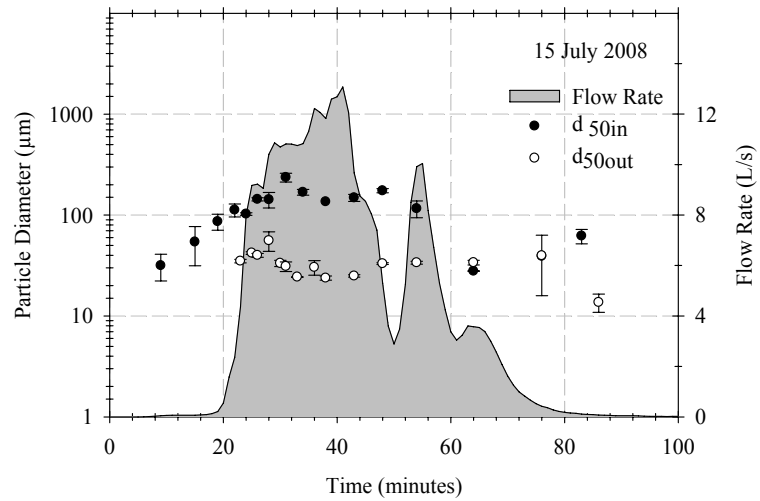
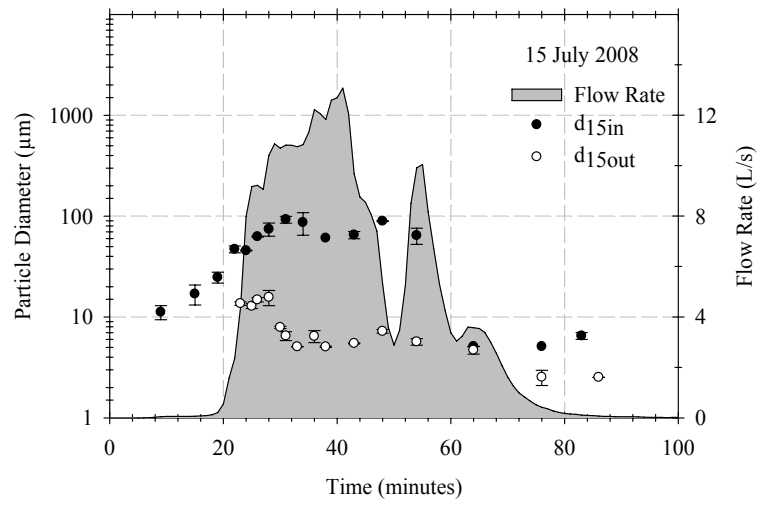


Figure 55 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 15 July 2008 event

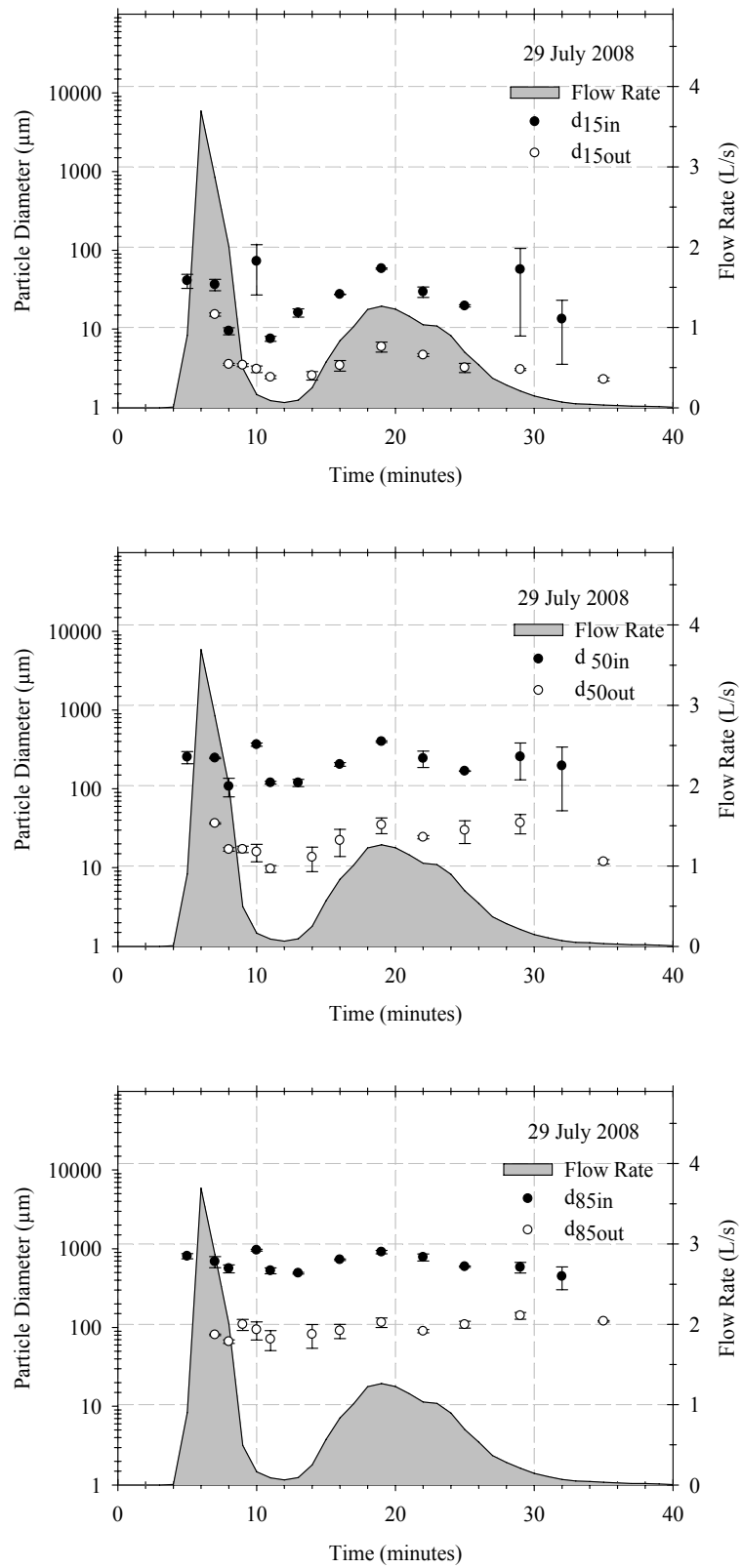


Figure 56 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 29 July 2008 event

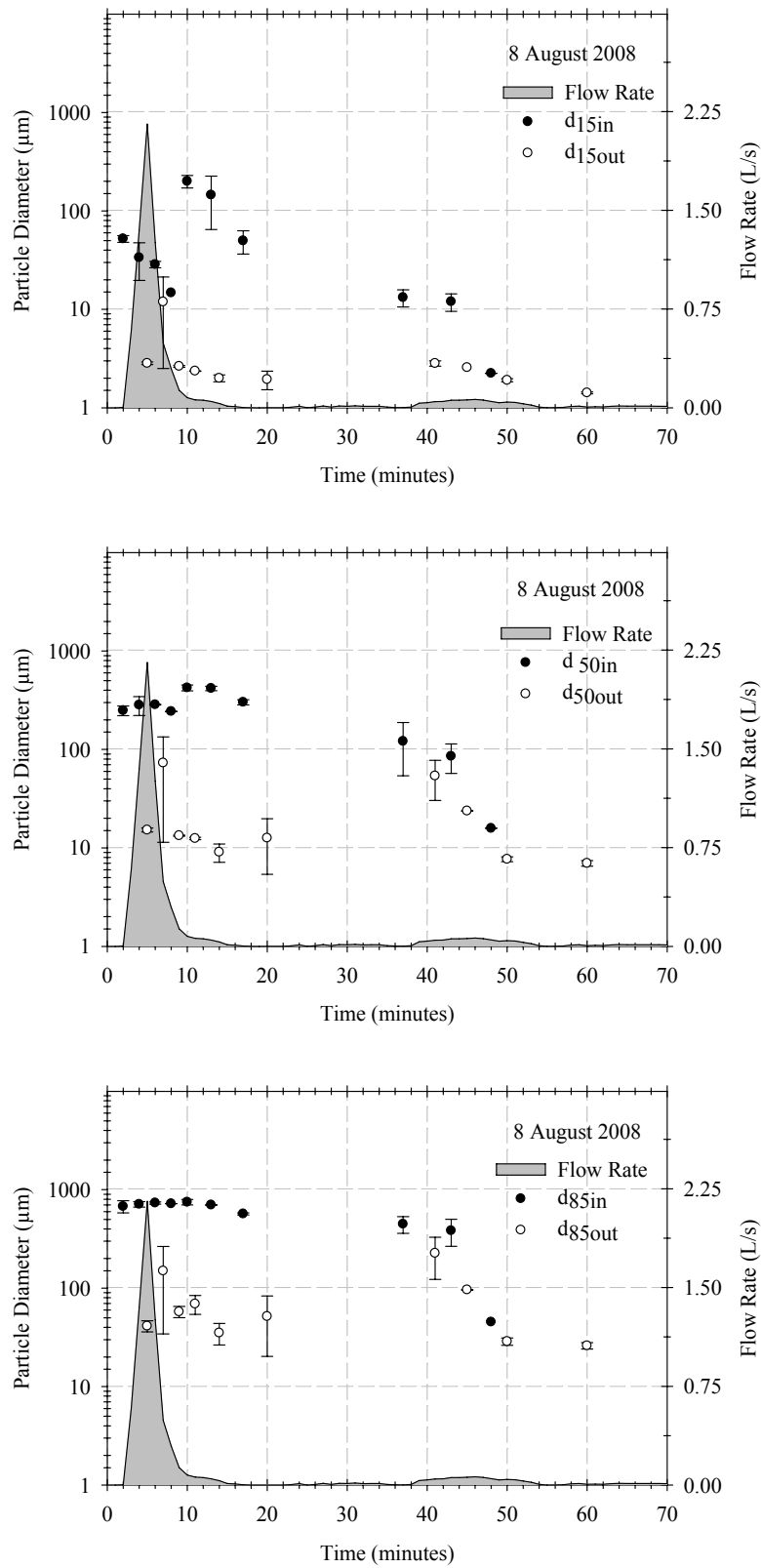


Figure 57 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 8 August 2008 event

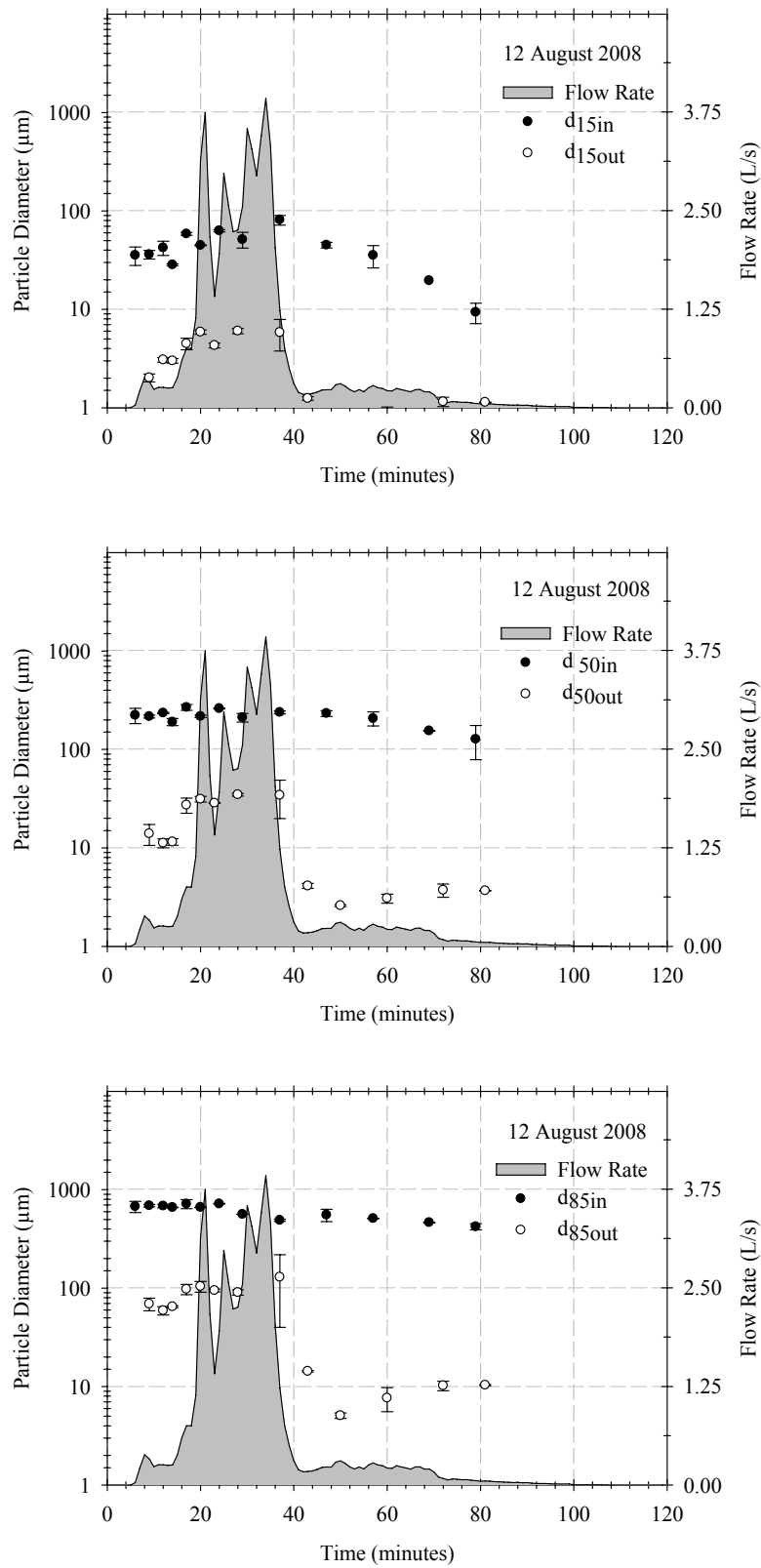


Figure 58 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 12 August 2008 event

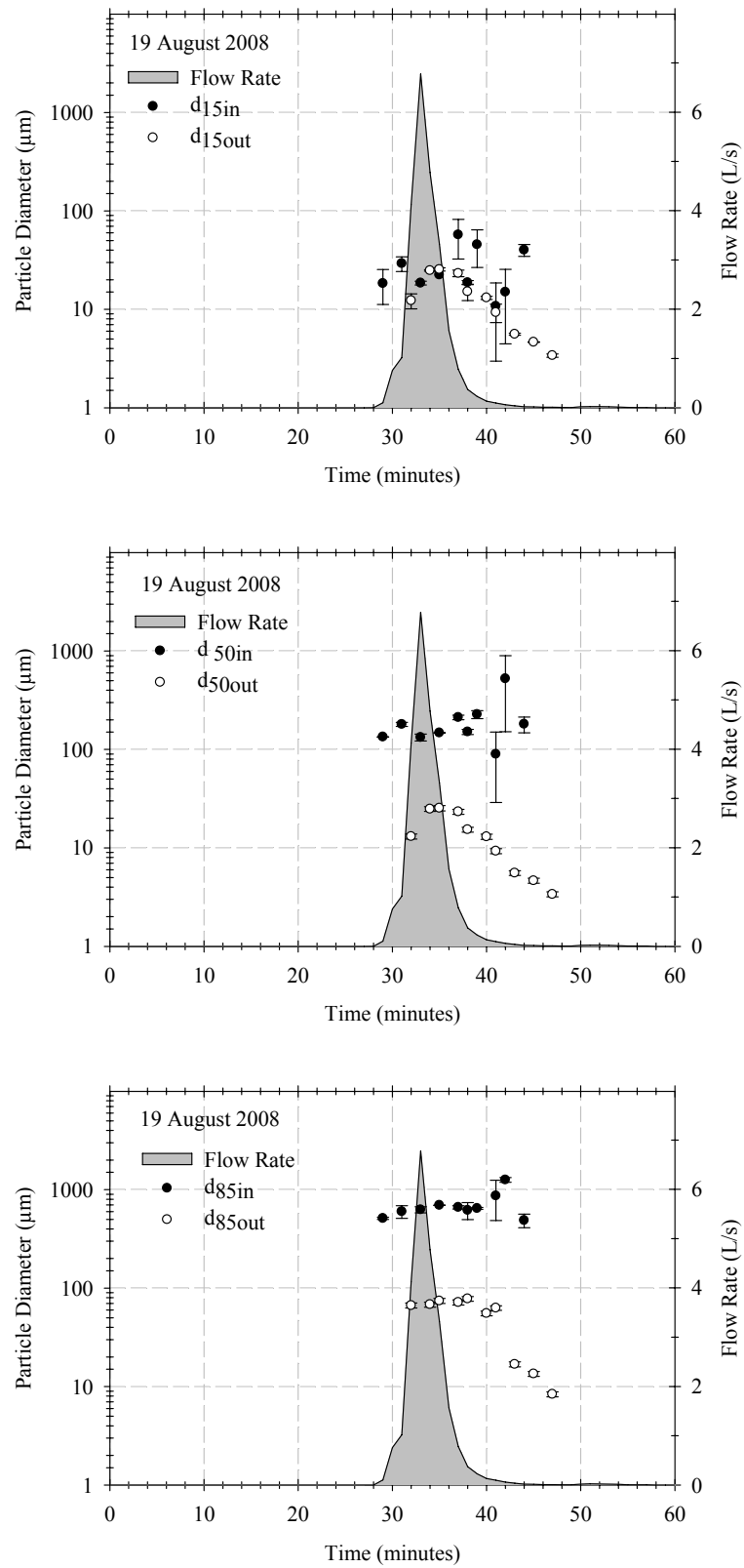


Figure 59 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 19 August 2008 event

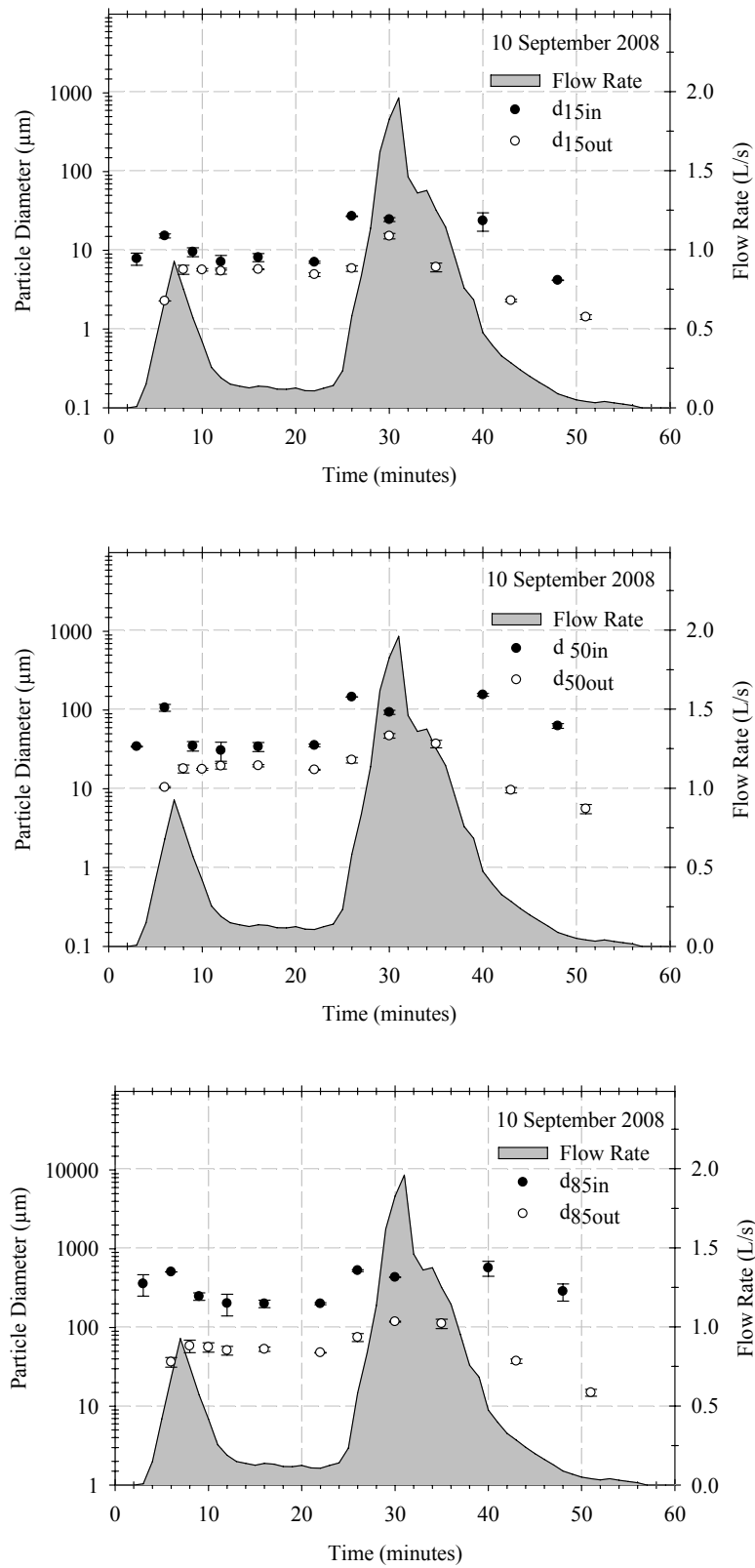


Figure 60 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 10 Sept 2008 event

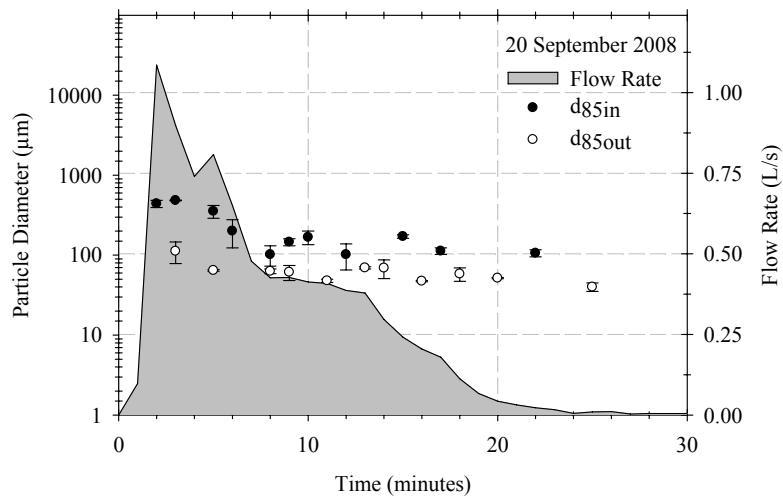
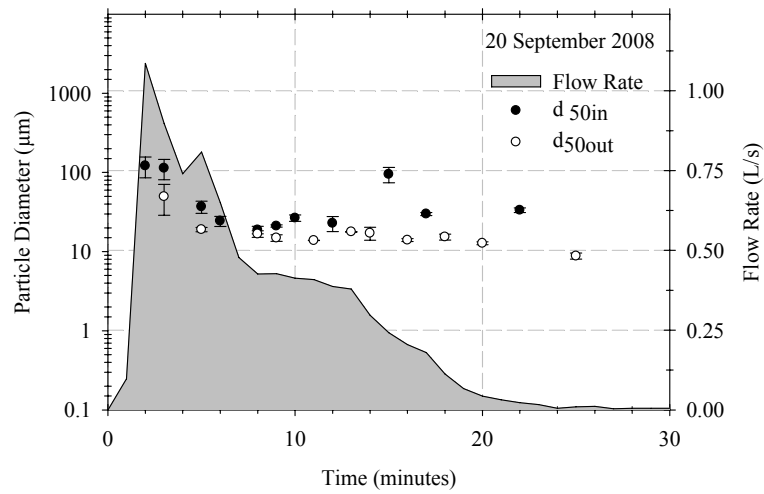
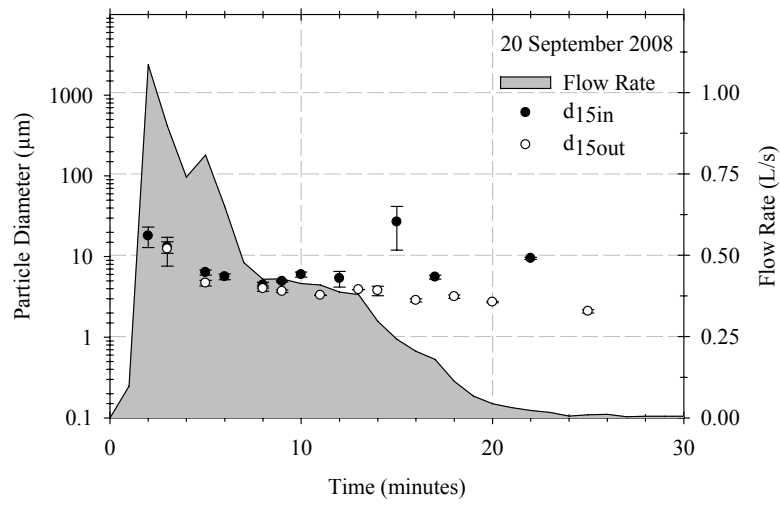


Figure 61 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 20 September 2008 event

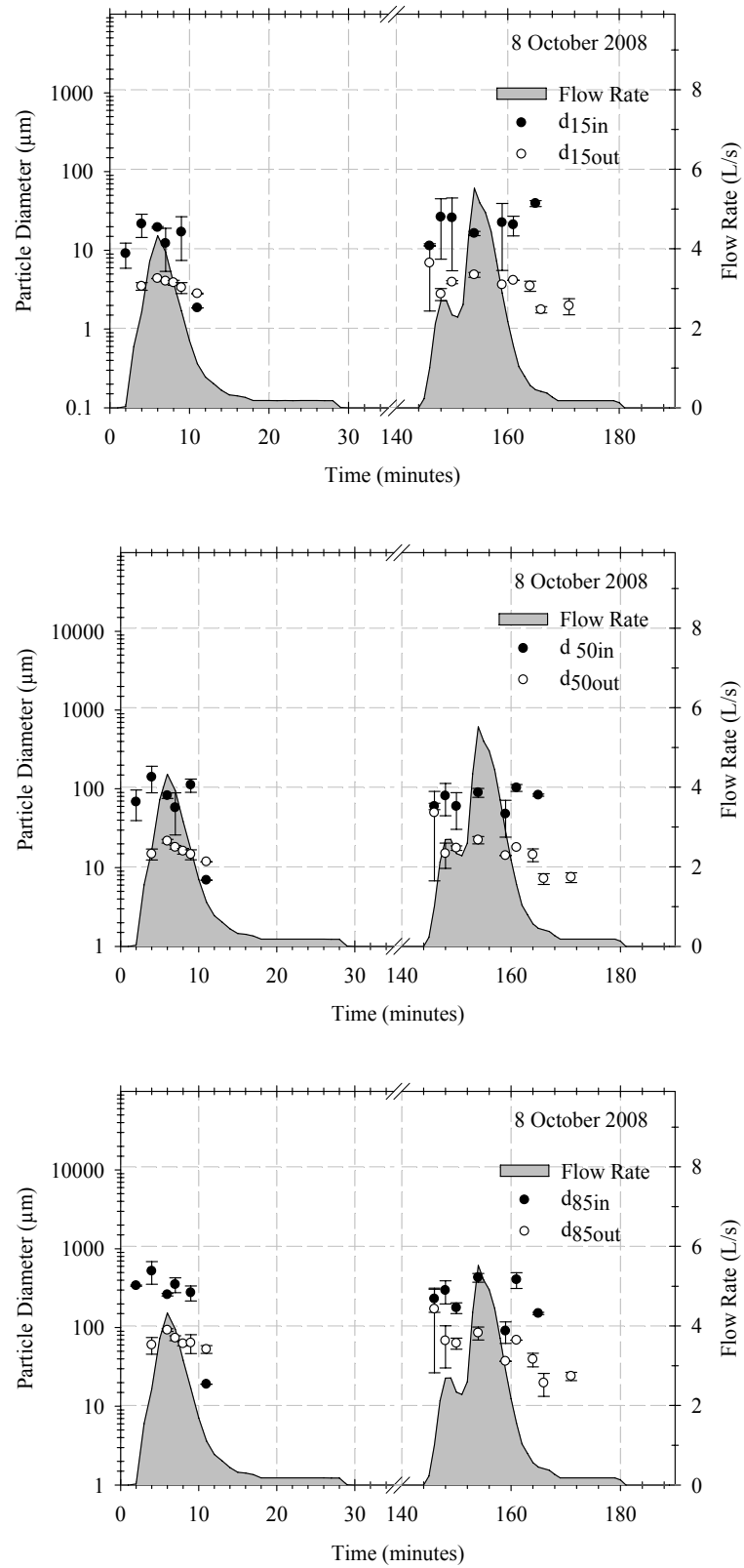


Figure 62 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 8 October 2008 event

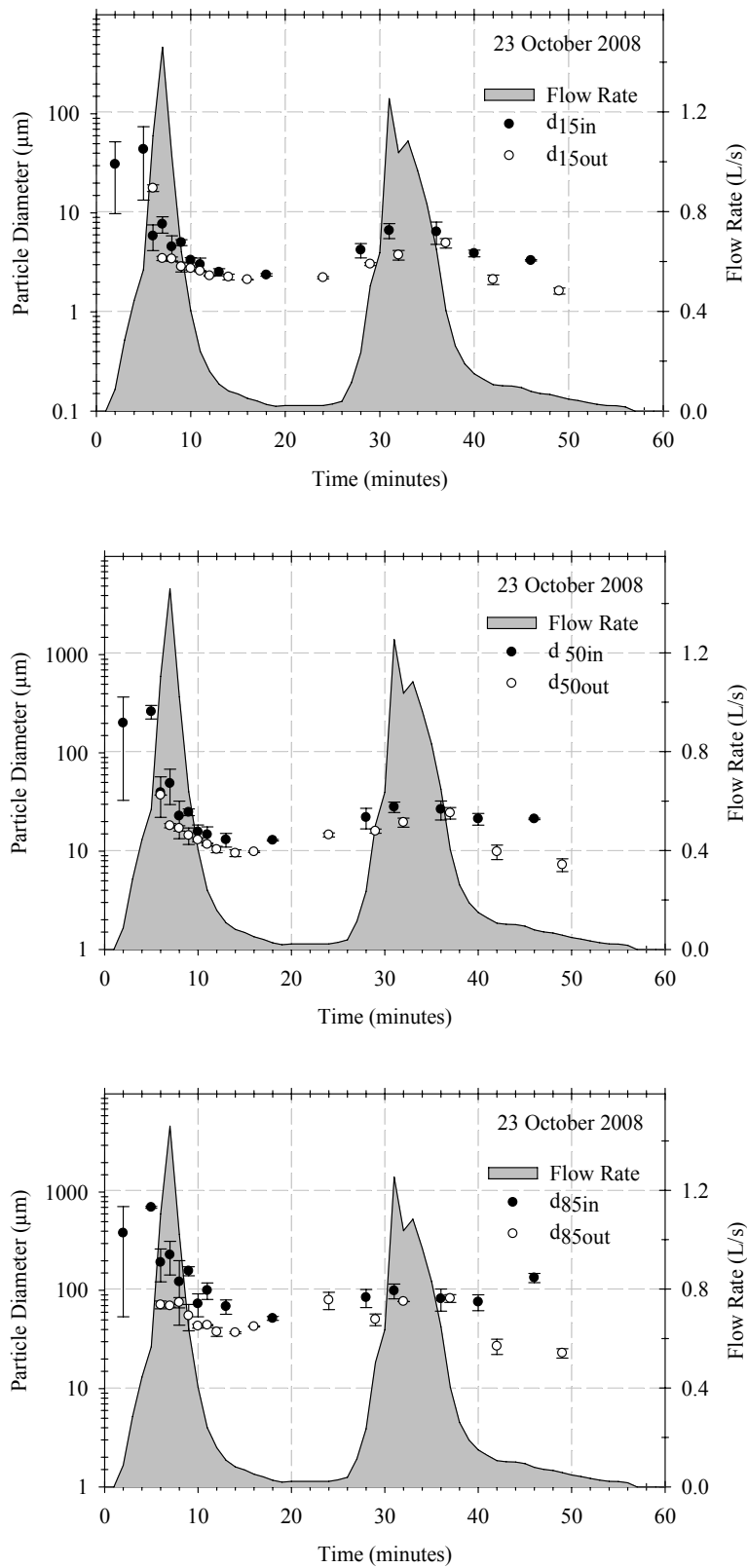


Figure 63 d_{15} , d_{50} and d_{85} behavior with respect to runoff hydrograph for 23 October 2008 event

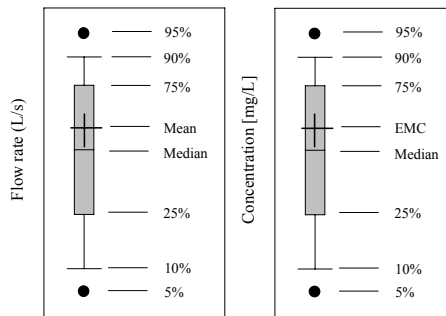


Figure 64 Box plot representation for flow rate and constituent concentration description

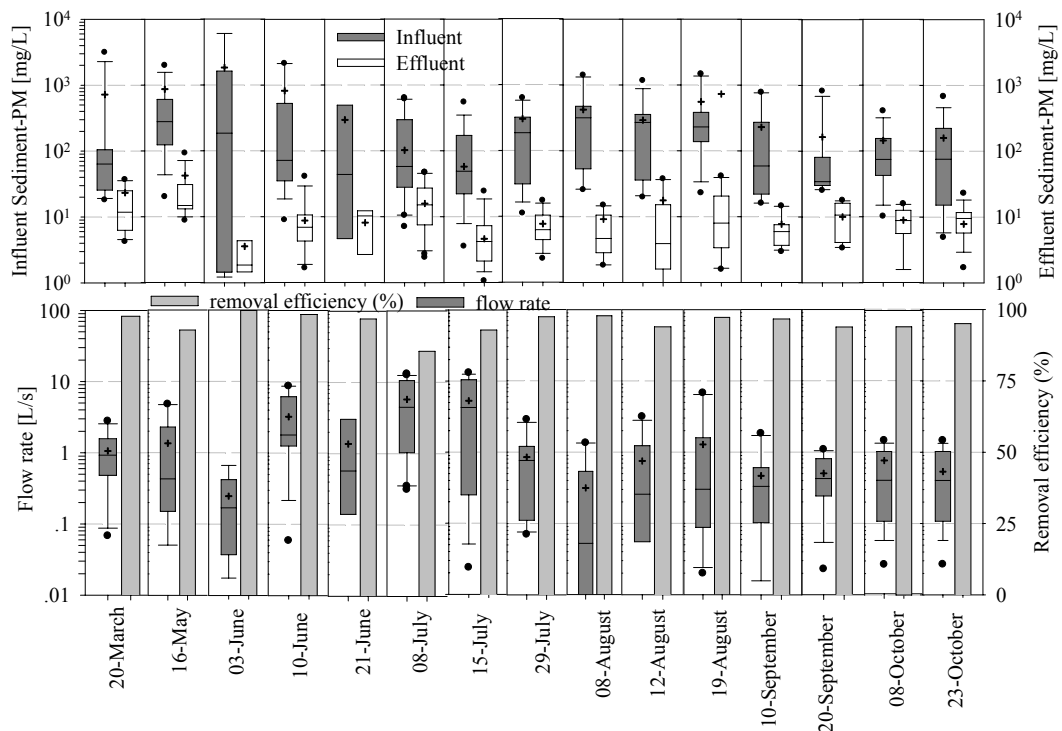


Figure 65 Coupled relationship between flow rate, influent and effluent sediment solid mass concentration and removal efficiency

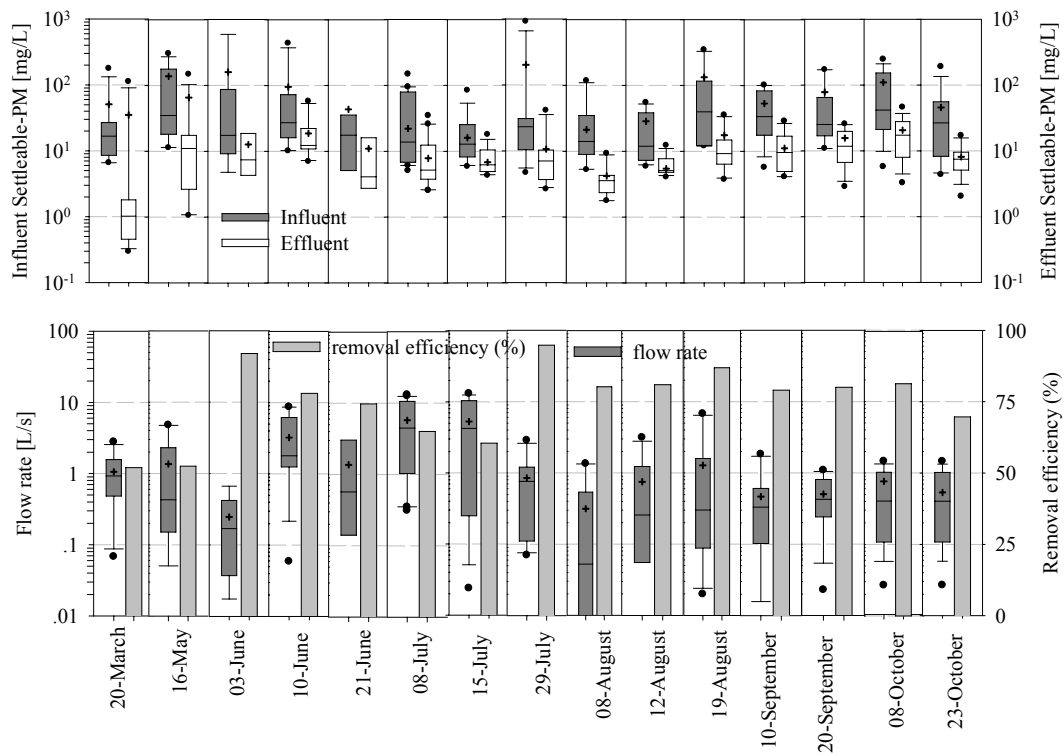


Figure 66 Coupled relationship between flow rate, influent and effluent settleable solid mass concentration and removal efficiency

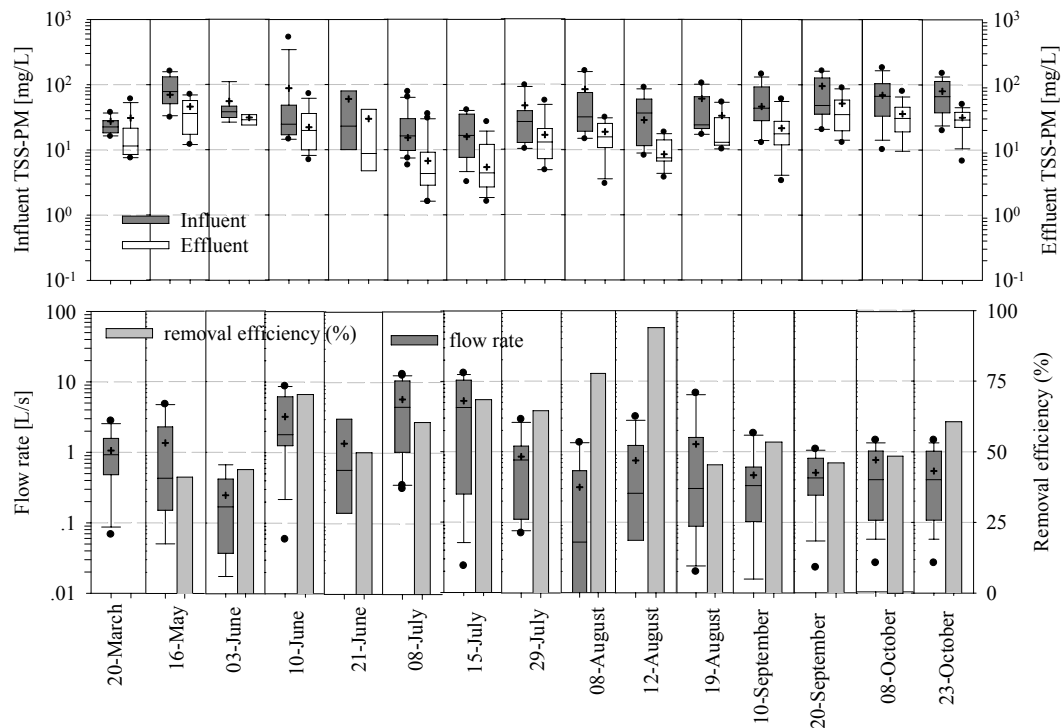


Figure 67 Coupled relationship between flow rate, influent and effluent suspended solid mass concentration and removal efficiency

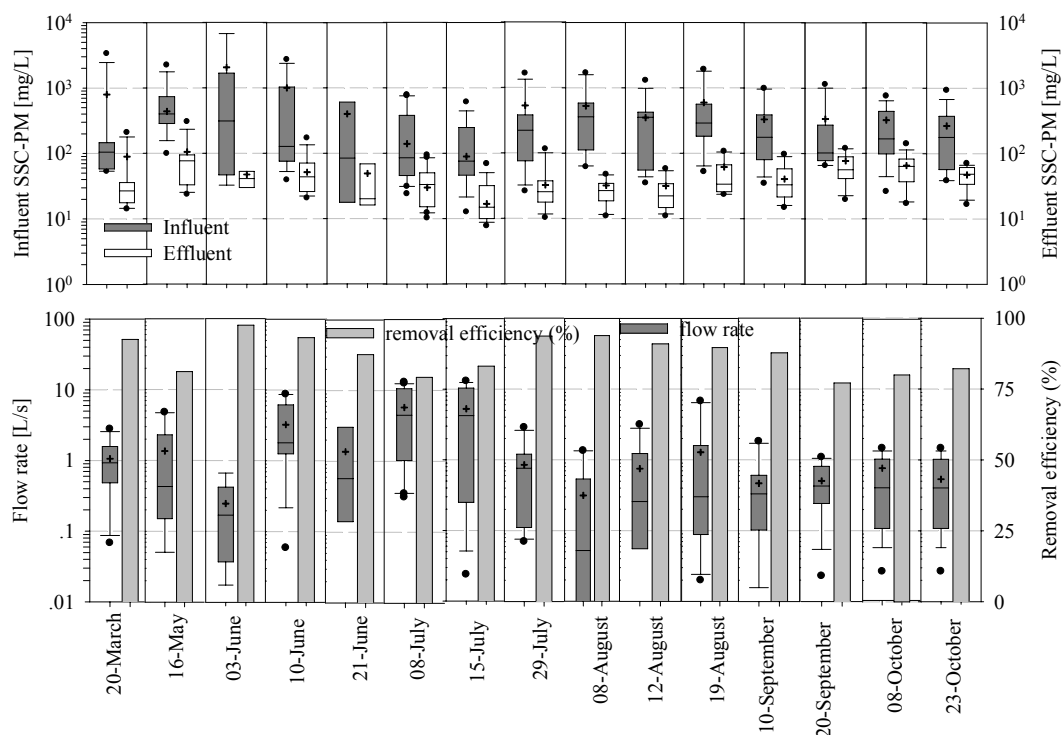


Figure 68 Coupled relationship between flow rate, influent and effluent SSC concentration and removal efficiency

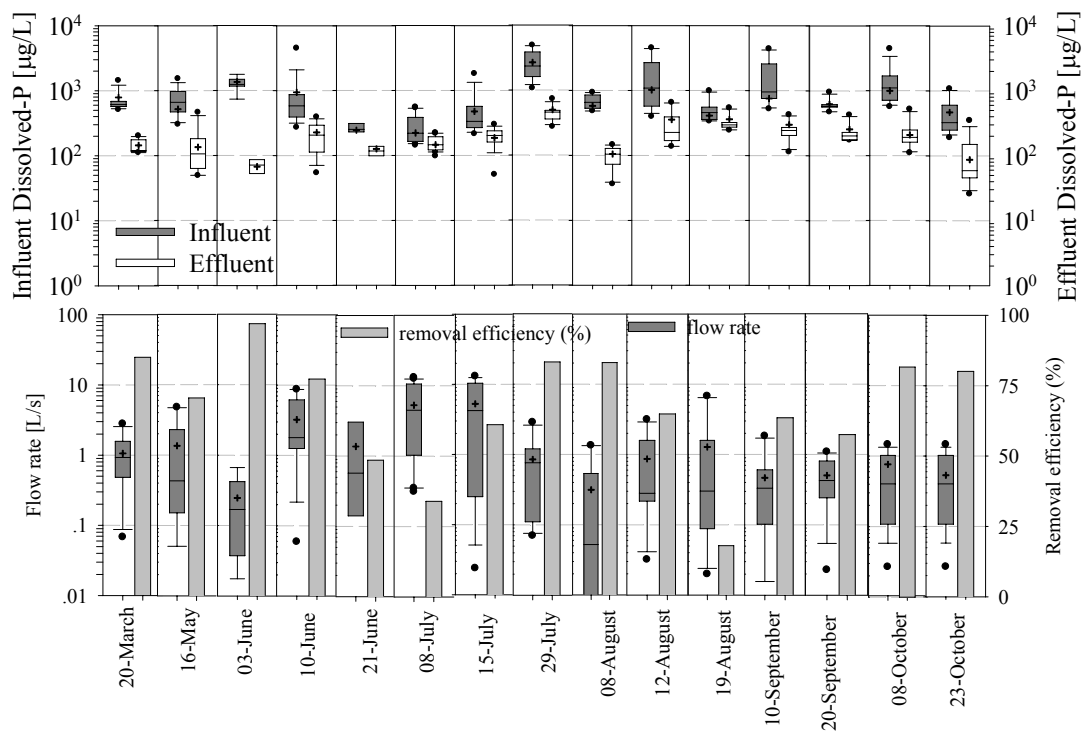


Figure 69 Coupled relationship between flow rate, influent and effluent dissolved phosphorus concentration and removal efficiency

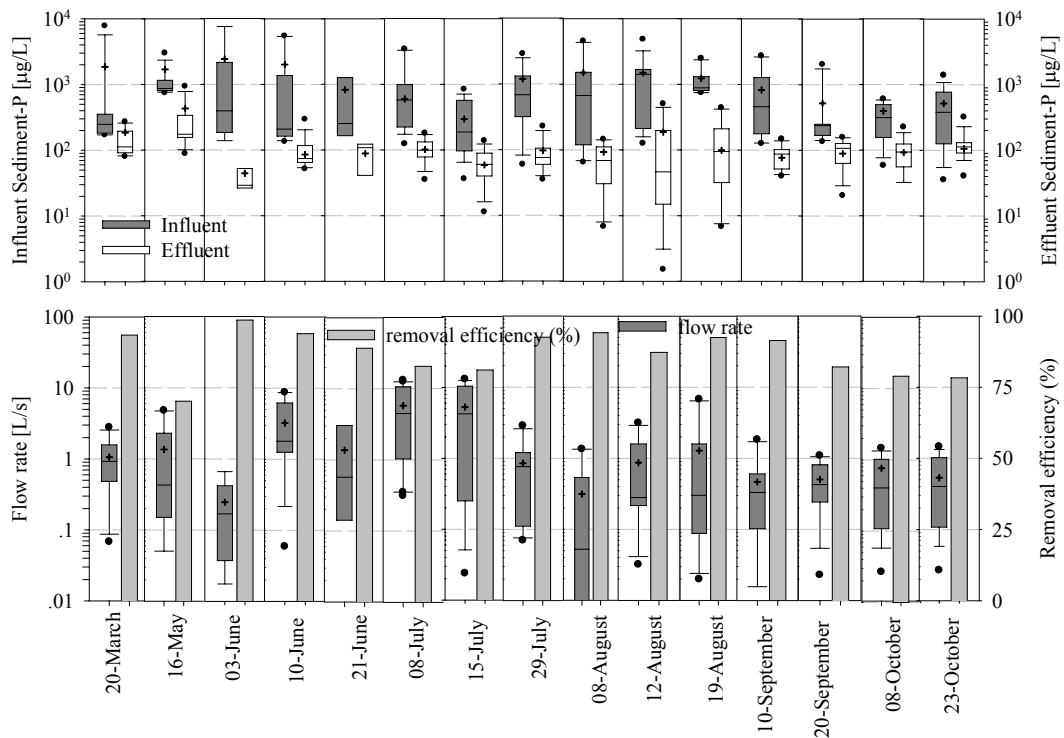


Figure 70 Coupled relationship between flow rate, influent and effluent sediment phosphorus concentration and removal efficiency

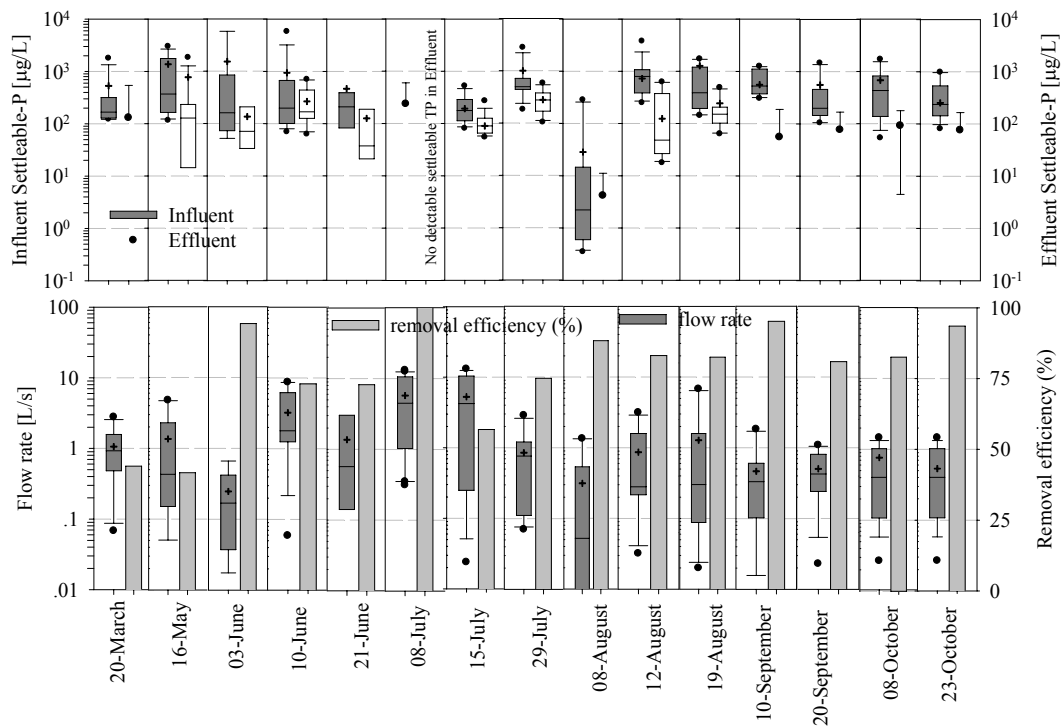


Figure 71 Coupled relationship between flow rate, influent and effluent settleable phosphorus concentration and removal efficiency

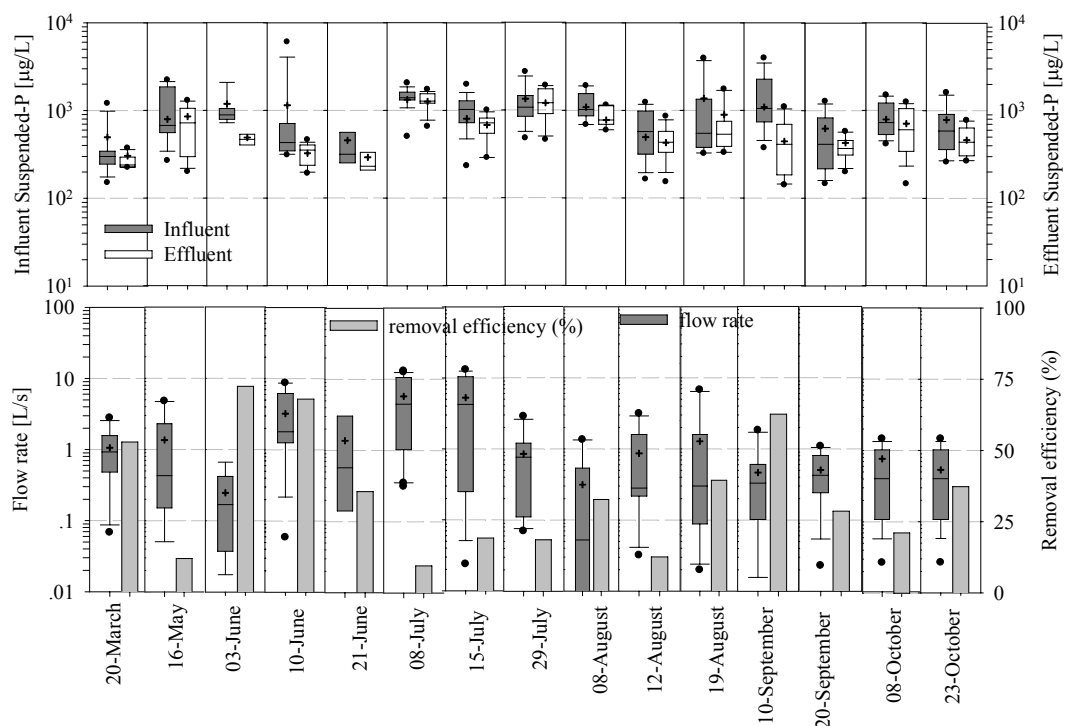


Figure 72 Coupled relationship between flow rate, influent and effluent suspended phosphorus concentration and removal efficiency

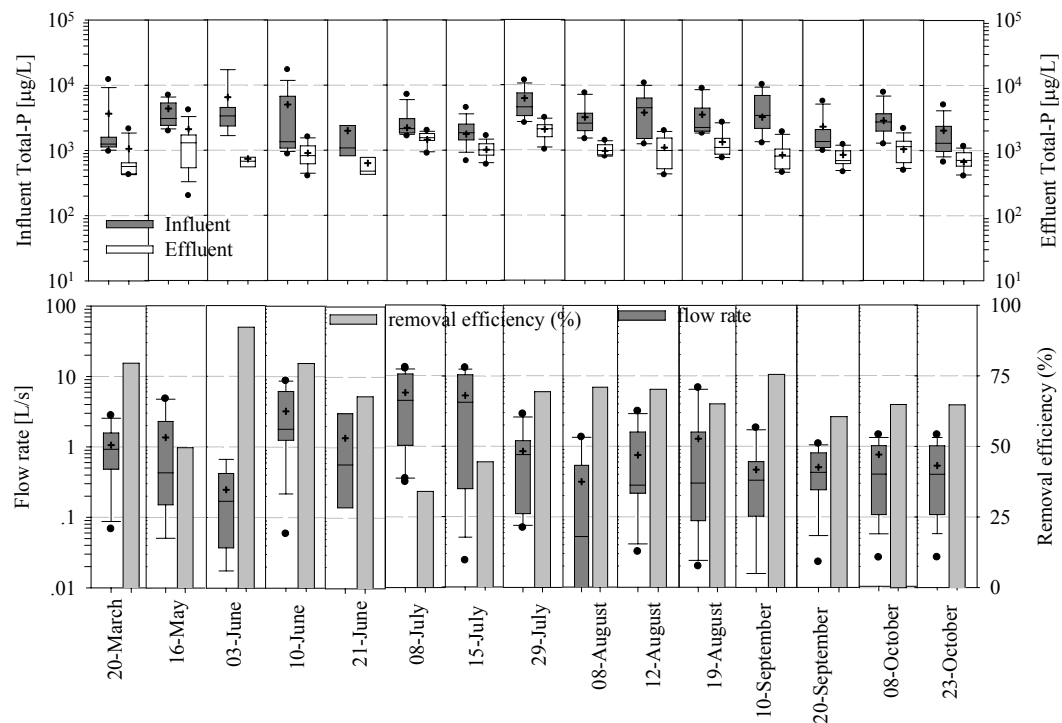


Figure 73 Coupled relationship between flow rate, influent and effluent total phosphorus concentration and removal efficiency

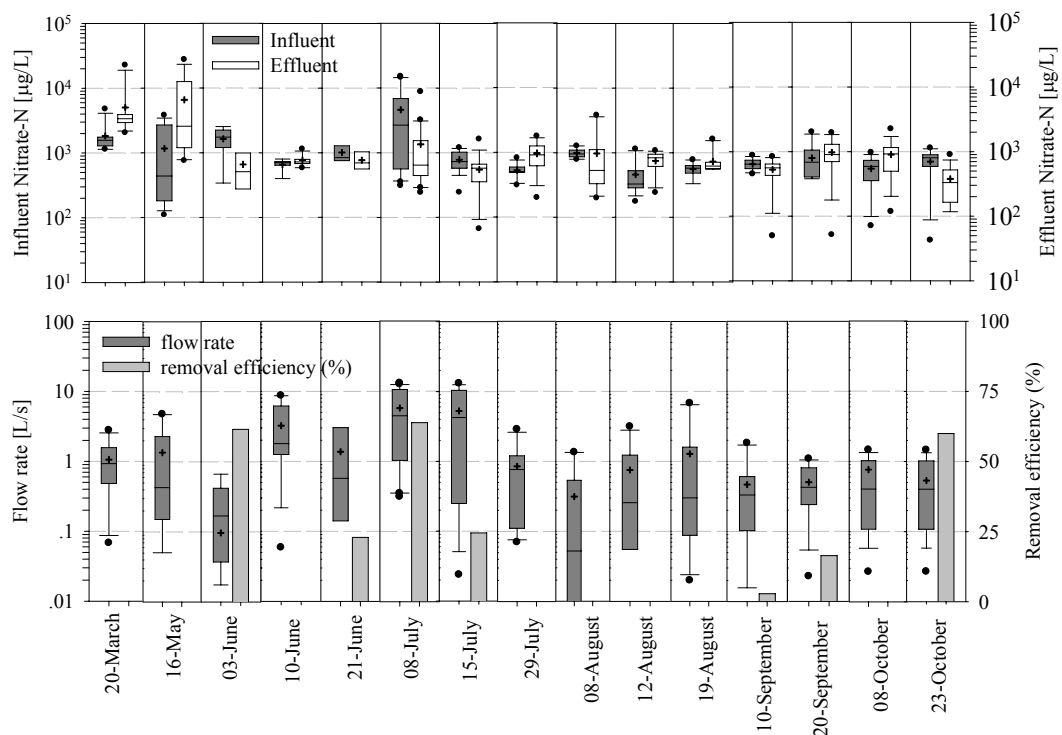


Figure 74 Coupled relationship between flow rate, influent and effluent nitrate concentration and removal efficiency

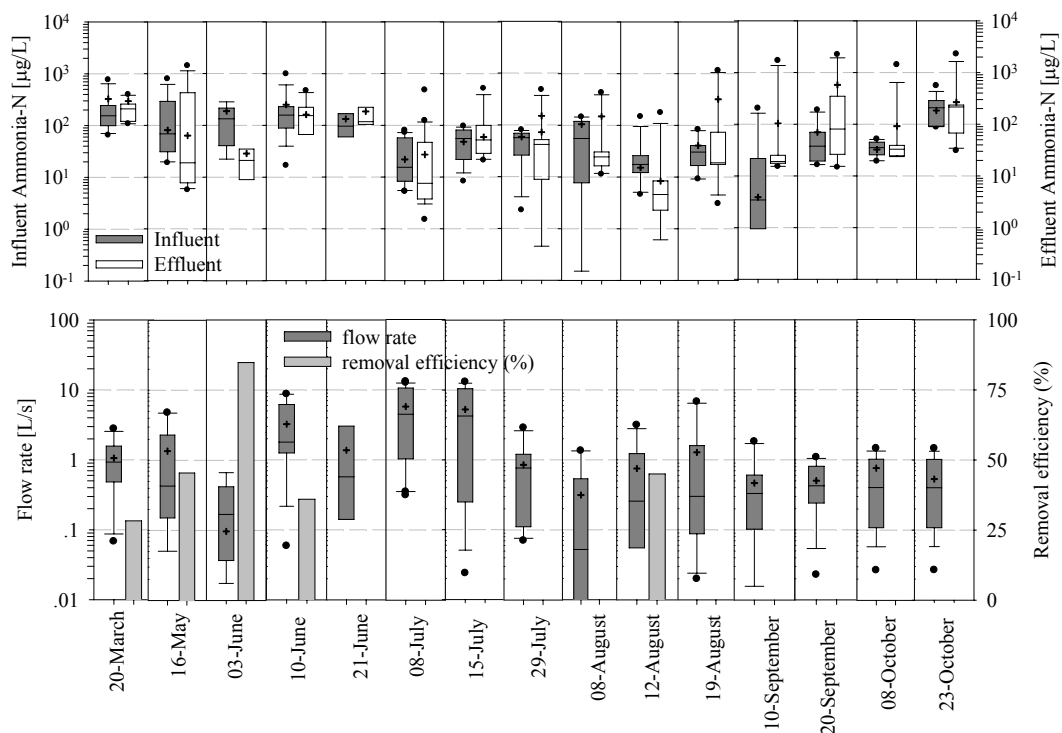


Figure 75 Coupled relationship between flow rate, influent and effluent ammonia concentration and removal efficiency

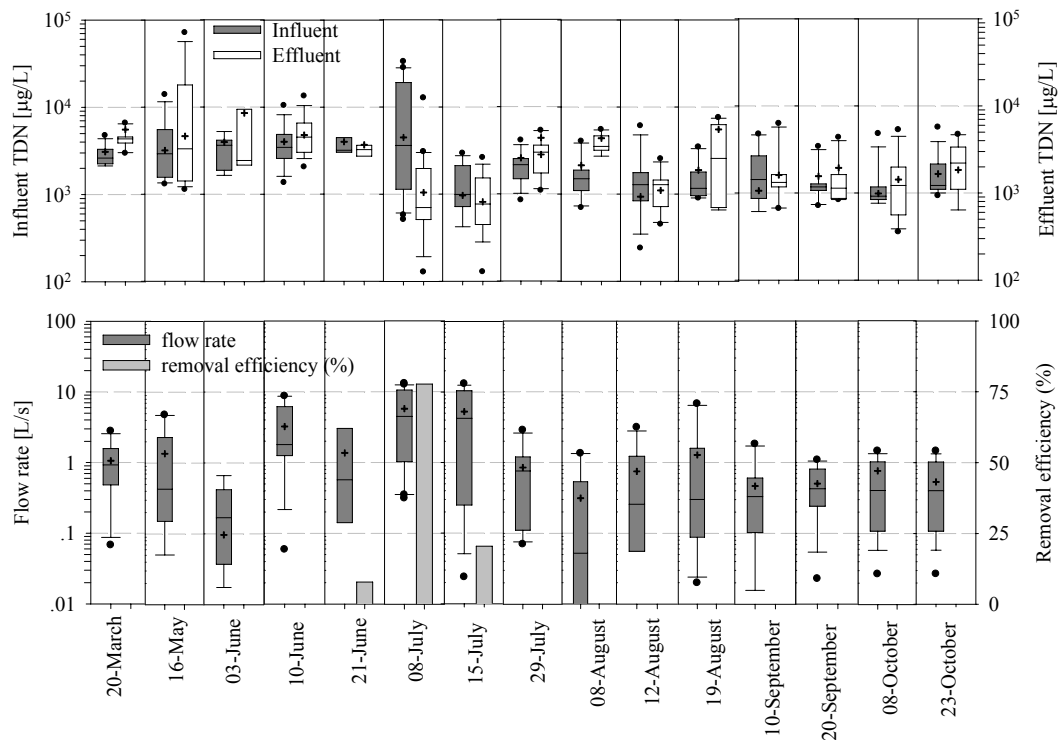


Figure 76 Coupled relationship between flow rate, influent and effluent total dissolved nitrogen concentration and removal efficiency

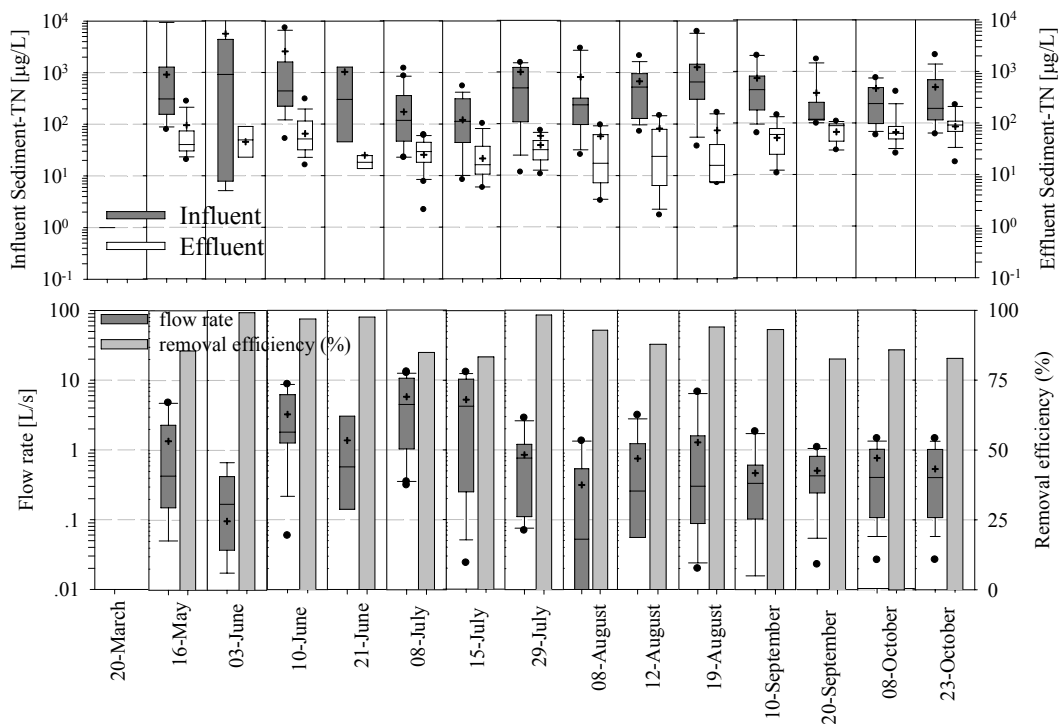


Figure 77 Coupled relationship between flow rate, influent and effluent sediment total nitrogen concentration and removal efficiency

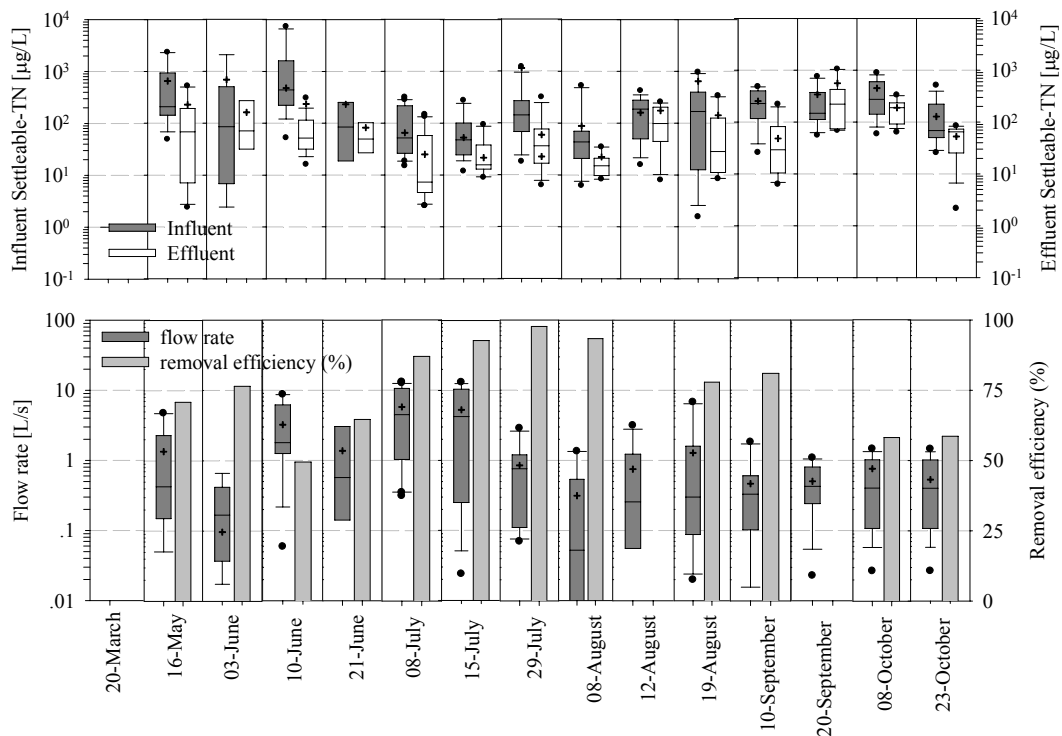


Figure 78 Coupled relationship between flow rate, influent and effluent settleable total nitrogen concentration and removal efficiency

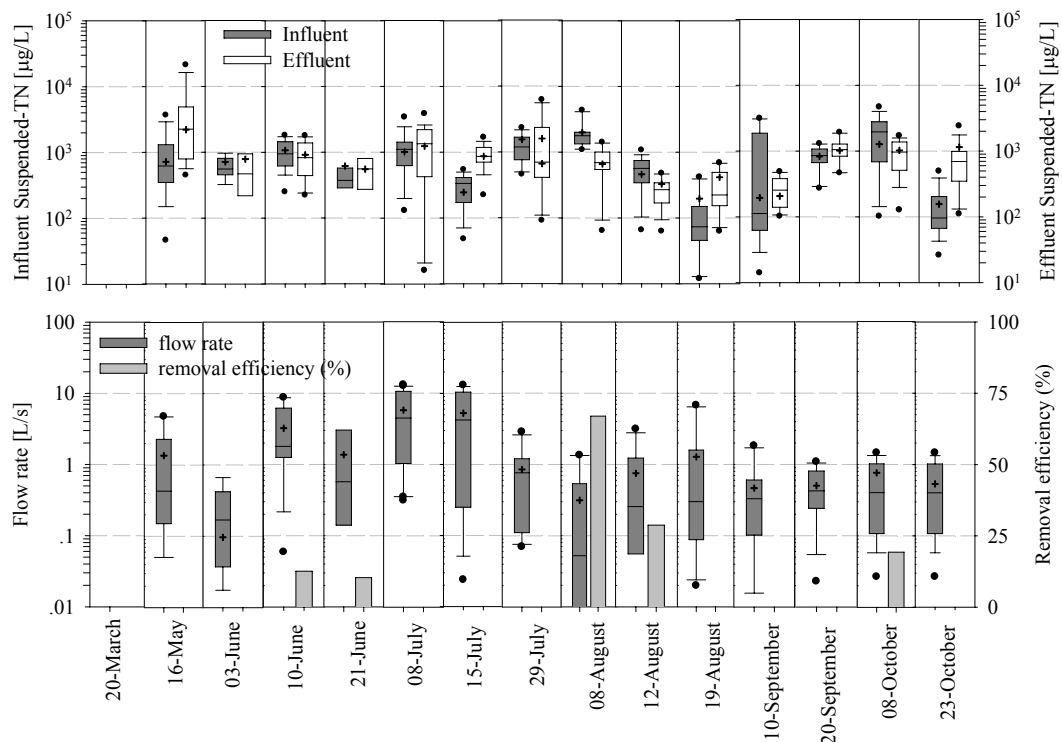


Figure 79 Coupled relationship between flow rate, influent and effluent suspended total nitrogen concentration and removal efficiency

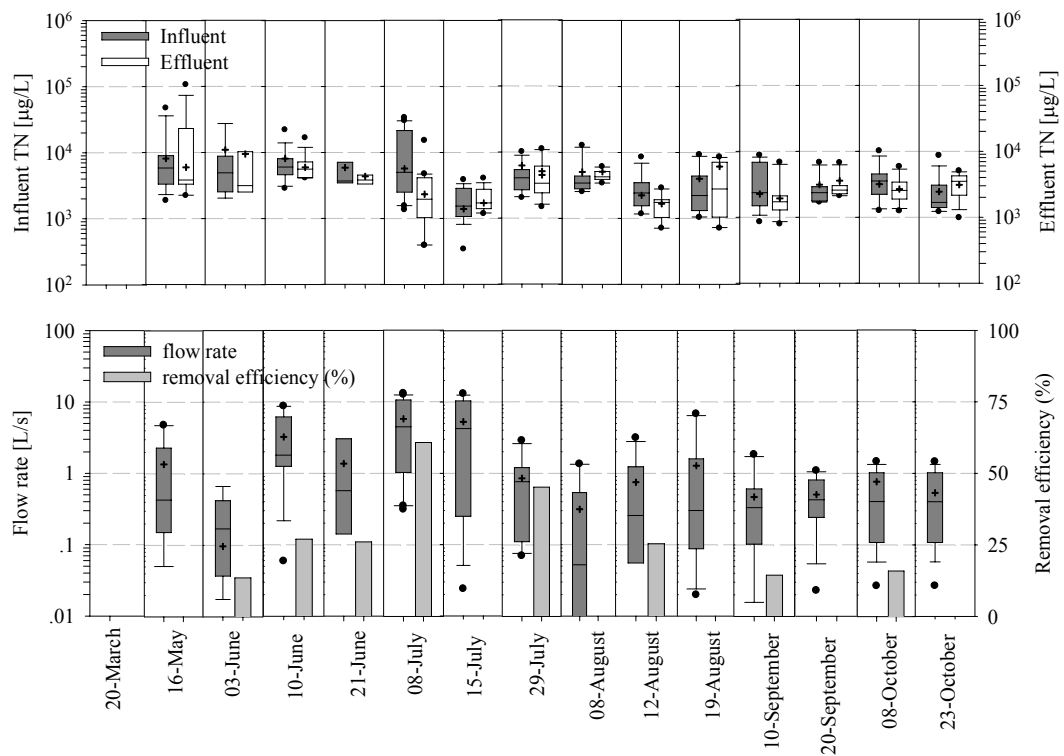


Figure 80 Coupled relationship between flow rate, influent and effluent total nitrogen concentration and removal efficiency

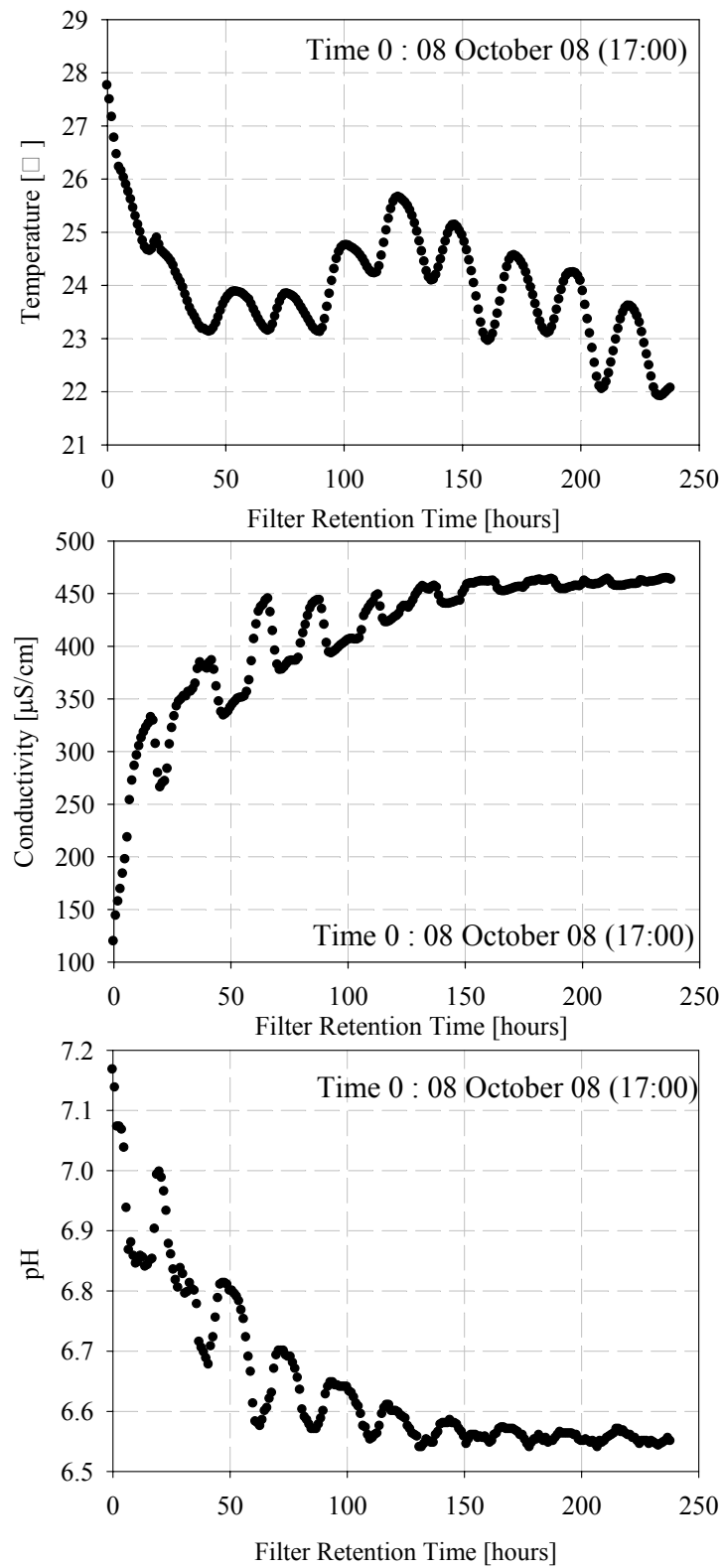


Figure 81 Temperature, conductivity and pH behavior during the filter retention time following the 8 October 2008 event

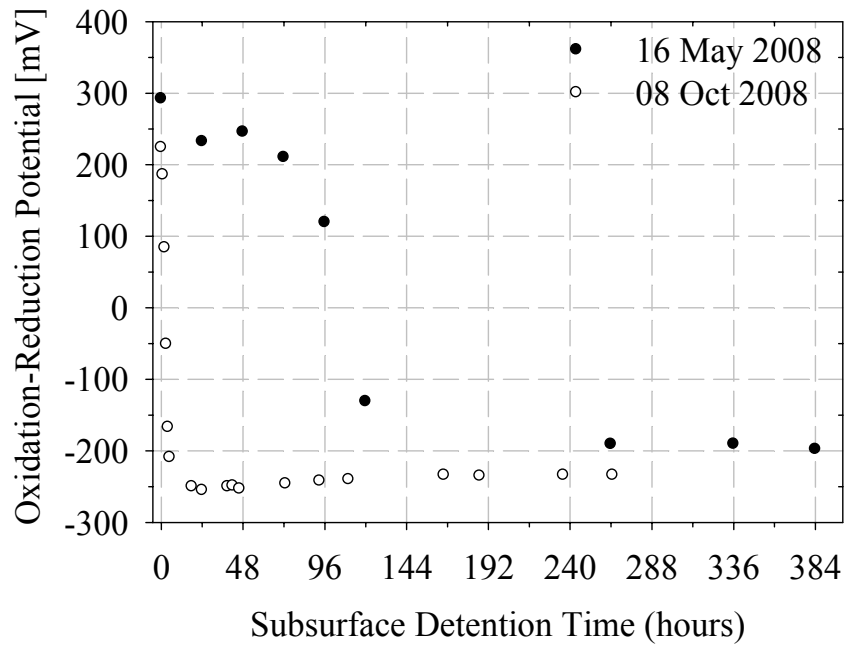


Figure 82 Redox Potential behavior of the runoff stored into the filter system during retention time

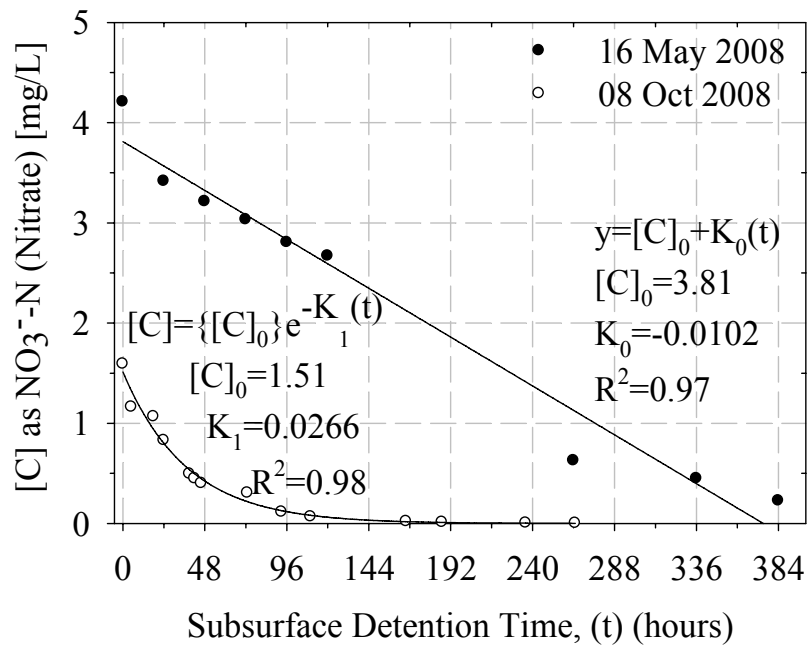


Figure 83 Nitrate-N behavior of runoff stored into the filter system during retention time

CHAPTER 6: RETROFITTING IMPERVIOUS URBAN INFRASTRUCTURE WITH GREEN TECHNOLOGY FOR RAINFALL-RUNOFF RESTORATION, INDIRECT REUSE AND POLLUTANT LOAD REDUCTION

List of Tables	6-ii
List of Figures	6-iii
ABSTRACT	6-1
INTRODUCTION	6-2
Site Information	6-2
Rainfall Data	6-2
Water Chemistry	6-2
Phosphorus	6-3
Nitrogen	6-3
Statewide Unified Stormwater Rule	6-3
OBJECTIVE	6-4
METHODOLOGY	6-4
RESULTS AND DISCUSSION OF DESIGN OPTIONS	6-6
DISCUSSION OF RESULTS.....	6-8
Pre-Development and Post-Development Pollutant Loading	6-8
Survey and Topographic Testing Analysis Results	6-9
Nitrate Decay Testing Results and Resulting Treatment.....	6-9
Subsurface Contaminant Results	6-9
Elaboration and Discussion of Design Results	6-10
Cost Analysis Results and Discussion	6-10
CONCLUSIONS AND RECOMMENDATIONS	6-11
ACKNOWLEDGEMENTS	6-12
REFERENCES	6-13

List of Tables

Table 1 Annual Runoff Load and Untreated Wastewater Load from Gainesville, Florida 1	6-18
Table 2 Reitz Union Parking Lot Specifications (existing condition of site design).....	6-18
Table 3 Rainfall Statistics for Gainesville, FL between August 1999 and July 2008	6-18
Table 4 Design Options	6-18
Table 5 Comparison of Pre-Development (FDOT 2007) and Post-Development Conditions	6-19
Table 6 Slope Arrows Table	6-19
Table 7 Existing Site Conditions	6-19
Table 8 Pollutant Load Export for Reitz Union Parking Lot Site Under Pristine Conditions.....	6-19
Table 9 Pollutant Loads for Reitz Union Parking Lot Site for Design Option 3a (6 ft LIR, BAR).....	6-20
Table 10 Summary of Costs for Design Option 2 (BAR Only).....	6-20
Table 11 Summary of Costs for LIR.....	6-20
Table 12 Summary of Costs for Design Option 3a (LIR options with BAR).....	6-21
Table 13 Cost Comparison to current mean Florida BMPs for Design Option 3a (6 foot LIR with BAR)	6-21

List of Figures

Figure 1 Total Impervious Area (TIA) in Florida and Land Use in Palm Beach County as of 2009. Note from the color legend that as % TIA increases deleterious impacts increase.	6-22
Figure 2 Topographical View of Reitz Union Parking Lot (Existing Condition)	6-22
Figure 3 Stormwater EMCs for Phosphorus, Nitrogen, and PM Fractions of 15 Storms Monitored at Design Site. SSC = Sum of Suspended (< 25 μ m) + Settleable + Sediment (> 75 μ m) PM	6-23
Figure 4 Design Option 1 Crowned Cross Section (existing condition or “do-nothing” option).....	6-23
Figure 5 Design Option 2 Cross Section (the inverted biofiltration area reactor, BAR only)	6-23
Figure 6 SSC and Hydrograph from Storm Monitored at Reitz Union Parking Lot	6-24
Figure 7 TSS and Hydrograph from Storm Monitored at Reitz Union Parking Lot	6-24
Figure 8 Event Mean PSD for Hydrograph in Figures 6 and 7	6-24
Figure 9 Consumption of Oxygen in the Subsurface BAR as Indicated through Oxidation-Reduction Potential (Redox) and Resulting Denitrification Rates as the BAR acclimates.....	6-25
Figure 10 Design Option 3a Cross Section (f.infiltration).....	6-25
Figure 11 Design Option 3b Cross Section (f. infiltration)	6-25
Figure 12 Illustration of filtration of a regulatory PSD (NJDEP) and associated PM removal as a function of particle size for CPP utilized in the proposed design.....	6-26
Figure 13 Permeable CPP width that formed the LIR (linear infiltrating reactor) design element.....	6-26
Figure 14 Cross Sectional View of BAR Design with proposed check dam.....	6-27
Figure 15 Surface Model of Existing Site with Elevation Contours	6-27
Figure 16 Typical East West Profile of Existing Grade	6-28
Figure 17 Site Slope Arrows for a Typical Existing Pavement Area on the South End of the Site	6-28
Figure 18 Slopes of Pavement from Crown to Gutter and Along East West Curb and Gutter	6-28
Figure 19 Nitrate Data Frequency Distribution in an Aerobic Batch Reactor.....	6-29
Figure 20 Lack of Nitrate Decay in an Aerobic Batch Reactor, Simulating Surface Water Conditions in a BAR subject to atmospheric re-aeration.....	6-29
Figure 21 LIR Design Option (width of CPP) Breakthrough for Dissolved Phosphorus.....	6-29
Figure 22 LIR Adsorption of Dissolved Phosphorus Over 9 Years Based on Historical Continuous Simulation Data from SWMM combined with CPP properties in VS2D.	6-30

Figure 23 Dissolved phosphorus plume formation for 6 ft LIR. The left half illustrates plume development with a bounding CPP curb. The right half illustrates plume development with runoff flowing directly into the BAR with no curb. Results are based on historical continuous simulation data from SWMM combined with CPP properties in VS2D. Each figure represents a period of two years, starting from year 0 to year 9; the length of historical data. Results also portray the importance of the curb for the LIR.	6-31
Figure 24 Hydrologic Cycle for Reitz Union Parking Lot Site Under Pristine Conditions	6-32
Figure 25 Hydrologic Cycle of Reitz Union Parking Lot with Design Option 3a (6 ft LIR, BAR)	6-32

ABSTRACT

Impervious surfaces alter rainfall-runoff relationships and resources. Rainfall-runoff (stormwater) transports significant levels of runoff and pollutant loads from impervious surfaces. In Florida, impervious surface runoff impacts hydrologic and chemical balances of water resources. Runoff chemical and particulate matter (PM) loads of concern include nutrients (nitrogen, phosphorus), PM, metals and other biogenic and anthropogenic chemicals. Altered hydrologic components impact resource waters, floodplains, wetlands, and reuse while impairing habitat. Acute and chronic concerns include contamination of resource waters such as Florida's springs. Historically, flooding dominated stormwater management objectives. While flooding is still a major concern, stormwater chemistry, loads, aesthetics and reuse are companion concerns. Promulgation of Total Maximum Daily Loads (TMDL) across the USA including Florida has occurred. While there has been decades of structural Best Management Practices (BMPs), such treatment has not kept pace with load control and reuse needs. For example, Florida's Unified Stormwater Treatment Rule promulgates a no net load increase for pollutants and runoff when comparing pre- and post-developed site conditions. With recent trends towards quantitative low impact development (LID) and green infrastructure materials there is the realization that hydrologic and pollutant loads are coupled. As such, hydrologic restoration, reuse and source control are part of any successful retrofit design that incorporates water resource conservation.

At the University of Florida, significant areas of the campus are impervious pavement; altering rainfall-runoff relationships and consequential pollutant load delivery; similar to most urban areas of Florida. At the University of Florida the impacts to Lake Alice (the main receiving water for stormwater from campus) include eutrophication. In an attempt to demonstrate the potential of LID and green infrastructure design to manage pollutant loads and reduce water resource stresses, the design quantitatively demonstrates that hydrology and pollutant load can be managed on site with site re-design; illustrating the goal of no net load increase for a long-term time series of rainfall-runoff events from 1999 through 2008. Specifically, the proposed design retrofits the Reitz Union Parking Lot with a series of design elements. A biofiltration area reactor (BAR) is lined with a bounding clay liner for localized perched water table management and managed denitrification. The BARs are downstream of a linear infiltration reactor (LIR) combining the infiltration/evaporation potential and filtration of PM by cementitious permeable pavement (CPP) that includes oxide admixture for adsorption of phosphorus and/or metals. Monthly pavement sweeping is included for source control and infiltration capacity of the CPP. Continuous simulations using SWMM (surface water) and VS2DTI (subsurface water), time series data, site geometrics and soil properties as well as a pollutant loading database indicate that design options can achieve no net load increase from pre-developed conditions. Cost estimates demonstrate that re-design is comparable to conventional construction costs while also incorporating Florida-friendly landscape. Additionally, design options yield a lower cost per pound for nitrogen and phosphorus treated, as compared to conventional Florida BMPs.

INTRODUCTION

Over the last century, Florida has experienced rapid population growth. From 1960 to 1997, the population increase in the United States averaged 1.1 percent each year; the State of Florida experienced a growth rate of 2.95 percent each year during this time period (Reynolds 2001). With this growth, Florida has experienced increased urbanization. In 1965, 1.2 million acres of land in the state were urbanized. By 1997, more than 5 million acres in the State of Florida had been converted for urban use. Between 2000 and 2020, nearly 2.6 million more acres of land are expected to be converted for urban use. Palm Beach County alone will convert 125,000 acres to urban land use (Bergstrom 2001). Figure 1 illustrates total impervious area (TIA) across Florida and, for example, the current land use and TIA in Palm Beach County. By 2010 Florida will reclaim approximately 1 billion gallons per day; primarily wastewater for non-potable uses.

Treatment and reuse of stormwater in Gainesville, Florida as well as other areas in the USA is just as important as treatment and reuse of wastewater, albeit more difficult due to episodic arrivals of large runoff volumes. Table 1 compares runoff loading and wastewater index loading.

Site Information

The project's subject site, the Reitz Union Parking Lot, is located west of Center drive, directly south of Museum drive on the University of Florida campus. During the working week from the hours of 7:30 AM until 4:30 PM, the parking lot provides parking for faculty and staff. Outside those hours, the parking lot is free for public use. The road and parking surfaces are impervious asphalt, while the sidewalks are constructed of impervious concrete. A topographical view of the site can be seen in Figure 2 and the site specifications of the study site can be seen in Table 2.

Rainfall Data

Historical rainfall time series data were utilized to characterize precipitation loadings for the site design. 1999-2008 hourly data from the Gainesville Regional Airport (GNV) station, the nearest (7 miles) rain gage with continuous recording was used (NCDC 2009). These data were validated with on-site rain gage data which was not continuous. The results were aggregated to monthly totals, summarized in Table 3. These data show a delineation of rainfall between a "wet season" and "dry season." The dry season occurs between October and May and the wet season between June and September. Based on the number and frequency of events from these data, the mean number of events on an annual basis for Gainesville, FL is 152 events.

Water Chemistry

Proper hydrologic and pollutant load characterization was required to complete this project. Rainfall-runoff data were collected and analyzed from the Reitz Union Parking Lot site from 15 storms. Of the 15 storms collected, both mass limited (first-order washoff) events and flow limited events were represented. Mass limited events exhibit a classic first flush, while in flow limited (zero order, linear washoff) events runoff load is directly related to runoff intensity at any given time. Figure 3 represents influent event mean concentration (EMC) values for TP, phosphate, TN, nitrate, ammonia, and PM fractions monitored and analyzed for the 15 storms.

Phosphorus

Phosphorus contributes to problems in the environment such as eutrophication. Phosphorus in runoff can originate from lawn and garden chemicals, animal excrement, pavement, and anthropogenic sources (Whipple 1983). Though many sources can be identified, there is variability between land uses and cover conditions, making the stormwater regulations and LID controls more challenging for design and permitting. Thus, a larger pool of hydrologic functional units (HFUs) and land use factors must be developed to predict nutrient loadings. It is also necessary that specific site field studies and monitoring be carried out to determine actual phosphorus loads and verify phase and speciation for a class of site design or land use condition.

Anthropogenic PM, biogenic material and erodible soil from the existing raised islands of the Reitz Union Parking Lot (the existing condition) can cause large PM loads and associated phosphorus to be transported across an impervious surface throughout the duration of a rain event. Phosphorus can partition to and from the surface of these materials and is transported in runoff. The relationship between the PM and phosphorus results in a distribution of TP partitioning in runoff as a function of PM size; and therefore the particle size distribution and partitioning between TP and phosphate were examined. These relationships also enable the treatment of TP-associated PM to be developed as quantitative constitutive relationship for separation of PM sizes, for example through filtration by the LIR or sedimentation by the BAR.

Nitrogen

Like phosphorus, nitrogen compounds can enter runoff through a variety of sources and can cause eutrophication in receiving waters when in excess. Nitrogen compounds are cause for concern in runoff and runoff treatment due to their high mobility over impervious surfaces and in soils. Sources of nitrogen in stormwater runoff include fertilizers, animal waste, organic matter, automobile exhaust, natural nitrogen cycling, and atmospheric deposition (Hsieh et al. 2007). At this site atmospheric nitrogen accounts for 20% of the total nitrate load in runoff. Ecosystems receiving excess nitrogen and phosphorus loads are likely to undergo eutrophication; typically involving unchecked nutrient stimulus to biological systems such as algal blooms. The bloom requires high levels of available oxygen, leaving diminished oxygen for fish and other species in the water. As a result, there is loss of biodiversity which may become irreversible (Mayer et al. 2005). If high levels of nitrates percolate to groundwater, a major potable water source, young children are at risk for “blue-baby” syndrome. In the body of these children nitrates are converted to nitrites. Nitrites inhibit the blood cells to carry oxygen to vital parts of the body such as the brain. As a result brain damage can occur (Carpenter et al. 1998). Transport of nitrate in subsurface formations, especially in Florida’s prevalent Karst areas is significant. Many pristine springs throughout Florida, for example, Wakulla Springs just south of Tallahassee have been significantly damaged due to eutrophication. The proposed Unified Stormwater Rule addresses nitrogen as it does phosphorus, requiring pre-developed nutrient loads to be met. A review of regulations that have led to the proposed Unified Stormwater Rule is reviewed.

Statewide Unified Stormwater Rule

As a result of growth, Florida is still subject to the effects of increased nutrient loading into surface water and groundwater, despite current regulations. Currently, 45% of Florida’s known impaired waters have impairments associated with nutrients (Statewide Stormwater Treatment Rule Development Background 2008). With these problems, it is increasingly clear that new unit

operations and processes, UOP (as opposed to conventional BMPs), LID and source control must be developed to better facilitate stormwater management. The proposed rule for site development requires post-development pollutant loads not to exceed the pre-development loads (Statewide Stormwater Treatment Rule Development Background). Nutrient loading is specifically defined as TP and TN. Since TP and TN are generally limiting factors in stormwater runoff, it is implicitly (but not with certainty) assumed that treating these factors will also provide adequate load reduction for all the other contained pollutants. Previously, post-development loadings were the only loads considered and reduced. Now, the new proposal encourages the use of UOP treatment trains and LID to meet the unique conditions of a given pre-developed land use. The UOP and LID options can provide the opportunity for direct stormwater reuse and indirect reuse with a focus on hydrologic restoration; and also pollution prevention through source control

OBJECTIVE

The primary project objective is to combine the benefits of green infrastructure (cementitious permeable pavement, CPP), biofiltration, hydrologic restoration and denitrification to manage hydrologic and pollutant load control for the Reitz Union Parking Lot stormwater. This management through re-design of the existing condition to create a passive LID system with green infrastructure will result in the re-designed system's ability to meet pre-development load conditions. The selected design alternative will be able to provide hydrologic restoration, removal of nutrient loads and PM at a cost less than typical Florida BMPs and equivalent to conventional design and construction for surface parking systems. The system provides indirect reuse with evapo-transpiration and significant infiltration and recharge capacity of surficial soils.

METHODOLOGY

To accurately model the existing topography and infrastructure, the site was surveyed. The location and elevation for a proximate benchmark was obtained from the University of Florida Physical Plant (UFPPD) and point elevations and coordinates were obtained through a 10 foot horizontal survey grid. The geodetic location of the benchmark was in the NAD83 Florida State Plane North zone coordinate system. AutoCAD® was used to assist with the design process; allowing for creation of 2D and 3D surfaces for export to surface and subsurface numerical models as well allowing the visualization rendering to be produced. The elevations recorded in the field were input into a database. Linear interpolation between points was required to calculate all site elevations. State Plane Northing and Easting coordinates were computed for all elevations. Additionally, Light Detection and Ranging (LIDAR) data was obtained and added to the data set, providing the outlying area's existing topography. Survey and LIDAR data were used to create a Triangulated Irregular Network (TIN) surface of the site. With the 3D surface model slope vectors of the existing surfaces were determined. ArcGIS as a geographic information system was chosen providing several project requirements; an industry standard with a large user base, ability to import geospatial data from AutoCAD with ability for analysis of geospatial data, export of shape files and export to the stormwater management model (SWMM). ArcGIS was used to delineate subcatchments for SWMM, calibrated with existing site data.

USEPA SWMM 5 was chosen as an unsteady continuous model providing hydrologic and hydraulic routing. The model is a rigorous unsteady hydrologic model with over four decades of

utilization world-wide, having been originally developed at the University of Florida. SWMM is a comprehensive unsteady hydrology and hydraulics model in contrast to peak flow models that have been adapted to provide approximate transience and hydrologic components. SWMM capabilities include transient and historical rainfall for continuous simulation, evapotranspiration, depression storage, variably-saturated infiltration models for the CPP, BAR and existing soil layers, percolation of infiltrated water into groundwater layers, and bidirectional flow between groundwater and the drainage system or nonlinear reservoir routing of overland flow. Other useful functions include very flexible system size constraints, wide compatibility with field equipment, modeling of elements such as storage/treatment units and flow dividers, applying external flows and pollutant load inputs from surface runoff, and modeling various flow regimes. User-defined load components can be included, such as dry-weather pollutant buildup, pollutant washoff, direct contribution of rainfall deposition, reduction in washoff load due to UOPs, LID or BMPs, routing of pollutant loads, or changes in loads through treatment in storage units or by processes in pipes and channels. The Reitz Union Parking Lot catchment was modeled using a total of 89 subcatchments comprised of varying hydrologic function units (HFUs) and properties. Twenty-one subcatchment descriptors were provided for SWMM. These descriptors, including area, percent slope and infiltration model (the Green-Ampt model), were determined for the site. In the case of these analyses, three HFUs were specified, forming 24 attributes for each of the subcatchments. A basic object in SWMM is the rain gauge. Six attributes and a time interval of fifteen minutes were specified. In order properly retrofit the Reitz Union Parking Lot, historical rainfall data were used. The rainfall data available for Gainesville are from the NOAA National Climatic Data Center (NCDC). Rainfall was utilized from a NOAA gauge at the Gainesville Regional Airport for 1999 to 2008. A time step of one hour was used from the NCDC, however shorter time steps were needed to match the catchment time of concentration. The one hour NCDC data were disaggregated into 15 minute intervals to match the catchment. The United States Geological Survey (USGS) VS2D numerical model was used to further examine and solve variably-saturated, 2-D flow problems in the BAR and CPP porous systems as green infrastructure. The model essentially combines mass conservation with Darcy's law. The model is useful in predicting the movement of water and solutes in variably-saturated flow and for transient or continuous simulations to predict the effects of green infrastructure retrofits on the quantity and chemistry of water entering the subsurface. VS2D is capable of modeling complex non-linear infiltration into porous systems with abruptly-changing porosity and hydraulic conductivity; analyzing 1-D and 2-D problems with planar and cylindrical geometry; capable of calculating adsorption or ion exchange to simulate solute movement in the domain and capable of simulating evapo-transpiration. VS2D was utilized to examine the variably-saturated infiltrating/percolating transport of runoff through the CPP and BAR and predict the fate of phosphate and nitrate in these green infrastructure systems and in the subsurface soils.

For each green infrastructure design option, a 2-D cross-section including the impervious pavement, the pervious LIR and the BAR was created for each LIR width. Material and fluid flow properties and material-solute interaction properties were determined; either measured for this site; for example hydraulic conductivity of porous systems, or from previous material property datasets. Van Genuchten parameters were used to solve the flow equation and the Freundlich isotherm and kinetics parameters were used to equilibrium phosphorus adsorption by the CPP. Adsorption isotherm, kinetics and breakthrough data were utilized for the BAR and LIR systems. Recharge periods between runoff events and intermittent dry days were generated in

SWMM from the historic data and utilized in the VS2D model. The boundary condition at the top of each surface was a inflowing flux during a rainy recharge period and evapo-transpiration (ET) during a dry recharge period. Inflow fluxes for each wet period were taken from SWMM results. ET values based on 1999-2008 data were used, each for summer and winter months.

RESULTS AND DISCUSSION OF DESIGN OPTIONS

There are many pollutants that are elevated in urban stormwater as a result of impervious design and resulting conversion of rainfall to runoff. Both the volume and load must be managed in-situ in order to ensure a well-designed hydrologic restoration system with reduced load discharges. The new Statewide Unified Stormwater Rule stresses the utilization of LID and UOPs that promote hydrologic restoration and no-net load increase from pristine conditions. This proposed design focuses on LID and green infrastructure materials for consideration of constructing a UOP treatment train that can combine both those efforts by using a combination of CPP with an aluminum oxide admixture, a BAR, clay isolation, denitrification in the subsurface environment of the BAR to treat the runoff from the site and provide indirect reuse. There are three design options that were selected for this project as summarized in Table 4, with a focus on Option 3a.

Illustrated in Figure 4 is a typical raised island cross sectional view of the Reitz Union Parking Lot in the current conditions, with no BARs, no addition of CPP and no clay liner to generate water table management for denitrification.

While design option (1) requires no re-design or reconstruction, this option provides no treatment for nitrogen, phosphorus, PM or hydrologic restoration as compared to pre-developmental loads. PM (for example, measured as total suspended solids, TSS), TP and TN loads are significantly increased as a result of (1) pavement and (2) raised islands that drain to the impervious pavement with the transport of associated biogenic nutrients and PM from the islands.

These pollutant concentrations add to the argument that other design options and elements must be considered. For Design Option 2, the raised islands will be transformed into inverted BARs. A cross sectional drawing can be seen in Figure 5.

This design option utilizes the natural slope of the site to centralize runoff from the watershed in the inverted BAR sections of the parking lot. At this point, the runoff will infiltrate into the BAR through the soil and filter out the suspended PM ($< 25 \mu\text{m}$) while settling the larger settleable and sediment PM. A confining clay layer is included to allow for subsurface denitrification.

As shown in Figure 6 and Figure 7, only a small mass fraction of the PM (as suspended sediment concentration, SSC) associated with runoff is suspended PM (measured as TSS, $< 25 \mu\text{m}$) during the passage of the majority of the hydrograph (from the southwest catchment of the site). Due to this, most of the sediment ($> 75 \mu\text{m}$) and settleable PM ($> 25 \mu\text{m}$) transported to the BAR will settle within the BAR and not be transported offsite by runoff.

The particle size distribution (PSD) associated with this storm, and characteristic of the site, for the sub 1000 μm PSD is shown below. The site-mean PSD is shown to similar to a regulatory NJDEP PSD. This design will also treat the phosphorus species that are bound to sediment PM (which accounts for nearly 70% of all TP species); with the balance of the phosphorus will be dissolved and by adsorbed or precipitated in the CPP. Once the runoff is infiltrated into the subsurface another constituent of concern will be nitrate, which requires denitrification.

This PSD fits a regulatory gradation typical of the East Coast of the USA (a hetero-disperse NJDEP gradation), shown for comparison. This PSD is utilized later in this study to examine filtration of PM through the CPP. PM larger than 1000 μm is strained on the surface of the CPP and removed by street cleaning.

Nitrogen species in the runoff will be treated through isolation and denitrification. The isolation of nitrate species will prevent the potential of nitrate transport into other receiving waters (surface and groundwater) and potential eutrophication. This will be possible as a result of the sodium bentonite clay liner that will be constructed under the BAR. This clay liner will act to isolate nitrogen species that are remaining within the water; trapping these species and ensuring that these extra loads do not leave the site. Additionally, at a depth around 1.5 feet, anoxic conditions will occur and denitrification will occur. The results for redox and denitrification rates are shown in Figure 9 for a BAR after the 2nd and 14th storm loading to a monitored BAR.

The biofiltration system was loaded by 15 rainfall events from the southwest catchment of the existing source area watershed and utilized only the microbial consortium present washed-off in the existing rainfall-runoff. Once the microbial consortium consumed oxygen, nitrate served as the electron acceptor and was denitrified to N_2 gas. Kinetics of denitrification $\{\text{NO}_3^- (\text{aq.}) \rightarrow \text{N}_{2(\text{gas})}\}$ in the BAR subsurface during the wet season are based on rainfall-runoff collected from the subject source area watershed. Results illustrate that as the microbial consortium in the subsurface biofiltration system acclimated, the kinetics of denitrification transitioned from a consistent zero-order reaction (k_0) after eight rainfall-runoff events to a more rapid and consistent first-order reaction (k_1).

While the BAR design can denitrify and provide settling, it does not reduce phosphorus or PM below pre-developed conditions. The phosphate species will still be present in the runoff and not be treated by the BAR alone, given the silica-based silty-sand of the site. For this reason, Design Option 3 will utilize the potential of CPP (cementitious permeable pavement with an aluminum oxide admixture as part of the mix design) to adsorb phosphorus and filter PM. In Design Option 3, a permeable pavement strip of selected widths (2, 4 or 6 feet) can be added along the sides of all the BARs as seen below in Figure 10, or completely replace the entire parking lot with CPP to distribute the runoff throughout the entire area, as seen below in Figure 11 for Design Option 3b.

CPP is a low impact development material and green infrastructure system that maintains rainfall-runoff control. This green infrastructure material allows for infiltration and ultimately reduces runoff, treats infiltrating runoff, and reduces nutrient, sediment and thermal pollution

while providing the load-carrying capacity of conventional concrete pavement. Figure 12 illustrates the sub 1000 μm PSD and removal efficiency associated with PM levels.

Using Figure 12, the removal efficiency of PM by CPP was determined. The efficiency of CPP decreases as particle size decreases. However, as illustrated in Figure 7, TSS for the site is approximately 50 mg/L, while the sediment fraction ($> 75 \mu\text{m}$) dominates the PM loadings.

Allowing infiltration restores the natural hydrologic cycle of the area by permitting evaporation from the CPP and evapo-transpiration from the BAR. Additionally, CPP leaches beneficial calcium and alkalinity, as compared to permeable asphalt which leaches phenolic compounds, PAHs, endocrine disrupting compounds (EDCs) and thermal loads. In Design Option 3, the CPP used will have an aluminum oxide admixture with an 80%⁺ removal efficiency for total phosphorus. Of course, with any working unit operation and process, there must be some level of maintenance involved. Maintenance for CPP would include either a vacuum or mechanical street sweeper. Since the CPP acts as a filtration system, there will be a high level of PM that fills the CPP pores if not maintained. By pavement cleaning with street sweepers for CPP, hydraulic capacity can be maintained. Frequencies of two to three times per year are sufficient (Sansalone et al 2008) to maintain hydraulic performance, with more frequent for load source control.

A variable in Design Option 3a is the variable width (X) of the CPP that separates the current pavement from the BAR. A visual explanation is shown in Figure 13.

By utilizing SWMM (Storm Water Management Model) simulations for widths of 2, 4 and 6 feet, data was collected to create a chart relating the difference between different widths of the CPP strip and how these design changes generate runoff from the site. By calculating the minimum width for maximum runoff infiltration, a design option decision was made. Additionally, three check dams were added per island row (400 ft) to ensure maximum storage of runoff and decrease the likelihood of flooding due to the slope of the BAR surfaces. An image of a check dam section can be seen in Figure 13. No flooding occurred based in the historical data.

DISCUSSION OF RESULTS

Pre-Development and Post-Development Pollutant Loading

In order to meet the new Statewide Unified Stormwater Rule, it is necessary to compare pre- and post-development runoff volume and quality. A report by Harper, 2003, recommended pristine condition EMC values now utilized by Florida Department of Environmental Protection. In addition, the Reitz Union Parking Lot site studies provide current (post-development) runoff EMC values. TSS, TP, TN, Copper (Cu), Lead (Pb), and Zinc (Zn) values are shown in Table 5

It is important to consider that the post-development pollution loadings and runoff are significantly higher due to an increase in impervious surface area. The added impervious surfaces have increased the amount of runoff from a given watershed and altered the hydrologic cycle. With the LIRs and BARs added to the site, infiltration amounts will increase and loadings will be more evenly distributed; lowering the potential for eutrophication in receiving waters.

The following sections will describe site characterization results, followed by detailed descriptions of design performance for (1) retrofitting depressional storage in the form of bioretention (BAR); (2) retrofitting engineered CPP of various widths with bioretention; (3) and installing CPP on the entire site. Analysis of the design options provides an opportunity to compare the site discharge pollution loads post-retrofit to both pristine and current conditions.

Survey and Topographic Testing Analysis Results

With survey data analyzed and input into AutoCAD® Civil 3D, a complete 3D surface model of the site with contours was created and shown in Figure 15. The surface model accurately shows the existing site topography. The surface model shows sharp rises in elevation at all curbs, along with a crowned paved parking surface. All four parking lanes have similar vertical profile geometry. Figure 16 shows the existing grade of a typical east west parking lane. Using the surface model created from the survey data, slopes of the existing surface were determined. With AutoCAD Civil 3D the varying slopes over the site by color variation are illustrated.

The arrows illustrated in Figure 17 indicate that the pavement slopes trend toward the existing curb and gutters. The typical slopes from the crown toward the gutter on the existing condition pavement ranged from 0.00% to 3.29%.

Table 6 tabulates the slope values according to the colors displayed in Figure 16. To examine the mean slope values over longer distances slope algorithms were utilized from AutoCAD Civil 3D was used. Slope values of the pavement along the gutter for the east west parking lanes range from 3.0% to 0.0%. Figure 18 shows a section of the site with slopes for the pavement from the crown to gutter and along the east west gutters. \

Nitrate Decay Testing Results and Resulting Treatment

While Figure 9 illustrates that denitrification occurs in the subsurface BAR under anaerobic conditions; the fate of nitrate was also examined in an aerobic batch reactor. Results in figure 19 illustrate that the data followed a normal distribution with a mean of 1.4 mg/L; representative of the site. The resulting nitrate data are normally distributed at a 95% confidence level. Figure 20 illustrates nitrate change as a function of time. A nearly horizontal trend line indicates that in an aerobic batch reactor such as the BAR after a runoff event there would likely be no decrease in nitrate. The mean results across 80 hours are nearly equal to the initial nitrate value.

Since nitrate does not decay under aerobic conditions, it was important to ensure the BAR subsurface would undergo anaerobic conditions in the perched water table conditions of the BAR subsurface. Anaerobic conditions in the BAR subsurface will allow for denitrification to occur.

Subsurface Contaminant Results

As expected, there is a gradual increase in phosphorus breakthrough from the CPP over time. Figure 21 shows a breakthrough around 5.5 years for Design Option 3a (2 ft LIR). At this point, total phosphorus concentrations subsurface begin to exceed pristine conditions; although 2.5 years are required before any concentration below the CPP begins to appear. When changed to the 4 foot LIR, the design takes about 5 years before there is any phosphorus concentration under the CPP. The 6 foot LIR reaches pristine-level concentrations after 14 years. The 6 foot LIR

design was coupled with monthly sweeping to recover PM-based TP. Results produced a design and design life that could achieve pristine-level conditions for approximately 20 years.

Without the curb on the side, the potential for runoff to overflow in the native silty-sand of the BAR without infiltration through the LIR increases, and the level of treatment decreases. The LIR on the right side of each figure has been modeled without the curb. The curb as a design element illustrates the importance of training the flow to infiltrate through the CPP. As time progresses, the effects of the absence of the curb are vividly seen and can be compared to its presence on the left hand side model with a curb with flow trained to infiltrate through the CPP. It should also be noted that the influent concentration used for these simulations does not take into account the potential reduction due to regular, well-planned street-sweeping practices.

Elaboration and Discussion of Design Results

Applying 9 years of the historical rainfall series (1999 – 2008) to the calibrated SWMM model yielded an overall rainfall/runoff ratio of 10:6.2 (Table 7) for the existing impervious condition.

The rainfall data from Gainesville during the period of August 1999 through 2008 were used for all the modeled design scenarios. By using the same historical rainfall and pollutant load data from the site, but varying design element combinations of a BAR and various CPP surface widths, a series of overall efficiency indices and load evaluations could be created. These design evaluations were used in making comparisons to the catchment under pristine conditions. Using pristine forest/rangeland conditions, the pre-development hydrologic cycle for the Reitz Union Parking Lot was produced as shown in Figure 24. Additionally, using event mean concentrations (EMCs) for a “pristine” site as provided by Harper and Baker (2003), pollutant loads from the site under pre-development (pristine) conditions was modeled. Loads were calculated assuming runoff from the pristine site contained EMCs as identified in the Harper and Baker report. While recognizing the controversy over such values; pristine values as reported by Harper and Baker have been required by FDEP (Florida Department of Environmental Protection). The use of prescriptive “pristine” conditions offers a precise metric, albeit a metric of uncertain accuracy at this time, to gauge design option load performance. Tables have been built to summarize the hydrologic results for design options as compared to “pristine” (pre-developed) conditions. Figure 24 illustrates the hydrologic budget for “pristine” conditions. Only the chosen design option (Design Option 3a, a 6 foot LIR with BAR) is illustrated herein.

As expected, there is a strong correlation between the extended LIR widths and decrease of phosphorus, nitrogen and PM (as TSS) loadings. By expanding the width of the LIR to 6 feet, the design is capable of treating all the runoff pollution loads down to levels lower than pristine conditions and achieving a 20 year design life with regular pavement cleaning. Other designs did not meet pristine conditions for all pollutants and had a shorter design life.

Cost Analysis Results and Discussion

Table 10 summarizes the costs for Design Option 2, which is the design of the BAR only, to provide a cost breakout for the BAR design element. Capital costs were calculated and then added to the annual O&M (operation and maintenance) costs over a 20 year period to find the net

present value (NPV) of the cost. Engineering fees and contingency fees were then added giving a total cost for the BAR as a design element for the site of \$154,900.

Table 11 summarizes the costs for Design Option 3a, which includes retrofitting the parking lot with LIR options of 2 feet, 4 feet, or 6 feet width. Capital costs were calculated for each width, and added to the annual O&M costs over a 20 year period. Results yield the net present value of cost. Engineering fees and contingency fees were then added to give a total cost of \$61,510, \$116,140, and \$170,880 for widths of 2 feet, 4 feet, and 6 feet respectively.

Table 12 summarizes costs for Design Option 3a, which includes retrofitting the parking lot with an LIR of varying width, and a BAR. Costs for 2 foot, 4 foot, and 6 foot LIR were computed, and then for each width the cost for the BAR were added to find the overall cost. The overall costs for Design Option 3a for 2 feet, 4 feet, and 6 feet widths were \$216,410, \$271,040, and \$325,780 respectively.

Table 13 summarizes the cost to remove nitrogen and phosphorus using Design Option 3a to the mean costs of current conventional BMPs in Florida. A list of different BMP projects from around the state of Florida was compiled by FDEP, and the cost to remove nitrogen and phosphorus per pound per year was computed from the FDEP database. The average of these values was computed and compared to the cost to remove nitrogen and phosphorus per pound per year using Design Option 3a (and the other Design Options). Design Option 3a with a 6 foot LIR and BAR had a balance between treatment efficiency that met “pristine” load reduction levels and cost effectiveness with cost values that were 13% lower for nitrogen, and 15% lower for phosphorous removal than the current mean Florida BMP.

CONCLUSIONS AND RECOMMENDATIONS

Ultimately, if any pavement area, whether the Reitz Union Parking Lot as illustrated herein, a commercial or retail parking area or a highway/roadway system, is to be constructed or retrofitted using a BAR/LIR system, it is recommended to drain the area to regularly spaced engineered treatment islands similar to the BAR, where infiltration, evapo-transpiration, storage and treatment can occur with upstream treatment facilitated by engineered CPP. With such hydrologic communication, a target level of hydrologic restoration and load reduction can be achieved; with benefits to components of the hydrologic cycle; and ultimately provide indirect reuse of stormwater. Such benefits further include reductions in pollutant loads and concentrations with reduced thermal loads. Design components such as the BAR also provide beneficial aesthetic with Florida-friendly landscape in an otherwise hot expanse of asphalt pavement. Additionally, the engineered cementitious permeable pavement (CPP) eliminates the deleterious environmental and thermal impacts of asphaltic binders while providing beneficial alkalinity to the infiltrated runoff. Results illustrate that the cost of such green infrastructure and LID is on par with conventional construction, even before the costs of pollutant and runoff load reduction are included. When load reduction costs are accounted for the system construction costs are lower; and costs per unit load of nutrient treated are lower than current mean Florida BMP costs. This study has illustrated the benefits of matching green infrastructure design elements to target specific pollutants based on pollutant-specific chemistry and known UOP

mechanisms. Results are also quantitative and illustrate that LID or sustainable urban drainage practices and designs can be quantified; removing such practices from the category of “black-box” systems. For example the bounding clay layer design element within the BAR allows for denitrification utilizing the natural consortium of microbes in runoff and kinetics are illustrated. At the same time, a simple modification of CPP as a filtration medium with an aluminum oxide admixture provides an interface for the removal of phosphorus that would otherwise produce rapid breakthrough from a stand-alone BAR design element. The use of engineered CPP or media systems with oxides provide significant benefits compared to many available bio-filtration media that have been shown to leach nutrients. The combined system of a BAR and LIR with CPP has the additional benefit of providing a more comfortable urban environment for humans and local ecology, minimizing the local heat island impacts, and allowing more evaporation and phyto-pumping, and reduced overall energy utilization. Utilizing this type of system in different ways can create a variety of pollutant load reductions, summarized in Table 14.

Utilizing continuous simulation models (SWMM and VS2D), physical and chemical properties of the green infrastructure elements and physical modeling of these elements, Design Option 3a (6 ft LIR and BAR) is the Design Option that meets load reduction for phosphorus, nitrogen and TSS to achieve requirements of the promulgated Unified Stormwater Rule where post-development loads cannot exceed pre-development (“pristine”) loads. By creating a quantitative and targeted approach to hydrologic and load control the benefits of CPP, bio-filtration, infiltration, natural assimilation, ionic isolation, and denitrification, the project objectives can be achieved. This design utilizes LID and green infrastructure design in a fashion that enables this site, representative of many similar paved urban sites in Florida, to fit the new Statewide Unified Stormwater Rule.

In addition to the added benefit of nutrient removal, this design is also cost and energy effective. It is able to treat phosphorus down to a level below pre-development conditions and maintain a cost that is more economical than the mean Florida BMP. Nitrogen is also capable of being treated down to levels below pre-development conditions while maintaining a cost that is more economical than the mean Florida BMP. To summarize, Design Option 3a (6 ft LIR and BAR) achieves project design objectives at a cost that is competitive with conventional construction and mean Florida BMP treatment costs.

ACKNOWLEDGEMENTS

Dr. Christian Berretta, Felipe Behrens, Tracy Fanara and Hao Zhang for all their work in determining the EMC values that characterized the Reitz Union Parking Lot. Giuseppina Garofalo for her work in compiling ten years worth of rainfall data for the City of Gainesville, FL; Eban Bean for allowing us to use the double ring infiltrometer testing equipment; Chuck Hogan from the University of Florida Physical Plant Department for all the utility data and Ron Osteen and Darrin Vogeli for all the professional cost analysis quotes.

REFERENCES

- (1981). Chapter 62-25 Regulations of stormwater discharge. Retrieved March 18, 2009, from Florida Department of Environmental Protection Web site: <http://www.dep.state.fl.us/legal/rules/surfacewater/62-25.pdf>
- (1998). FGDL Search/Download Data USGS 1:24,000 ROADS. Retrieved February 27, 2009, from U.S. Geological Survey Web site: <http://www.fgdl.org/metadataexplorer/explorer.jsp>
- (2007, November 14). FGDL Search/Download Data Generalized land use derived from 2006 parcel specific land use – FDOT District 4. Retrieved February 25, 2009, from University of Florida GeoPlan Center Web site: <http://www.fgdl.org/metadataexplorer/explorer.jsp>
- (2007). FGDL Search/Download Data National Highway Planning Network. Retrieved March 1, 2009, from U.S. Department of Transportation, Bureau of Transportation Statistics, Federal Highway Administration <http://www.fgdl.org/metadataexplorer/explorer.jsp>
- (2008, July 22). Florida Department of Environmental Protection. Retrieved February 10, 2009, from Statewide Stormwater Treatment Rule Development Background Web site: <http://www.dep.state.fl.us/water/wetlands/erp/rules/stormwater/background.htm>
- (2008, November 14). FGDL Search/Download Data Florida Scenic Highways and Byways 2008. Retrieved February 27, 2009, from Florida Department of Transportation Web site: (1998). FGDL Search/Download Data. Retrieved February 27, 2009, from U.S. Geological Survey Web site: <http://www.fgdl.org/metadataexplorer/explorer.jsp>
- (2009). Cost Books. Retrieved March 15, 2009, from Cost Works RS Means Web site: <http://www.meanscostworks.com/MyCostBook/MyCostBookHome.aspx>
- (2009). FGDL Search/Download Data MAJOR ROADS - STATEWIDE - JANUARY 2009 . Retrieved March 2, 2009, from U.S. Department of Transportation, Bureau of Transportation Statistics, Federal Highway Administration <http://www.fgdl.org/metadataexplorer/explorer.jsp>
- (2009). Generalized Future Land Use. Retrieved March 10, 2009, from City of Gainesville <http://www.cityofgainesville.org/LinkClick.aspx?fileticket=IsEzXXmqreQ%3d&tabid=259>
- (2009, January). Statewide Stormwater Unified Rule. Retrieved February 10, 2009, from South Florida Water Management District Web site: https://my.sfwmd.gov/pls/portal/docs/PAGE/Common/PDF/Splash/SPL_STORMWATER_RULE.PDF
- Arcement, G. Jr. (1984). "Discharge and Sediment Data for Baratavia Pass, Louisiana." *U.S. Geological Survey Open-File Report 84-701*. United States Geological

- Survey, Washington D.C., pp 1-22.
- ASCE (American Society of Civil Engineering) and WEF (Water Environment Federation) (1992). *Design and Construction of Urban Stormwater Management Systems*. ASCE Manuals and Reports of Engineering Practice No. 77, New York.
- Bergstrom, C. (Ed.). (2001). Current Issues Associated with Land Values and Land Use Planning: Urbanization and Land Use Change in Florida and the South: Southern Rural Development Center and Farm Foundation.
- Carpenter, S., Caraco, N., Correll, D., Howarth, A., Sharpley, A., & Smith, V. (1998). Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen. Ecological Applications, 8(3), 559-568.
- Causseaux & Ellington (2000). *University of Florida Stormwater Management Master Plan and Permit Application*. University of Florida Physical Plant Department, Gainesville FL.
- Chow, V. T., Maidment, D. R., & Mays, L. W. (1988). Applied Hydrology. New York: McGraw Hill.
- DeWiest, D., & Livingston, E. (2000). *The Florida Stormwater, Erosion, and Sedimentation Control Inspector's Manual*. Florida Department of Environmental Protection, Tallahassee, FL. <http://www.dep.state.fl.us/water/nonpoint/ero_man.htm> (March 6, 2005).
- Dunne, T., & Leopold, L. (1978). *Water in Environmental Planning*. San Francisco: W. H. Freeman.
- Exum, L., Bird, S., Harrison, J., & Perkins, C. (2005). Estimating and Projecting Impervious Cover in the Southeastern United States. Environmental Protection Agency.
- Fetter, C.W. (1999). *Containment Hydrology*. Upper Saddle River, NJ: Prentice Hall.
- Florida Department of Transportation. (2007). Application and Assessment for the Florida Airports Stormwater Study (State of Florida State Airport Stormwater Study).
- GeoSyntec Consultants, Oregon State University, University of Florida, The Low Impact Development Center (2006). *Evaluation of Best Management Practices and Low Impact Development for Highway Runoff Control- User's Guide for BMP/LID Selection 2006*. National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, D.C. <<http://www.iwaponline.com/wio/2006/01/wio200601WF02SW1.htm>> (June 26, 2006).

- Gucker , Corey L. (2008). *Typha latifolia*. Retrieved March 1, 2009, from U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory Web site: <http://www.fs.fed.us/database/feis/plants/graminoid/typlat/all.html>
- Harper, H., and Baker, D. (2003). Evaluation of Alternative Stormwater Regulations for Southwest Florida, Final Report (Revised Sept. 8, 2003), Environmental Research & Design, Inc.
- Horton, R. E. (1940). An approach toward a physical interpretation of infiltration capacity. Soil Science Society of America Proceedings, 5, 399-417.
- Hsieh, C., David, A., & Needelman, B. (2007). Nitrogen Removal from Urban Stormwater Through Layered Bioretention Columns. Water Environment Research, 79, 2404-2411.
- Korhnak, L.V. (1996). "Water, Phosphorus, Nitrogen, and Chloride Budgets for Lake Alice, Florida and Documentation of the Effects of Wastewater Removal." M.S. Thesis, Dept. of Fisheries and Aquatic Sciences, University of Florida. Gainesville, FL.
- Lappala, E., Healy, R., & Weeks, E. (1987). *Documentation of Computer Program VS2D to Solve the Equations of Fluid Flow in Variably Saturated Porous Media*. Denver: U.S. Department of the Interior.
- Li, Y., Buchberger , S. G. , & Sansalone , J. J. (1999). Variably saturated flow in storm-water partial exfiltration trench . *Journal of Environmental Engineering* . 125:6, 556-565.
- Livingston, E., (2008) TMDL Costs of Florida BMPs for Nitrogen and Phosphorus, Bureau of Watershed Restoration, Florida Department of Environmental Protection, Tallahassee FL.
- Liu, B., Berretta, C., Gnecco, I., Ying, G., & Sansalone, J. (2009). Control of Highway Stormwater During Event and Inter-Event Retention in BMPs", Transportation Research Record (in publication).
- Liu , S., Graham, W. D., & Jacobs , J. M. (2005). Daily potential evapotranspiration and diurnal climate forcing: influence on the numerical modeling of soil water dynamics and evapotranspiration. *Journal of Hydrology*. 309, 39-52.
- Low Impact Development Center, GeoSyntec Consultants, University of Florida, and Oregon State University (2006). *Low Impact Development Design Manual For Highway Runoff Control-Design Manual*. Final Report to the National Cooperative Highway Research Program. Transportation Research Board, National Research Council, Washington, D.C.
- Mayer, P., Reynolds, S., McCutchen, M., & Canfield, T. Riparian buffer width, vegetative cover, and nitrogen removal effectiveness: A review of current science and regulations. EPA/600/R-05/118. Cincinnati, OH, U.S. Environmental Protection Agency, 2006.

- Metcalf and Eddy, INC. (1991). *Wastewater Engineering - Treatment, Disposal, and Reuse*, 3rd Edition, McGraw-Hill, INC., New York.
- NCDC (National Climatic Data Center), (2009, 3, 23). <http://cdo.ncdc.noaa.gov/dly/DLY>. Retrieved March 22, 2009, from Record of Climatological Web site: <http://cdo.ncdc.noaa.gov/dly/DLY>
- Oregon State University, GeoSyntec Consultants, University of Florida, The Low Impact Development Center (2006). *Evaluation of Best Management Practices and Low Impact Development for Highway Runoff Control-Research Report 2006*. National Research Council, Washington, D.C.
<[http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+25-20\(01\)](http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+25-20(01))> (June 26, 2006).
- Pierce County Public Works and Utilities. (2009). Appendix F Impervious Surface Percentages for Different Land Use Types.
<<http://www.co.pierce.wa.us/pc/services/home/environ/water/ps/basinplans/bpguide.htm> > (March 9, 2009).
- Reible, D., & McCutcheon, S., (2003). *Fundamentals of Environmental Engineering*, CRC Press.
- Reynolds, J.E. (2001). Urbanization and Land Use Change in Florida and the South. from http://srdc.msstate.edu/publications/220_ch2.pdf
- Rossman, L. (2004). *Storm Water Management Model User's Manual Version 5.0*. Water Supply and Water Resources Division, National Risk Management Research Laboratory, Cincinnati, OH.
- Sansalone, J. J., & Teng, Z. (2005). Transient rainfall-runoff loading to a partial exfiltration system: implication for urban water quantity and quality. *Journal of Environmental Engineering* . 131:8, 1155-1167.
- Sansalone, J, Kuang, X, & Ranieri, V (2008). Permeable Pavement as a Hydraulic and Filtration Interface for Urban Drainage. *Journal of Irrigation and Drainage Engineering*. 134:5, 9.
- Sansalone, J., & Ma, J., Parametric evaluation of batch equilibria for stormwater phosphorus adsorption on aluminum oxide media”, *ASCE Journal of Environmental Engineering*, (in press) 135(6), 2009.
- St. John's River Water Management District. (2006). Applicant's Handbook (Regulation of Stormwater Management Systems Chapter 40C-42, F.A.C.

- Stormont, J., & Shenxiong, Z. (2001). *Improving pavement sub-surface drainage systems by considering unsaturated water flow*. MIHE/HBCU Competitive Assistance Program U.S. Department of Transportation Federal Highway Administration.
- Strecker, E., Huber, W., Heaney, J., Bodine, D., Sansalone, J., Quigley, M., Leisenring, M., Pankini, D., & Thayumanavan, A. (2005). *Critical Assessment of Stormwater Treatment and Control Selection Issues Report 02-SW-1*. Water Environment Research Foundation, Alexandria, VA,
<<http://www.iwaponline.com/wio/2006/01/wio200601WF02SW1.htm>> (June 30, 2006)
- University of Florida (2006 a). "Conservation Data & Analysis." *Campus Master Plan, 2005 – 2015: Data & Analysis Reports*. University of Florida Facilities Planning, Gainesville, FL, pp 9-1 – 9-10.
- University of Florida (2006 b). *Campus Master Plan, 2005 – 2015: Plan Elements*. University of Florida Facilities Planning, Gainesville, FL, pp 9-1 – 9-4.
- Water Environment Federation & American Society of Civil Engineers. (1998). Urban Runoff Quality Management. Virginia.
- Whipple, W., Grigg, N.S., Grizzard, T., Randall, C.W., Shubinski, R.P., & Tucker, S.L. (1983). Stormwater Management in Urbanizing Areas. New Jersey: Prentice Hall
- Zarriello, P.J., Breault, R.F., & Weiskel, P.K. (2002). *Potential effects of structural controls and sweeping on stormwater loads to the lower Charles River, Massachusetts*. Northborough:

Table 1 Annual Runoff Load and Untreated Wastewater Load from Gainesville, Florida ¹

Quantity	Untreated Runoff ¹	Untreated Wastewater ¹
Flow (m ³)	5.00E+07	3.10E+07
COD [mg/L]	350	500
PM [mg/L]	346	220
TN [mg/L]	4.7	40
TP [mg/L]	1.3	8
Cu [µg/L]	40	35

Table 2 Reitz Union Parking Lot Specifications (existing condition of site design)

Watershed Area (acres)	3.23
Surface Area of Elevated Islands (acres)	0.79
Surface Area of Pavement (acres)	2.45
Volume of Pavement (0.5 ft depth) (yd ³)	1970
Total Area of Islands (%)	24.39
Total Area of Pavement (%)	75.61

Table 3 Rainfall Statistics for Gainesville, FL between August 1999 and July 2008

Month	Precipitation (in)	Mean Event Precipitation (in)	Number of Events	Mean Event Duration (hr:mm)	Average Inter-Event-Time (hr:mm)
January (1)	28.92	0.28	104	2:31	66:37
February	28.88	0.32	89	3:08	74:27
March	32.61	0.30	108	2:53	71:20
April	17.06	0.22	79	2:04	87:05
May	14.57	0.21	70	1:37	92:47
June	67.27	0.29	236	2:17	27:54
July	61.7	0.30	204	1:32	34:34
August	56.19	0.28	199	1:35	37:42
September	61.89	0.37	166	2:32	39:45
October	23.89	0.22	109	1:47	72:56
November	16.22	0.23	72	2:12	103:20
December (12)	21.33	0.25	86	2:33	73:54

Table 4 Design Options

Design Option 1	Existing Condition: As is with current Post-Development Conditions
Design Option 2	Add an inverted BAR in place of each raised island (no LIRs)
Design Option 3a and 3b	a. Add partial CPP retrofit (2, 4 or 6 ft wide LIRs), include BAR
	b. Completely replace all pavement with CPP and include BAR

Table 5 Comparison of Pre-Development (FDOT 2007) and Post-Development Conditions

Development Condition	Pre-Development	Post-Development (Current)
SSC (Sediment + Settleable + Suspended) [mg/L]	≈ 7.8	346.1
TP [mg/L]	≈ 0.074	1.27
TN [mg/L]	≈ 1.15	4.72
Cu [μg/L]	≈ 0.001	0.031
Pb [μg/L]	≈ 0.005	0.20
Zn [μg/L]	≈ 0.006	0.064

Table 6 Slope Arrows Table

Slope Arrows Table			
Number	Minimum Slope	Maximum Slope	Color
1	0.00%	1.58%	
2	1.58%	2.42%	
3	2.42%	3.29%	
4	3.29%	4.30%	
5	4.30%	5.93%	
6	5.93%	12.25%	
7	12.25%	90.03%	
8	90.03%	122.59%	

Table 7 Existing Site Conditions

Parameter	Value
Total Precipitation (Acre-Feet)	99.6
Evaporation Loss (Acre-Feet)	20.0
Infiltration Loss (Acre-Feet)	17.3
Surface Runoff (Acre-Feet)	62.3

Table 8 Pollutant Load Export for Reitz Union Parking Lot Site Under Pristine Conditions

	Phosphorus (lb)	Nitrogen (lb)	TSS (lb)
Pristine	7.79	301.61	296.26

Table 9 Pollutant Loads for Reitz Union Parking Lot Site for Design Option 3a (6 ft LIR, BAR)

	Phosphorus (lb)	Nitrogen (lb)	TSS (lb)
Pristine	7.78	301.61	296.26
6 ft LIR + BAR	2.17	133.18	239.85

Table 10 Summary of Costs for Design Option 2 (BAR Only)

Design Option		Cost
Capital	Excavation	\$38,290
	Plants	\$8,650
	Liner	\$19,010
	West Road Design	\$3,940
	Total	\$69,890
Annual O & M	Maintenance and Cleaning	\$4,190
NPV (net present value)		\$123,920
Engineering Fee (10%)		\$12,390
Contingency Fee (15%)		\$18,590
Total		\$154,900

Table 11 Summary of Costs for LIR

Design Option		Cost		
		2 ft LIR	4 ft LIR	6 ft LIR
Capital	AOCM	\$7,700	\$15,300	\$23,000
	Excavation	\$3,030	\$6,060	\$9,090
	Pavement	\$33,060	\$66,130	\$99,190
	Total	\$43,790	\$87,490	\$131,280
Annual O&M	Street Sweeping	\$420	\$420	\$420
NPV		\$49,210	\$92,910	\$136,700
Engineering Fee (10%)		\$4,920	\$9,290	\$13,670
Contingency Fee (15%)		\$7,380	\$13,940	\$20,510
Total		\$61,510	\$116,140	\$170,880

Table 12 Summary of Costs for Design Option 3a (LIR options with BAR)

Cost Category	LIR			BAR
	2 ft	4 ft	6 ft	
Capital	\$43,790	\$87,490	\$131,280	\$69,890
O&M	\$420	\$420	\$420	\$4,190
Engineering fee	\$4,920	\$9,290	\$13,670	\$12,392
Contingency fee	\$7,380	\$13,940	\$20,510	\$18,590
PV of Cost	\$61,510	\$116,140	\$170,880	\$154,900
Overall Cost	\$216,410	\$271,040	\$325,780	

Table 13 Cost Comparison to current mean Florida BMPs for Design Option 3a (6 foot LIR with BAR)

Option 3a (6 foot LIR with BAR)	Mass in Runoff from site per year (lb/yr)	Cost to remove with Option 3a (\$/lb/yr)	Mean Cost to remove using BMPs in FL (\$/lb/yr)	Difference (\$/lb/yr)	Percent Difference (%)
Nitrogen	100	3,260	3,730	470	13
Phosphorus	26	12,530	14,720	2,190	15

Table 14 Summary of Pollution Loadings for Pristine Conditions and all Design Options

	Phosphorus (lb)	Nitrogen (lb)	TSS (lb)
Pristine	7.78	301.61	296.26
Current	594.75	1065.83	61143.81
BAR	13.48	575.83	1907.14
2 ft LIR + BAR	5.56	270.57	731.76
4 ft LIR + BAR	3.95	210.23	489.11
6 ft LIR + BAR	2.17	133.18	239.85
All CPP + BAR	0.001	13.95	0.18

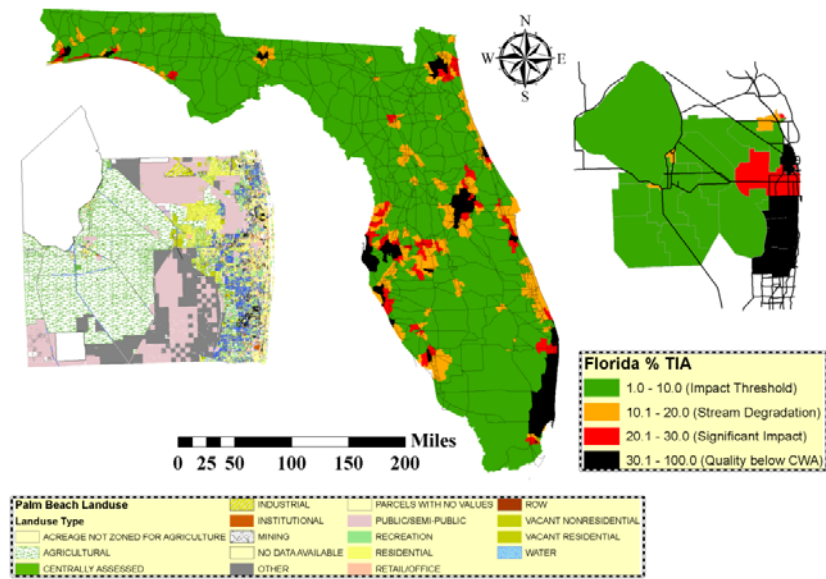


Figure 1 Total Impervious Area (TIA) in Florida and Land Use in Palm Beach County as of 2009.
Note from the color legend that as % TIA increases deleterious impacts increase.

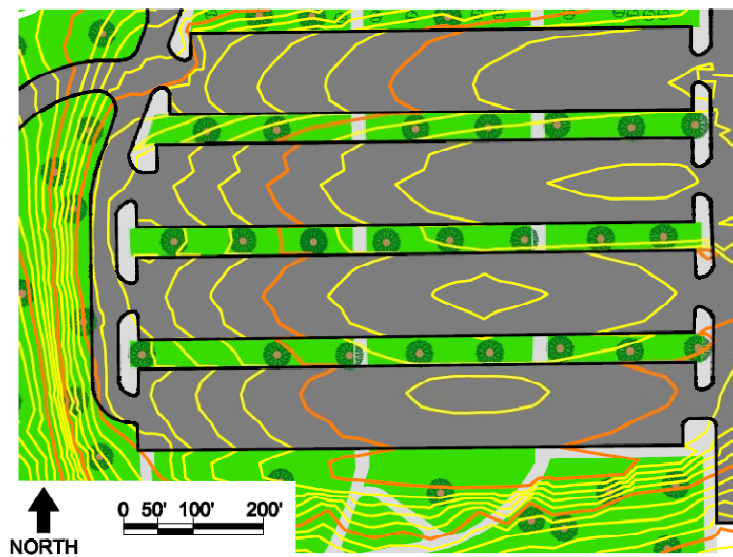


Figure 2 Topographical View of Reitz Union Parking Lot (Existing Condition)

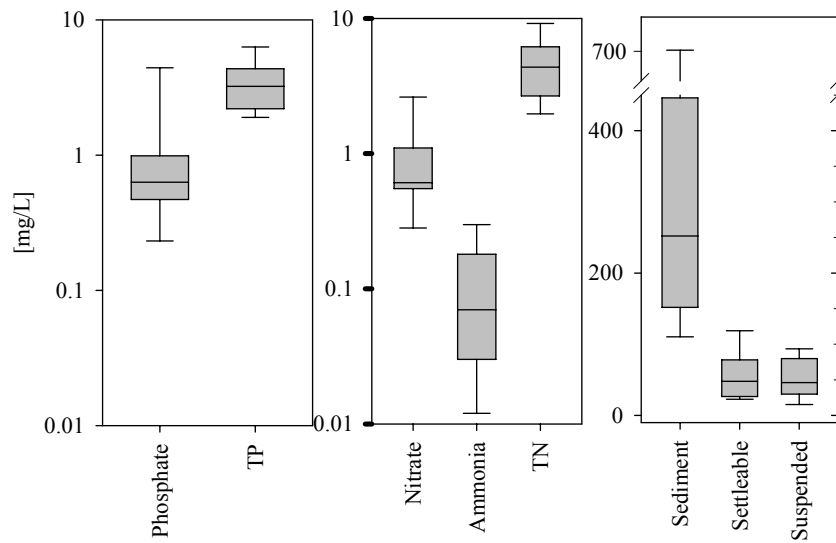


Figure 3 Stormwater EMCs for Phosphorus, Nitrogen, and PM Fractions of 15 Storms Monitored at Design Site. SSC = Sum of Suspended (< 25 μ m) + Settleable + Sediment (> 75 μ m) PM

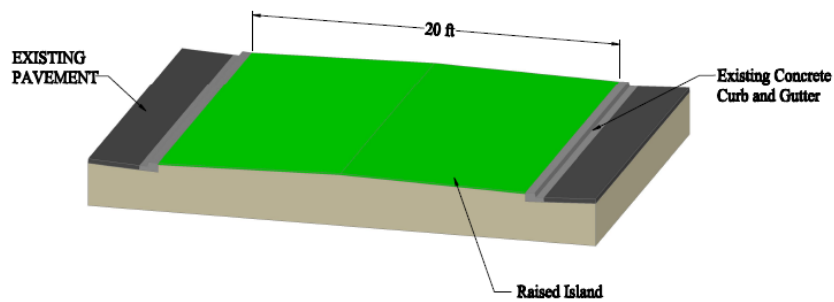


Figure 4 Design Option 1 Crowned Cross Section (existing condition or “do-nothing” option)

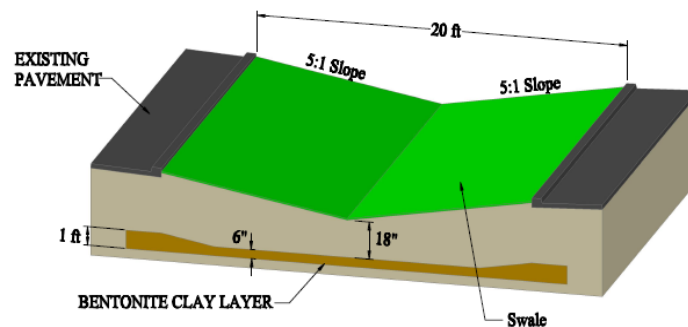


Figure 5 Design Option 2 Cross Section (the inverted biofiltration area reactor, BAR only)

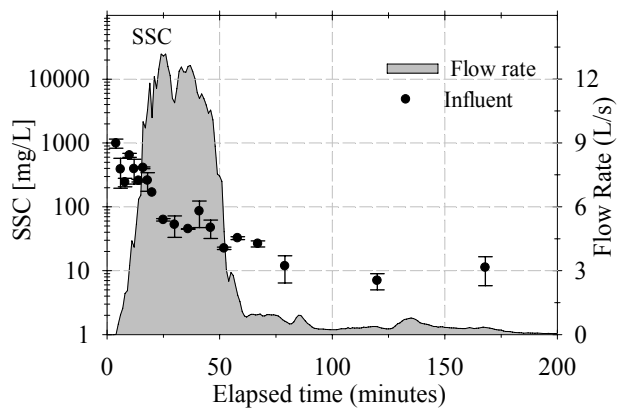


Figure 6 SSC and Hydrograph from Storm Monitored at Reitz Union Parking Lot

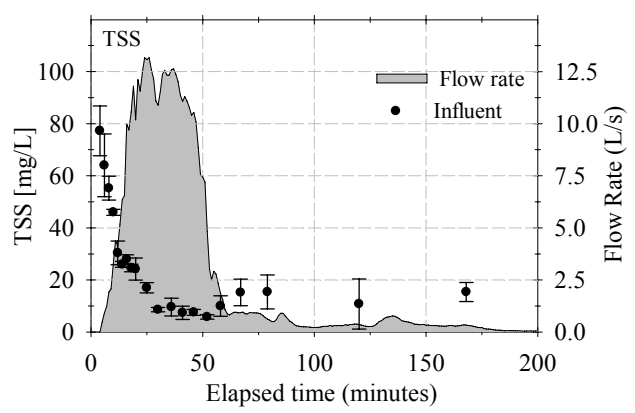


Figure 7 TSS and Hydrograph from Storm Monitored at Reitz Union Parking Lot

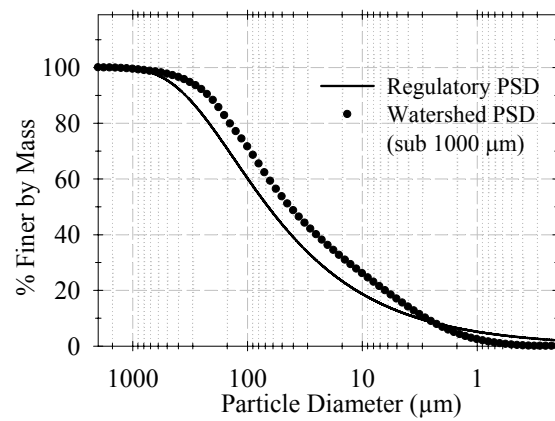


Figure 8 Event Mean PSD for Hydrograph in Figures 6 and 7

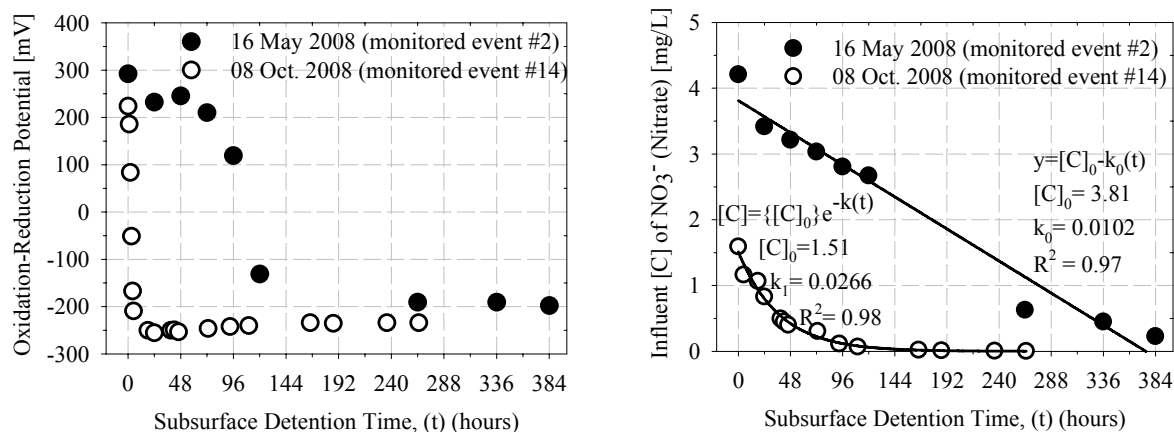


Figure 9 Consumption of Oxygen in the Subsurface BAR as Indicated through Oxidation-Reduction Potential (Redox) and Resulting Denitrification Rates as the BAR acclimates

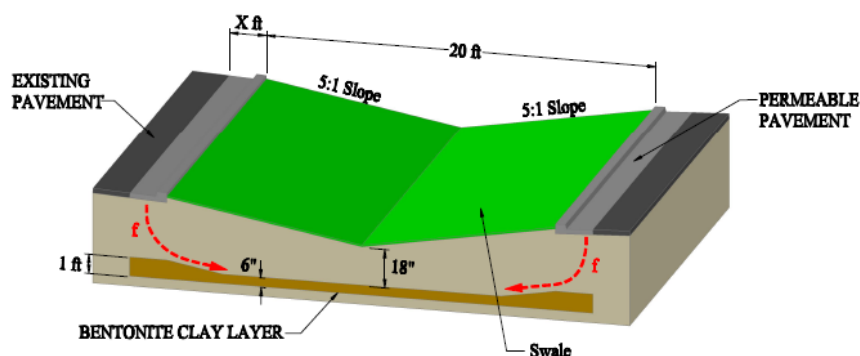


Figure 10 Design Option 3a Cross Section (f:infiltration)

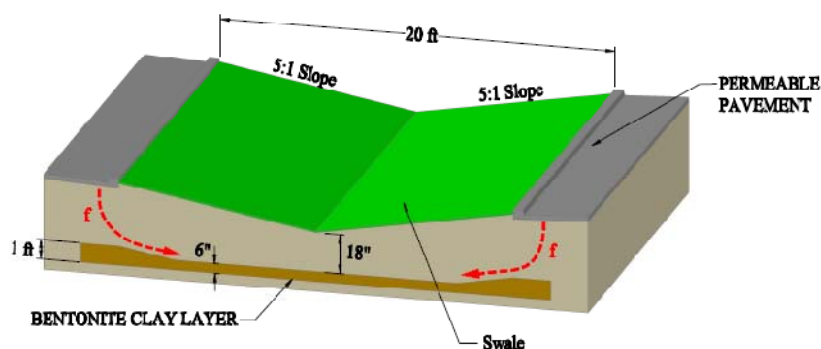


Figure 11 Design Option 3b Cross Section (f: infiltration)

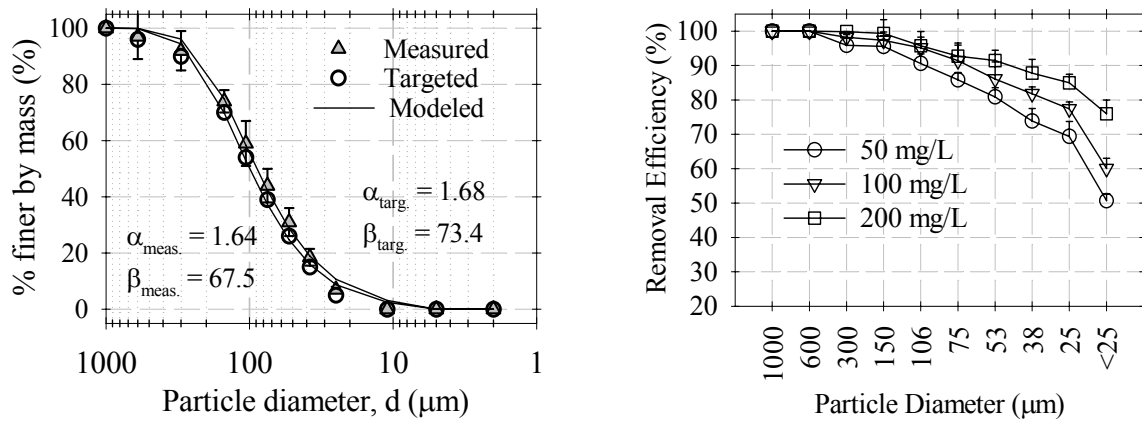


Figure 12 Illustration of filtration of a regulatory PSD (NJDEP) and associated PM removal as a function of particle size for CPP utilized in the proposed design

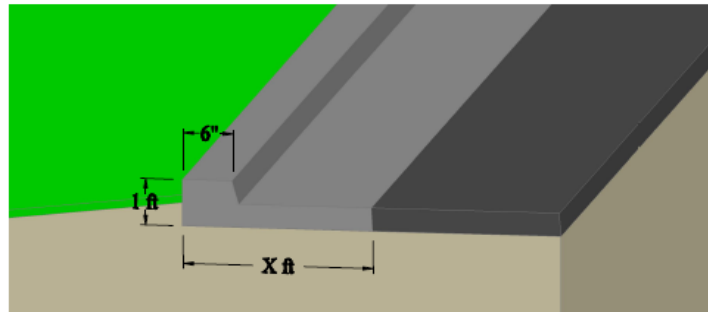


Figure 13 Permeable CPP width that formed the LIR (linear infiltrating reactor) design element

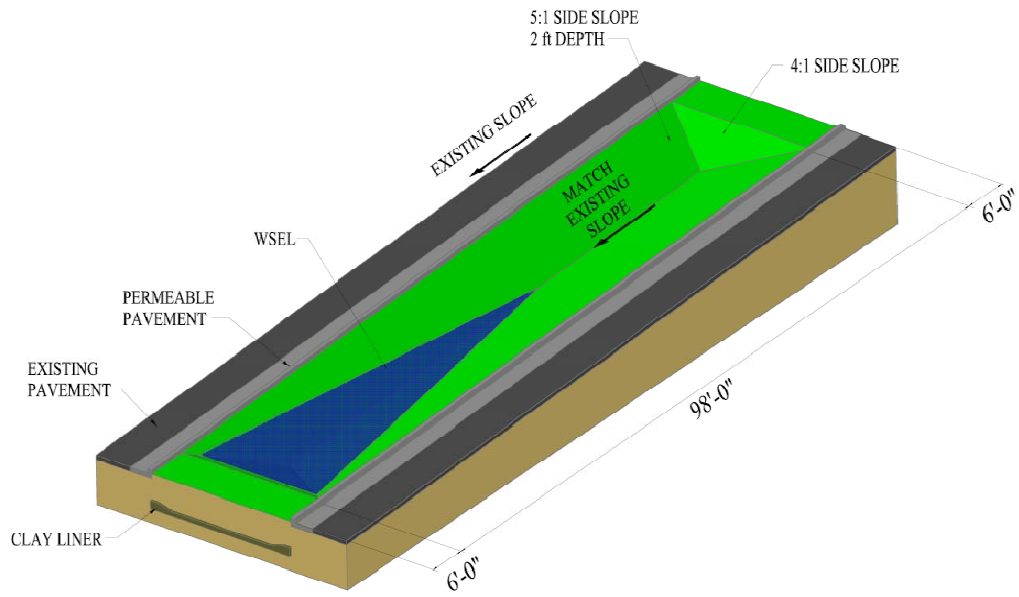


Figure 14 Cross Sectional View of BAR Design with proposed check dam.

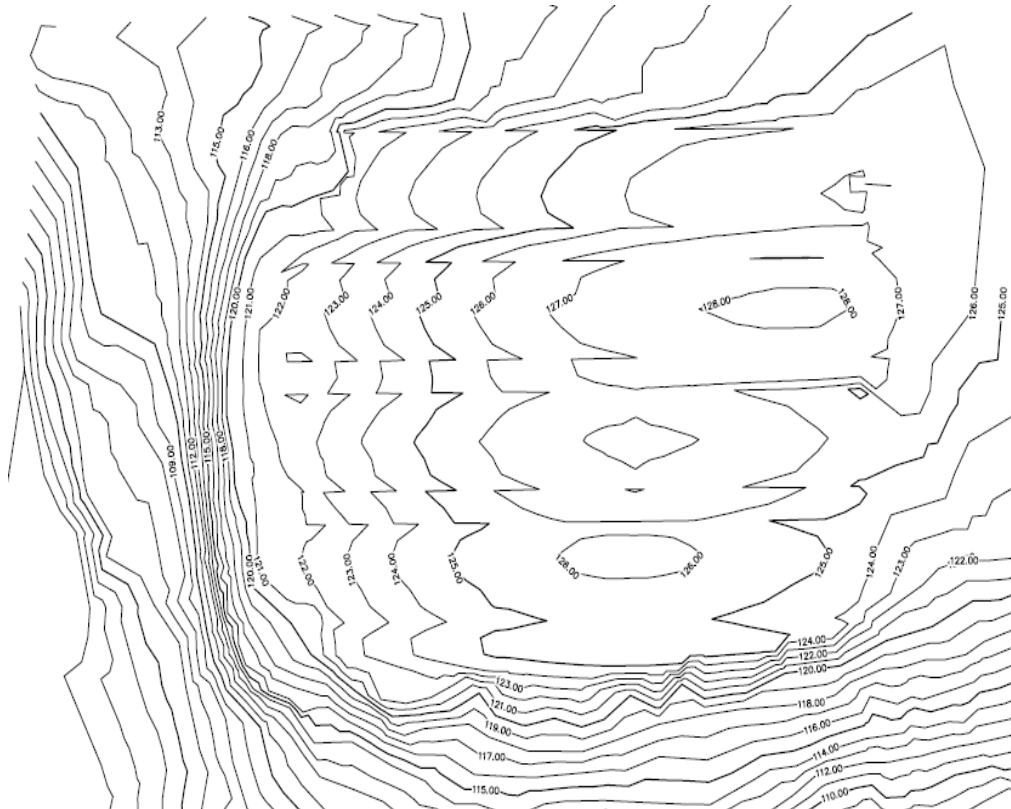


Figure 15 Surface Model of Existing Site with Elevation Contours

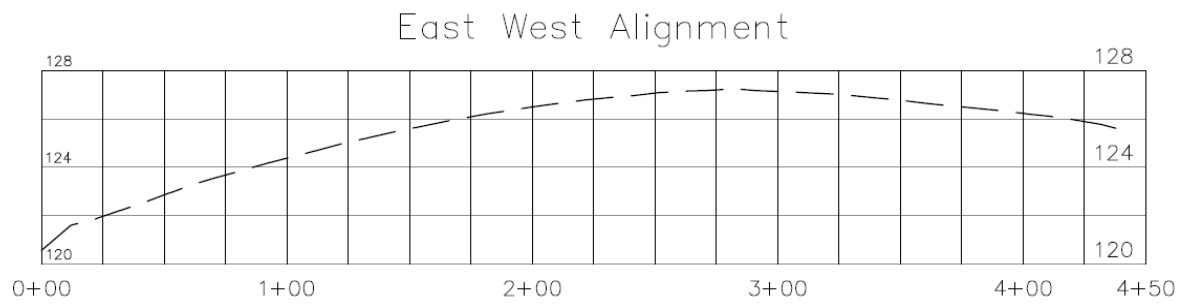


Figure 16 Typical East West Profile of Existing Grade

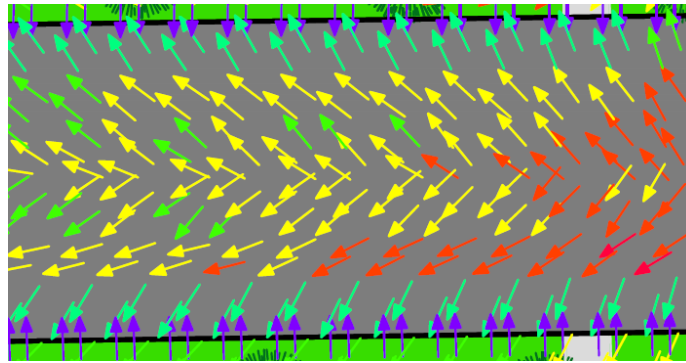


Figure 17 Site Slope Arrows for a Typical Existing Pavement Area on the South End of the Site

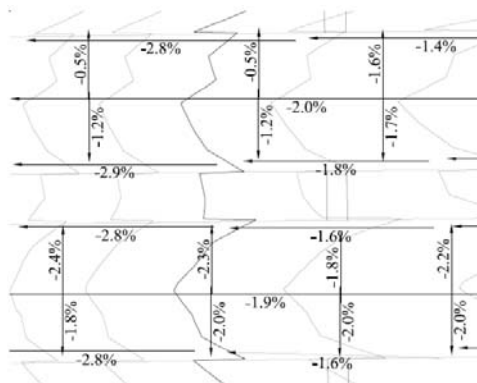


Figure 18 Slopes of Pavement from Crown to Gutter and Along East West Curb and Gutter

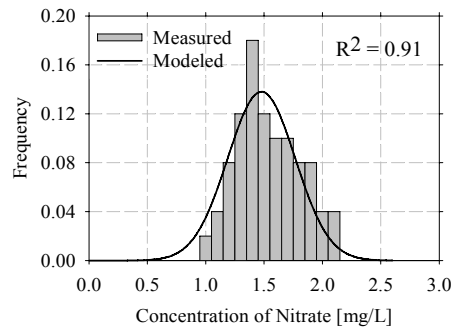


Figure 19 Nitrate Data Frequency Distribution in an Aerobic Batch Reactor

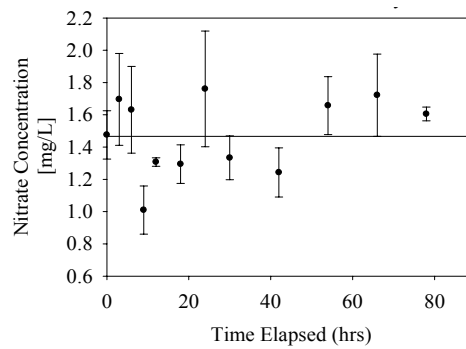


Figure 20 Lack of Nitrate Decay in an Aerobic Batch Reactor, Simulating Surface Water Conditions in a BAR subject to atmospheric re-aeration.

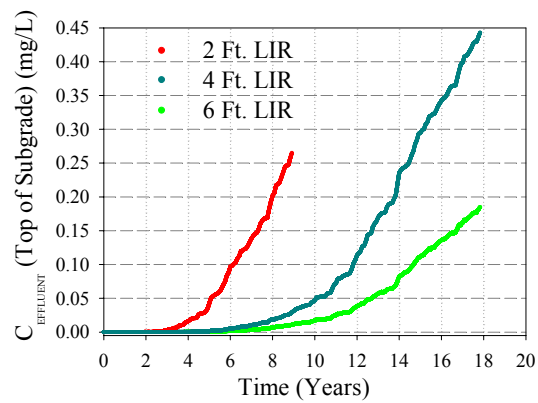


Figure 21 LIR Design Option (width of CPP) Breakthrough for Dissolved Phosphorus

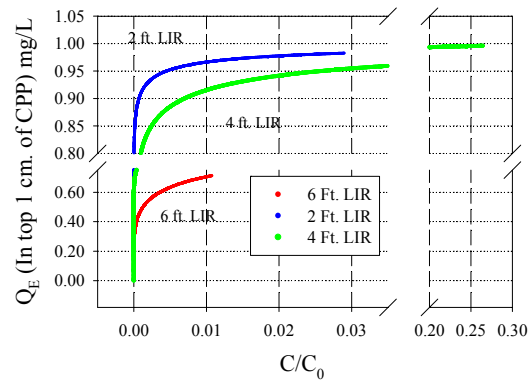
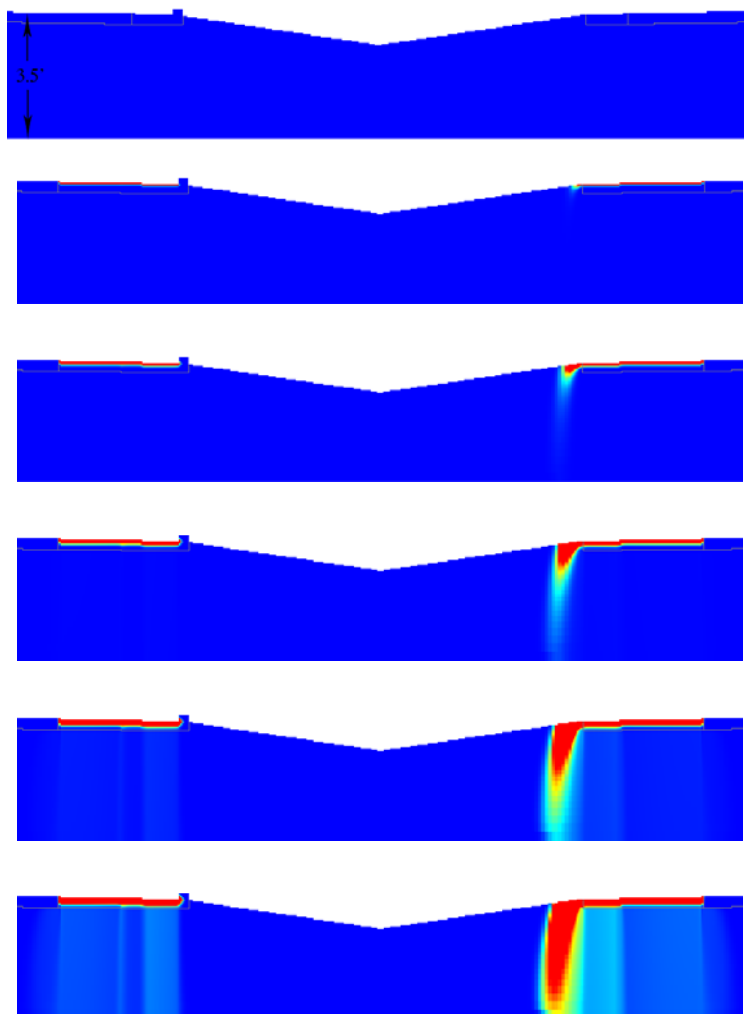


Figure 22 LIR Adsorption of Dissolved Phosphorus Over 9 Years Based on Historical Continuous Simulation Data from SWMM combined with CPP properties in VS2D.



Time = 0 years
Mass Balance Error:
Solute: 0.00%
Fluid: 0.00%

Time = 1 year
Mass Balance Error:
Solute: 0.06%
Fluid: -0.39%

Time = 3 years
Mass Balance Error:
Solute: 0.06%
Fluid: -0.12%

Time = 5 years
Mass Balance Error:
Solute: 0.06%
Fluid: -0.06%

Time = 7 years
Mass Balance Error:
Solute: 0.06%
Fluid: -0.04%

Time = 9 years
Mass Balance Error:
Solute: 0.06%
Fluid: -0.03%

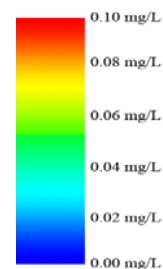


Figure 23 Dissolved phosphorus plume formation for 6 ft LIR. The left half illustrates plume development with a bounding CPP curb. The right half illustrates plume development with runoff flowing directly into the BAR with no curb. Results are based on historical continuous simulation data from SWMM combined with CPP properties in VS2D. Each figure represents a period of two years, starting from year 0 to year 9; the length of historical data. Results also portray the importance of the curb for the LIR.

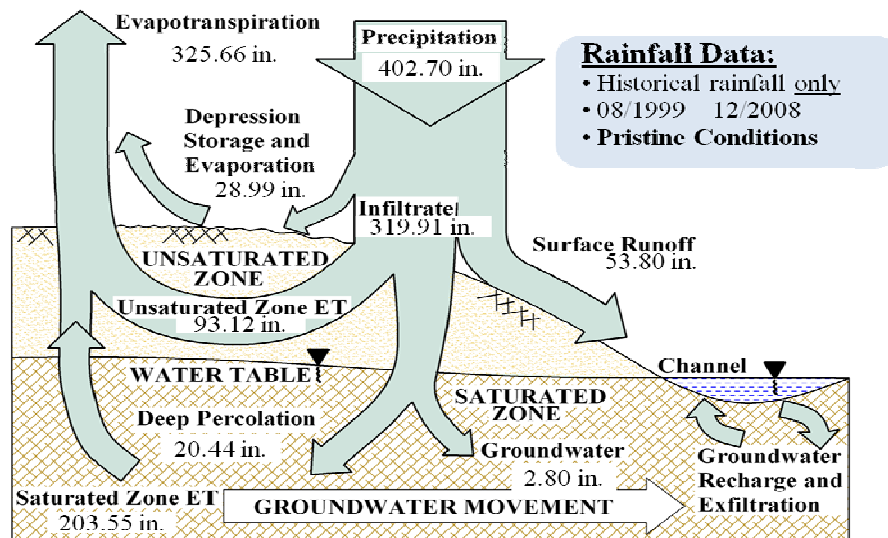


Figure 24 Hydrologic Cycle for Reitz Union Parking Lot Site Under Pristine Conditions

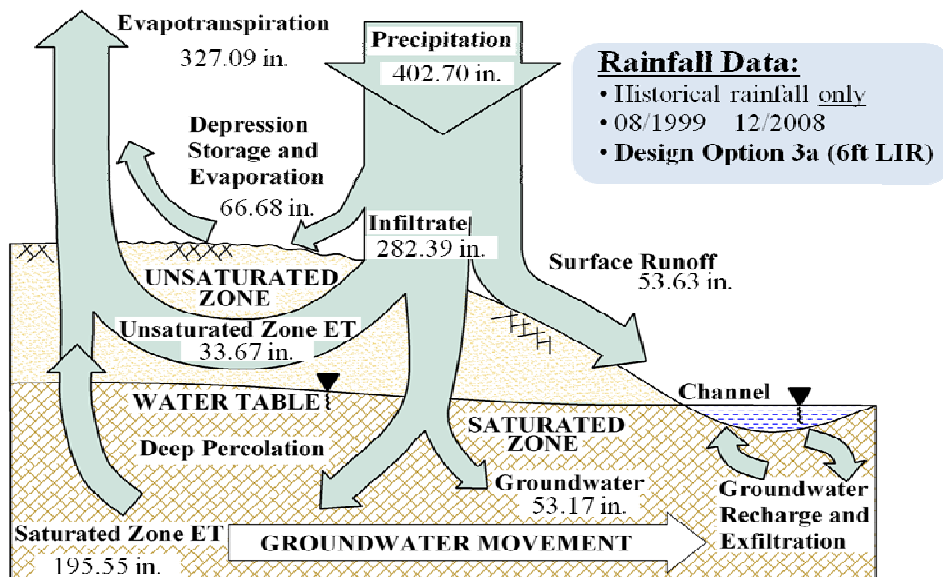


Figure 25 Hydrologic Cycle of Reitz Union Parking Lot with Design Option 3a (6 ft LIR, BAR)

CHAPTER 7: RECOMMENDATIONS

Based on combining results from the quantitative porous media testing (equilibria, kinetics, breakthrough, desorption) matrix and initial watershed rainfall-runoff characterization, a clay-based soil media system is designed, constructed and field-tested. System load and response testing are carried out through 15 rainfall-runoff event loadings and inter-event drainage management. Results from the intra- and inter-event field testing in 2008 are utilized with surface and subsurface modeling and low impact development (LID) retrofit design of the existing asphalt-paved watershed to demonstrate compliance with the proposed Unified Stormwater Rule for nutrient and PM loads as well as volume for a historical dataset from 1999 through 2008 at a cost equivalent to conventional Florida BMPs. The following recommendations in the order of project results are developed from study findings.

1. Initial water chemistry and hydrologic characterization of a watershed as illustrated in Chapter 3 is required before developing a treatment system for nutrients and PM. In this study four rainfall-runoff events are initially characterized. Beyond intra-event N, P, PM and hydrologic analysis critical indices are partitioning between dissolved and particulate phases of N and P, particle size distributions (now a requirement for many states) and differentiation of PM fractions (suspended, settleable and sediment). Representative sampling throughout the event should be required with sample holding times until fractionation or preservation of less than 24 hours, preferably 12 hours due to partitioning. While the current practice of automated sampling will continue into the foreseeable future; such sampling should be recognized as non-representative and significantly underestimating the maintenance requirements for LID and BMP systems. Such sampling also significantly underestimates load which is critical aspect for MS4s.
2. There is a plethora of porous media that are either suggested, promoted or utilized for rainfall-runoff adsorptive-filtration. Standardized quantitative results in Chapter 4 indicate that different media perform very differently. The four quantitative tests presented in Chapter 4 should be a requirement for any media proposed for adsorptive-filtration of rainfall-runoff both under controlled laboratory testing with standardized physical and chemical loadings and separately subject to actual rainfall-runoff competitive chemistry with the same standardized physical loadings.
3. Media or media combinations such as sand, perlite, zeolite and granular activated carbon are ineffective adsorbents and should not be used where there is a requirement for adsorption. As shown in Chapter 4 a number of media actually leach phosphorus. Engineered soil-based porous media with Al-oxide illustrates a high capacity for phosphorus for all standardized quantitative tests (isotherms, kinetics, and breakthrough) and a low desorption potential. The clay-based porous media with Al-oxide is high surface area and charge and does not desorb phosphorus due to the predominance of chemical adsorption as opposed to physical adsorption.
4. A porous media system must balance head loss with required water chemistry and filtration behavior. While a coarse and mono-disperse porous media system will provide low head loss, the performance behavior also will be low until filter ripening progresses at the onset of

clogging. On the other hand a finer and more hetero-disperse porous media will produce high treatment performance behavior rapidly with longer contact times, higher head loss and more rapid filter ripening. The porous media system deployed in this study and summarized in Chapter 5 utilized a media that ranged in size from 0.85 mm (#20 sieve) to 4.75 mm (#4 sieve); considered texturally a moderately mono-disperse very coarse sand with a $d_{50m} = 2.7$ mm. The clean-bed hydraulic conductivity of the system is 0.7 cm/s. This high value is supported by the design decision to load the filter system at high surface loading rates. The system median surface loading rate (SLR) indices are 316 L/min-m² for the peak flow with a standard deviation of 180 L/min-m² and 47 L/min-m² for the median flow rate with a standard deviation of 54 L/min-m². It is recommended that soil media or engineered filter systems not exceed a SLR of 200 L/min-m² with an event median contact time for runoff with the filter media of at least one to two minutes.

5. Given the balance between head loss and treatment behavior for phosphorus a recommended porous soil or engineered media will have:
 - a. higher specific surface area ($> 10 \text{ m}^2/\text{g}$),
 - b. a hetero-disperse pore size distribution within the medium,
 - c. a moderately mono-disperse particle size distribution,
 - d. a d_{50m} in the range of 1 to 4 mm,
 - e. a point of zero charge (pzc) at a high pH maximizing positive charge density
 - f. low friability and crushability,
 - g. amendments that do not leach or desorb phosphorus or metals or are not more soluble or degradable in cyclic redox conditions such as in BMP filter systems,
6. The current state of the practice for engineered media filter systems generally should require aerobic applications given changes in solubility within an anaerobic filter system.
7. Porous media or engineered media systems must be maintained on a regular basis. If such systems are effective their adsorptive capacity will be exhausted and as a filter, will clog without maintenance. Maintenance of porous soil media or engineered media systems is typically on a six month to an annual basis. Beyond design based on representative physical and chemical loadings, the critical parameters of reducing and attenuating influent loads and managing microbiological growth in a filter.
8. As shown with the LID design in Chapter 6, design components can be coupled to provide the unit operation and process treatment train in a sustainable and maintainable manner. For example, in the current state of the practice denitrification is passively managed as separate unit process from the upstream filtration, volume control and phosphorus adsorption of the CPP and hydraulic, sedimentation and evapotranspiration mechanisms of the BAR. It is recommended that anthropogenic carbon sources are not needed, as shown by results in Chapter 5 and 6. It is recommended that the natural consortium of microbiology and organic matter be advantageously used in such bio-filtration systems as the BAR. Management of nitrate is a critical for in-situ systems.
9. Ultimately, if any paved area is to be constructed or retrofitted using a LID practices as described in Chapter 6, it is recommended to drain the area to regularly spaced engineered treatment biofiltration areas similar to the BAR, where infiltration, evapo-transpiration, storage and treatment can occur with upstream treatment facilitated by engineered cementitious permeable pavement, CPP in this case

deployed with an amphoteric admixture for phosphorus adsorption. With such hydrologic communication, a target level of hydrologic restoration and load reduction can be achieved; with benefits to components of the hydrologic cycle; and ultimately provide indirect reuse of stormwater through local recharge. Such benefits further include reductions in pollutant loads and concentrations with reduced thermal loads. It is recommended that reduction in thermal loads is given equal priority to nutrient loads. A critical aspect of the design is engineered CPP that illustrates up to a 20 year design life for the design illustrated. Engineered CPP can make a significant difference in Florida for load reduction, more viable maintenance practices, safety, hydrologic restoration and thermal load reduction. CPP should be coupled with pavement cleaning is also a valuable tool for anthropogenic and biogenic load control. However, such maintenance practices require documentation and validation. The combination of engineered CPP, an engineered BAR system and regular pavement cleaning demonstrates that load control meeting the Unified Stormwater Rule is viable at a cost equal to or less than conventional BMP practices. However; continuous simulations tools are required to illustrate this. It is recommended that the continuous simulation tools of SWMM and VS2D be required for LID design; with a minimum of 10 years of rainfall data.

10. Design components such as the BAR also provide beneficial aesthetic with Florida-friendly landscape. Additionally, the engineered cementitious permeable pavement (CPP) eliminates the deleterious environmental and thermal impacts of asphaltic binders while providing beneficial alkalinity to the infiltrated runoff. Results illustrate that the cost of such green infrastructure and LID is on par with conventional construction, even before the costs of pollutant and runoff load reduction are included. When load reduction costs are accounted for the system construction costs are lower; and costs per unit load of nutrient treated are lower than current mean Florida BMP costs. These design components are sustainable because of regular yet economical street sweeping maintenance. There is no escaping that effective and reliable performance of BMPs and LID systems require regular and verifiable maintenance. We would never operate our wastewater plants without frequent and documented maintenance practices; BMPs and LID systems are no different. There is no self-maintaining BMP or LID system and the non-stationary behavior of any BMP or LID system is a critical need in Florida and the USA.
11. It is recommended that the green infrastructure design elements are targeted for specific pollutants based on pollutant-specific chemistry and known mechanisms as illustrated in Chapter 5 of this report. Results are also quantitative and illustrate that LID or sustainable urban drainage practices and designs can be quantified; removing such practices from the category of "black-box" systems. For example the bounding clay layer design element within the BAR allows for denitrification utilizing the natural consortium of microbes in runoff and kinetics are illustrated. At the same time, a simple modification of CPP as a filtration medium with an aluminum oxide admixture provides an interface for the removal of phosphorus that would otherwise produce rapid breakthrough from a stand-alone BAR design element. The use of engineered CPP or media systems with oxides provides significant benefits compared to many bio-filtration media, friable media substrates or leachable media substrates.
12. It is recommended that any BMP or LID system must be examined by continuous simulation tools as opposed to many models that are essentially peak flow models. For example, utilizing continuous simulation models (SWMM and VS2D), physical and chemical properties of the green infrastructure elements, soil, vegetation and physical-chemical modeling of these elements it was demonstrated that the 6 ft LIR and BAR meets load reduction for phosphorus, nitrogen and PM to achieve requirements of the promulgated Unified Stormwater Rule where post-development loads cannot

exceed pre-development ("pristine") loads. It is recommended that SWMM and VS2D, both open-source codes become the standard in Florida as such codes are the standard elsewhere in the USA and in the case of SWMM around the world. While peak flow models are a useful heuristic tool, such considerations based on a single point in a hydrograph may only possibly be adequate for initial evaluations of hydraulic capacity and surface water profiles. A protocol for Florida LID and BMP monitoring should be developed.