Stormwater Treatment by Two Retrofit Infiltration Practices

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Abstract

Increases in impervious surfaces associated with urbanization change stream hydrology by increasing peak flow rates, storm-flow volumes and flood frequency, and degrade water quality through increases in sediment, nutrient, and bacteria concentrations. In response to water quality and quantity issues within the Stroubles Creek watershed, the Town of Blacksburg and Virginia Tech designed and constructed two innovative stormwater best management practices (BMPs). The goal of this project was to evaluate the effectiveness of a bioretention cell and a CU-Structural Soil™ infiltration trench. BMP construction was completed in July 2007. Twenty-nine precipitation events were monitored over a period of five months between October 2007 and March 2008. For each storm, inflow and outflow composite samples were collected for each BMP and analyzed for suspended sediment, total nitrogen, total phosphorus, fecal coliform bacteria and E-coli bacteria. The inflow and outflow concentrations and loads, as well as total inflow and outflow volumes and peak flow rates, were then compared to evaluate how well each BMP reduces stormwater flows, decrease peak runoff rates and improves water quality of stormwater runoff. Results for the bioretention cell indicate average reductions in stormwater quantity, sediment, total nitrogen, total phosphorus and fecal coliform bacteria that exceeded 99% by mass. The CU-Structural Soil™ infiltration trench produced reductions in stormwater quantity, total phosphorus and sediment that averaged 60%, 45% and 51%, respectively. Preliminary bacteria results indicated that both BMPs served as sources of E-coli, and the infiltration trench served as a source of fecal coliform bacteria.

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To my grandmothers,
whose laughter and love I miss dearly.

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1. Introduction

The conversion of forested and agricultural land to urban land is one of the most prevalent forms of land alteration in the United States of America (Schoonover and Lockaby, 2006). Urbanization is accompanied by increases in the amount of impervious surfaces and the number of pollutant sources. Impervious surfaces and traditional storm sewer systems disrupt the natural drainage processes of the land by decreasing infiltration and eliminating vegetation that filters and slows surface runoff. The resulting increase in surface-runoff quantity and the decreasing runoff quality leaving a site affects the hydrology and quality of downstream water bodies.

Higher urban runoff volumes and flow rates and the significant amount of land disturbance required by construction greatly increases the amount of sediment introduced to surface water bodies via hillslope erosion and channel incision (Colosimo and Wilcock, 2007). Sediment entering the stream causes increased turbidity, the creation of sand bars, and the continued suspension and transport of finer sediment particles to downstream sites (Wolman, 1967). A decrease in vegetative and soil filtering processes, combined with an increase in the number of pollutant sources, lead to increases in surface-water pollutant concentrations. Increases in nitrogen levels in urban surface waters are attributed to lawn fertilizer applications, pet waste, combined sewer overflows and leaky or dysfunctional sanitary sewer systems. The majority of phosphorus comes from lawn fertilizers, wastewater treatment plant effluent, and leaky sanitary sewers, or is bound to sediments entering the water from the watershed (Atasoy et al., 2006; Schoonover and Lockaby, 2006). Increases in nitrogen and phosphorus lead to increased algal growth and eutrophication (Busse et al., 2006). Bacteria are also a concern in urban waters; major contributors of fecal coliform and E-coli to surface waters are impervious surfaces and dry-weather storm sewer discharges (Tufford and Marshall, 2002; Petersen et al., 2005).

The concept of low impact development (LID) arose in the 1990s as the impact of increasing urbanization and traditional stormwater management became more apparent. The overall goal of this relatively new approach to stormwater management is to minimize and distribute stormwater across a site, while promoting infiltration (Dietz, 2007). LID specifically promotes the use of multiple onsite best management practices (BMPs) such as bioretention, porous pavement, infiltration trenches and vegetated swales to provide decentralized retention and treatment of surface runoff.

LID has become a popular form of stormwater management. Many municipalities have instituted regulations that require the implementation of LID practices in new developments; others use financial incentives to promote this new form of stormwater treatment and control. However, there has not been enough research conducted on the effectiveness of LID, at either the individual BMP or the overall site level. Much more research is needed to ensure LID practices function as intended and there are no unexpected consequences associated with its use.

2. Goals and Objectives

The goals for this study were to assess the impact of a bioretention and CU-Structural Soil BMP on peak-flow rates and runoff volumes leaving an urban site, and to quantify total nitrogen, total phosphorus and bacteria (fecal coliform and E-coli) reductions due to each BMP treatment.

Specific objectives include:

1. Determine if the total volume of runoff leaving the BMP is less than the total volume entering the BMP;
2. Determine if the peak outflow rate is lower than the peak inflow rate;
3. Determine if the total inflow loads of total suspended sediment, total nitrogen, total phosphorus and bacteria are higher than the outflow loads; and
4. Determine if the mass removal efficiencies of the BMPs are correlated with BMP flow, concentration or load variables as well as storm characteristics.

3. Literature Review

3.1 The effects of urbanization on streams

The conversion of forested and agricultural land to urban land is one of the most prevalent forms of land alteration in the United States (Schoonover and Lockaby, 2006). The development of new urban land is typically characterized by vegetation clearing and removal, soil grading and compaction, introduction of large amounts of impervious surfaces and replacement of natural drainage systems with networks of impervious channels and piping (Nelson et al., 2006). Investigations of a variety of USA streams and rivers indicated urbanization was strongly associated with degraded water quality, poor habitat, low aesthetic quality, and health hazards (Schoonover and Lockaby, 2006). In 2000, 468,000 kilometers of rivers and streams did not meet water quality standards, with approximately 51,500 of these kilometers being impaired due to urban runoff and storm sewers (USEPA, 2000b).

There are many facets of urbanization that make it a threat to water quality. Increases in impervious surfaces and soil compaction reduce infiltration rates, thereby decreasing groundwater recharge, increasing the frequency and magnitude of high flows, and increasing flow variability (Meyer, 2005). The increase in runoff and the significant amount of land disturbance required by construction greatly increase the amount of sediment introduced to surface water bodies via erosion and channel incision (Colosimo and Wilcock, 2007). The removal of riparian vegetation often accompanies the transition to urban land, leading to the loss of streambank stability, stream physical and chemical buffering, and crucial organic inputs to the stream food web (Wheeler et al., 2005). Riparian vegetation also performs the essential role of regulating stream temperature by absorbing and reflecting sunlight (Wheeler et al., 2005). Urbanization increases temporal variability of stream temperature through the removal of riparian vegetation, the alteration of baseflow, and increases the temperature of stormwater runoff entering the stream (Krause et al., 2004).

While many effects of urban land are physical in nature, there are significant chemical consequences for streams when land is converted to urban use. Numerous studies demonstrated elevated concentrations of nutrients, such as nitrogen and phosphorus, as well as other substances such as chlorine, sulfate, and ammonium in urban areas (Biggs et al., 2004). Increases in the concentrations of heavy metals have also been correlated with increases in urbanization, particularly the construction of parking lots, roads and highways (Widianarko et al., 2000; Wheeler et al., 2005). A study in Croton Reservoir system in New York State showed streams that drain urban watersheds contained a greater number of pesticide-related compounds at significantly higher concentrations than streams draining non-developed watersheds (Phillips and Bode, 2004).

3.1.1 Hydrologic impacts of urbanization

The quantity of impervious surfaces within a given area has become the key indicator of urban intensity (Brabec et al., 2002), as this greatly influences the flow regime of a given watershed. The discharge magnitude, frequency, and rate of change of stormflow within the watershed are increased, while the duration of individual stormflows events is decreased (White and Greer, 2006). Urbanization also affects baseflow in streams, although research has produced contradictory results about whether dry-weather flows are increased or decreased (White and Greer, 2006).

Due to the reduction and/or elimination of infiltration and decreases in evapotranspiration rates (Rose and Peters, 2001), water enters surface water bodies as surface runoff, resulting in increased storm-flow volumes (White and Greer, 2006). A study conducted on Los Peñasquitos Creek in Southern California revealed that as the amount of urbanized land increased from 9 to 37% of the total watershed area, the total annual runoff increased an average of 4% per year. This resulted in a total increase of 200% from 1973 to 2000 (White and Greer, 2006). This finding supports the conclusion of Paul and Meyer (2001) who estimated that an average increase of 200-500% in runoff would occur for a watershed with greater than 10% impervious area. Wollheim et al. (2005) reported annual runoff in urban streams of the Plum Island Ecosystem watershed in Maryland was 25-40% higher than in forested streams, with total annual runoff of 272 mm/yr and 194 mm/yr, respectively. Similarly, a comparison of several Georgia streams showed that median runoff from the highly urbanized Peachtree Creek was 30-80% greater than streams with forested to moderately urbanized watersheds (Rose and Peters, 2001). Increases in flood magnitudes associated with urbanization are greater for floods of shorter recurrence intervals; the influence of urbanization on flow magnitude diminishes with increasing return intervals (White and Greer, 2006).

As urbanization increases, peak discharge rates increase as well. Analysis of watershed data during the 1960s and 1970s revealed increasing peak flows as urbanization within the watershed increased (Nelson et al., 2006). A study performed by Vicars-Groening and Williams (2007) in Dallas, Texas showed an increase of 385 m^3/s (or 118%) when comparing a watershed's undeveloped stage during the 1960s to its developed stage in the 2000s. Wheeler et al. (2005) stated that discharge rates occurring every two years under pre-development conditions may double in frequency following watershed development. During the first ten years of observation on a small watershed in Maryland, an average of two discharges above bankfull occurred per year; as the amount of urbanized area in the watershed increased during the following twenty years, this number increased to seven (Leopold et al., 2005).

Urban areas route surface runoff to streams quickly and efficiently through the use of storm sewers and gutters. Consequently, the watershed response to precipitation is accelerated and the lag time between precipitation and runoff is decreased; water is transported to nearby streams within hours instead of days. Furthermore, storm recession rates are significantly increased, resulting in a 'spiky' (or flashy) hydrograph for urban areas and a shortening of the total recession period by 1-2 days (Sala and Inbar, 1992; Rose and Peters, 2001; Nelson et al., 2006; Vicars-Groening and Williams, 2007).

Increases in flow volumes and peak discharges combined with shorter lag and recession times result in a higher potential for flooding. In comparing urban areas with non-urban areas, the annual flood may be as much as three times larger (Vicars-Groening and Williams, 2007). Thus, precipitation events that produced no increase in stream flow prior to urbanization may cause substantial flooding after urbanization (Wheeler et al., 2005).

Meyer et al. (2005) defined baseflow (also known as dry-weather flow) as "water that enters a stream from persistent, slowly varying sources and maintains streamflow between inputs of direct flow." Groundwater is the primary source for baseflow;

however, wastewater discharges and irrigation have been noted as substantial contributors in urban and agricultural watersheds, respectively (White and Greer, 2006).

Prior research indicated increases in impervious surfaces associated with urbanization decrease groundwater recharge, thereby reducing the inflow of groundwater to streams during dry-weather conditions (Sawyer, 1963; Seaburn, 1969; Pluhowski and Spinello, 1978; Simons and Reynolds, 1982; Rose and Peters, 2001). However, recent studies have also linked an increase in stream baseflow to increases in urbanization (Meyer, 2005; White and Greer, 2006). Urbanization is accompanied by a variety of activities that can contribute to baseflow: leaky storm sewers, sanitary sewer systems and septic systems, decreases in vegetation and associated evapotranspiration, and geomorphic changes in the stream such as straightening and deepening of the channel (Meyer, 2005). Stormwater detention basins can also be a source of dry-weather inflow to streams, as stormflow is detained and released slowly through infiltration (Meyer, 2005).

3.1.2 Geomorphologic impacts of urbanization

Construction is the first process that takes place as land is converted to urban use. As land is cleared and graded, there is a brief period of susceptibility to erosion. These exposed areas can produce sediment loads to nearby streams in excess of several thousand metric tons per square kilometer, nearly twice or more than similar areas not undergoing construction. Even without precipitation, large amounts of sediment can be introduced into streams via deposition or construction activities. A Pennsylvania study found that even when sediment control techniques were incorporated into highway construction, impacted streams carried 5-12 times more fine sediment than a control stream (Wheeler et al., 2005). Sediment entering the stream causes increased turbidity, extensive deposition of sand bars, and the continued suspension and transport of finer sediment particles to downstream sites (Wolman, 1967).

As construction is completed and the land is stabilized, sediment input to the stream decreases dramatically. Combined with increased runoff from impervious surfaces, this decline in sediment yield results in channel incision and/or bank erosion, followed by streambank instability (Bledsoe, 2002). The sediment-starved stream will progressively remove sediment from sand bars, streambanks, and any other sources of transportable sediment (Colosimo and Wilcock, 2007). The result is enlarged stream cross-sectional areas (on average 26-180% larger than non-urban streams) and a stream that is devoid of sediment storage features (Cianfrani et al., 2006). The corresponding channel deepening limits channel-floodplain interaction, decreases pool-riffle features and other structural habitats, and increases the frequency of bed mobilization (Doyle et al., 2000).

Erosion resulting from urbanization is often lateral as well, causing changes in the planform of streams. Higher flows eat away at streambanks, decreasing channel sinuosity and accelerating the channel migration process. Meanders are cut-off, causing the channel to straighten and the channel slope to increase (Nelson et al., 2006).

Urbanization also affects the characteristics of the stream bed material. Although urban streams contain more fine sediments (clay and silt) during the initial stages of land conversion (Ryan and Packman, 2006), higher flows during the latter part of the urbanization process strip the stream of smaller-sized sediments and transport them downstream (Colosimo and Wilcock, 2007). These processes lead to a stream with less fine sediment, more coarse sand and an armored bed (Doyle et al., 2000; Paul and Meyer, 2001).

A forested stream, on average, receives approximately 11-34 t/ha/yr; due to bank retreat and construction activities, an urban stream can receive more than 226,000 t/ha/yr (Wheeler et al., 2005). Long term channel retreat can be a substantial contributor to downstream sediment yield, contributing more than two-thirds of the measured sediment yield (Trimble, 1997).

3.1.3 Other physical effects of urbanization

Removal and/or loss of riparian vegetation, which is strongly associated with urbanization, results in 1) decreased shading; 2) increased stream temperature; 3) decreased diversity and quality of in-stream habitat for aquatic biota; 4) a change in aquatic community composition, and 4) a reduction of bank stability energy input to streams and filtering of sediment, nutrients and other pollutants (Allan, 2004; Roy et al., 2005; White and Greer, 2006).

The reduced infiltration of urban areas lowers the water table in riparian areas, creating a condition known as hydrologic drought. This, in combination with soil and hydrologic changes brought on by urbanization, affect the type, size and abundance of different vegetation species (Groffman et al., 2003). Studies of urban streams show a decline in the number and size of wetland tree species and an increase in upland tree species abundance when compared to non-urban streams (Groffman et al., 2003).

Stream temperature is a critical component of stream ecosystems and is directly affected by urbanization. Lower dry-weather flow, combined with channel widening and decreased shading, result in an increase in stream temperature, especially during summer months (Krause et al., 2004). Impervious surfaces, primarily parking lots, collect and heat runoff water before it reaches the stream (Wheeler et al., 2005). A study of Wisconsin and Minnesota streams estimated that the maximum daily water temperature of urban streams increases by 0.25°C for every 1% increase in impervious area in the watershed (Wheeler et al., 2005). An increase in temperature has detrimental consequences on stream biota: lowering of dissolved oxygen levels, altering of fish communities due to acute or chronic thermal stress, and a shift in species assemblages toward more tolerant species (Krause et al., 2004).

3.1.4 Chemical impacts of urbanization

Nutrients and ions

Streams draining urban watersheds contain higher nutrient and ion concentrations than those in non-urban watersheds (Brett et al., 2005; Busse et al, 2006). As vegetation is removed due to urbanization, the microbial and vegetative processes that consume and immobilize nutrients are diminished (Brett et al., 2005). The compaction of soils and the addition of impervious surfaces reduce infiltration and the subsequent filtering of runoff as it percolates through the soil (Atasoy et al., 2006). A study in Missouri reported total nitrogen and phosphorus loads were 2-10 times higher in an urban stream than in forested or agricultural streams (Wheeler et al., 2005).

Urban watersheds exhibit a steady accumulation and delivery of all forms of nitrogen (Wahl et al., 1997). Anthropogenic sources of nitrogen (nitrate/nitrite air emissions, lawn fertilizer applications, septic drain fields, leaky or dysfunctional sanitary sewer systems, pet waste, and combined sewer overflow inputs (Schoonover and Lockaby, 2006)) are the predominant contributor to raised concentrations in urban streams and are introduced to streams through runoff or infiltration (Wollheim et al., 2005). Erosion from construction sites and developed lands may also contribute to stream nitrogen levels through the transport of organic nitrogen (Atasoy et al., 2006). Additionally, nitrogen retention decreases an average of 5% for every 10% increase in impervious surface due to reduced wetland abundance, reduced rooting zone depths, increased surface runoff and increased flushing of water through pervious surfaces (Wollheim et al., 2005). Total nitrogen export in an urban watershed can be up to an order of magnitude higher than a forested watershed: A study conducted in the Plum Island watershed in Massachusetts reported nitrogen exports of 52 $kg/km^2/yr$ and 650 $kg/km^2/yr$ for forested and urban watersheds, respectively (Wollheim et al., 2005).

Urbanization also changes the types of nitrogen that dominate stream ecosystems. The ammonium (NH_4) form of nitrogen is the primary form of nitrogen in forested streams; however, inorganic nitrogen (NO_x) is the predominant form in urban streams (Wahl et al., 1997). As the water table descends, hydric soils that are ordinarily anaerobic become aerobic, leading to changes in nutrient cycling in the stream bank (Groffman et al., 2003). The aerobic soils develop higher levels of nitrification (a process that produces nitrate) and lower levels of denitrification (an anaerobic process that consumes nitrate) (Wahl et al., 1997; Groffman et al., 2003). The result is a more mobile oxidized form of nitrogen (inorganic nitrogen) and a riparian zone that is a source of nitrate instead of a sink (Wahl et al., 1997). The Little Tennessee River in the Blue Ridge Mountains exhibited baseflow nitrate concentrations 5-8 times higher in moderately-impacted areas than in lightly-impacted areas (Price and Leigh, 2006).

Phosphorus compounds tend to bind to sediment and enter streams during runoff events (Price and Leigh, 2006). Consequently, the introduction of large amounts of sediment to streams via construction activities and bank retreat provides the ideal mechanism for phosphorus transport. Other sources of phosphorus are lawn fertilizers, wastewater treatment plant effluent, septic drain fields and leaky sanitary sewers (Atasoy et al., 2006). Urban streams in the greater Seattle, Washington region exhibited a 95% increase in total phosphorous concentrations as compared to forested watersheds in the same region (Brett et al., 2005).

Dissolved organic carbon (DOC) loads to streams are also correlated with the amount of urbanization in a watershed. The reduction of vegetation and higher levels of soil compaction reduce watershed retention of DOC which, combined with anthropogenic inputs such as sewage, organic yard waste and pet waste, bring about significantly higher DOC concentrations in urban streams (Hook and Yeakley, 2005; Schoonover and Lockaby, 2006). Riparian vegetation is important in regulating DOC inputs to streams, however, urbanization is often associated with the loss of this vegetation (Hook and Yeakley, 2005).

Nitrogen and phosphorus are the most prominent regulators of stream algae growth (Busse et al., 2006). DOC is also a significant energy source for aquatic flora (Hook and Yeakley, 2005). Increases in stream concentrations of these nutrients result in eutrophication, a process in which the excess nutrients cause the overgrowth of algae. The algae blooms and then dies; the decomposing organic matter drastically reduces dissolved oxygen levels in the stream, causing the stress and/or death of other aquatic organisms (Wheeler et al., 2005).

The concentrations of several different ions are also elevated in streams draining urban areas. Elevated levels of chloride, sodium, calcium, potassium and magnesium are common in urban streams and could be the result of deicing practices in the watershed. These increases in ion concentrations cause an increase in stream conductivity (Paul and Meyer, 2001).

Heavy metals

It has become common to use stream concentrations of particulate and dissolved heavy metals as indicators of urbanization, as these metal concentrations are strongly correlated with the percentage of urban areas in a watershed (Chalmers et al., 2007; Widianarko et al., 2000). Research conducted on streams in New England, USA, revealed metal concentrations in urbanized watersheds up to six (6) times higher than those found in remote watersheds (Chalmers et al., 2007). The most common trace metals associated with urbanization include lead (Pb), zinc (Zn), chromium (Cr), copper (Cu), manganese (Mn), nickel (Ni), and cadmium (Cd); however, mercury (Hg), cobalt (Co), platinum (Pt) and barium (Ba) have also been identified as contaminants in urban streams (Chalmers et al., 2007; De Carlo et al., 2004; Paul and Meyer, 2001).

Elevated metal concentrations are most strongly associated with commercial, industrial and transportation (CIT) land uses due to the many anthropogenic sources these types of land use encompass; however, increases in metal concentrations are associated with all types of urbanization (Chalmers et al., 2007). Table 3.1 summarizes the primary sources of metals commonly associated with urban areas.

Table 3.1. Primary sources for metals commonly associated with urbanization.

Source	Metals									
	Zn	Cu	Cd	Pb	Hg	Ni	Co	Ba	Fe	Pt
Metal roofs	•	•	•			•				
Asphalt roofs				•	•					
Traffic										
Automobile exhaust				•			•			
Brake pads/dust		•								
Tire wear	•									
Motor oil	•			•						
Catalytic converter emissions										•
Deicing salt and anti-skid sand	•			•		•			•	
Industrial activities	•	•		•						
Fossil fuel burning							•	•		
Degradation of paints	•			•						
Degradation of brick				•						
Degradation of tiles, glass and rubber								•		
Corrosion of galvanized metals	•									
Corrosion of galvanized steel									•	

Heavy metals enter streams in both particulate and dissolved forms. In the particulate forms, metals adsorb to sediment particles and are introduced to the streams through erosion and heavy runoff events that transport loose sediment (Lee et al., 2004). Metals in the dissolved form are easily transported during storm events and do not require a minimum runoff velocity to be mobilized (Lee et al., 2004). "Aquatic sediments readily and labilely adsorb [the] heavy metals and…provide a sustaining repository for metal uptake by bottom dwelling [organisms]" (Ney and Van Hassel, 1983). Direct transfer through adsorption is considered a major path of exposure for aquatic organisms and the resulting accumulation of metals in animal tissue creates widespread impacts on the aquatic habitat due to bioaccumulation, biomagnification and metal toxicity within the food web (Wheeler et al., 2005).

Pesticides

Pesticides are another common urban-related pollutant found in streams. Research indicates that streams draining areas with higher populations and greater percentages of developed land contain a larger number of individual pesticides and degradates at higher concentrations. A sampling of 47 streams in a highly developed watershed of southeastern New York State, USA, revealed nine compounds (three insectides, one fungicide and five herbicides) with concentrations greater than 0.1 µg/L, two of which (both herbicides) were detected at concentrations greater than 1 µg/L. Similarly, a study of a highly developed Minnesota watershed reported 13 compounds (four insecticides, two fungicides and seven pesticides) with concentrations above 0.1 µg/L and four compounds (three herbicides and one fungicide) at concentrations higher than 1 µg/L. These results were compared to a lightly developed watershed that contained only three herbicides at concentrations greater than 0.1 µg/L; none of the three herbicides detected were present at concentrations higher than 0.4 µg/L (Phillips and Bode, 2004).

The most common compounds found in urban streams include the insecticides carbaryl, diazinon, melathion, chloropyrifos, imidacloprid, and N,N-diethyl-m-toluamide (known commonly as DEET), the fungicides metalaxyl and myclobutanil, and the herbicides 2,4-D, 2,4-D-methyl, diclorprop, diuron, imazaquin, bromocil, dicamba, sulfometuron, and glyphosate (Phillips and Bode, 2004; Sandstrom et al., 2005; Kolphin et al., 2006). Glyphosate, the most extensively used herbicide in the world, is a broad-spectrum herbicide used to control weeds; however, it may also be derived from the degradation of phosphoric acids in detergents, which are commonly found in wastewater treatment plant effluent (Kolphin et al., 2006). Diuron and imazaquin are herbicides that are commonly used in a variety of developed settings, including lawns, golf courses, and rights of way (Phillips and Bode, 2004). Diazinon and carbrayl are typically applied to turf grasses and gardens for the control of weeds, and melathion is used in the control of mosquitoes on ornamental grasses (Phillips and Bode, 2004). DEET, used as a personal insect repellent, is primarily introduced to streams through wastewater treatment effluent and is found at highest concentrations in urban areas (Sandstrom et al., 2005).

Some pesticides in dissolved phases enter streams through stormwater runoff or wastewater treatment plant effluent; however, most pesticides have a strong affinity for sediment particles and are thus mobilized through sediment movement. This method of introduction presents the same problem as heavy metals: the majority of pesticides are contained in streambed sediments, providing a direct method of transfer to bottom-dwelling organisms. The presence of pesticides in streams and stream bed sediments can cause acute or chronic ecotoxicological effects (Gan et al., 2005).

Other organic contaminants

A variety of other organic wastewater contaminants, such as prescription and non-prescription drugs, hormones, disinfectants, and fragrances, enter streams through wastewater treatment plants. As population density increases, wastewater treatment plant (WWTP) effluent volumes increase as well, adding more contaminants to streams: A study conducted in Iowa found that the concentrations and number of compounds detected in streams increased significantly downstream of urban centers. Research has shown concentrations of pharmaceutical compounds much lower than those used for medicinal purposes could have severe consequences for organisms; “select chemical combinations can exhibit additive or synergistic toxic effects, even when individual chemicals are present at harmless levels”. These contaminants have been found to alter algal growth and community structure (Kolphin et al., 2004).

The introduction of antibiotics and antimicrobial agents into streams through WWTP effluent is of considerable concern. Results from a study conducted in north-central Iowa revealed the presence of antibiotics in sections of streams downstream of WWTPs: Three different types of antibiotics (ofloxacin, sulfamethoxazole and trimethoprim) were found to be prevalent in these sections of streams. Antibiotics have a strong tendency to adhere to and accumulate in benthic sediments; concentrations of antibiotics in the benthic sediments of the Iowa streams were 20 - 1,000 times greater than concentrations in the overlying water column. The presence of antibiotics and antimicrobial agents (such as Triclosan) in streams and benthic sediments has been shown to increase antibiotic resistance in multiple bacteria lineages (Haggard et al., 2006).

Petroleum

Urbanization (and the resulting increase in population) is associated with increased traffic activity, which leads to the introduction of petroleum products into streams. Motor oil is deposited onto highways, roads and parking lots by leaking automobile crankcases and accidental spills and is then washed into stream during storm events. Parking lots have been designated as the primary source of oil and grease in urban runoff, with oil and grease concentrations up to 15 mg/l having been measured in parking lot runoff (Wheeler et al., 2005).

Polycyclic aromatic hydrocarbons (PAHs) are the products of the incomplete combustion of petroleum, coal, oil and wood and represent the largest class of suspected carcinogens (Van Metre and Mahler, 2003). Concentrations of PAHs are strongly correlated with urbanization, especially commercial, industrial and transportation land uses: average PAH concentrations in urban streams are approximately 30-times higher than streams in non-urban areas (Chalmers et al., 2007). Sources of PAHs include oil leaked from crankcases, tailpipe emissions and fuel oil spills (Hwang and Foster, 2005). PAHs are primarily particle-bound and are introduced into streams mainly through the washing and erosion of sediments accumulated on or around roadways and parking lots. Hwang and Foster (2005) found that basin yields of PAHs to the Anacostia River near Washington D.C. increase by up to 59 g/km^2/day during storm flows.

As PAHs have carcinogenic and mutagenic properties, their presence in streams is disconcerting. Wheeler et al., 2005 suggested that PAHs in stream sediments are responsible for the majority of macroinvertebrate toxicity. Hwang and Foster (2005) estimated that stormwater runoff was discharging approximately 989 g/day of PAHs into the river and provided evidence that linked liver and skin tumors in Brown Bullhead fish with elevated PAH levels in the Anacostia River.

3.1.5 Biological impacts of urbanization

Bacteria

In the year 2000, the USEPA released a report stating that 166,754 kilometers, or approximately 36% of all waters considered impaired, were impaired due to bacteria levels (USEPA, 2000b). Tufford and Marshall (2002) measured fecal coliform concentration in South Carolina streams and determined that the highest concentrations occurred in watersheds with the greatest proportions of commercial and mixed urban land use. Schoonover and Lockaby (2005) reported fecal coliform counts as high as 3,500 most probable number (MPN) per 100 mL in urban watersheds in western Georgia. This was higher than all other land uses included in the study, which produced maximum concentrations of 1,000 MPN/100 mL, 2,000 MPN/100 mL, 900 MPN/100 mL, and 600 MPN/100 mL for developing, pasture, unmanaged forest and managed forest land uses, respectively.

Research has indicated that adjacent impervious areas are the greatest source of fecal coliform in a given watershed; therefore, the amount of impervious surface is a strong indicator of fecal coliform load to nearby streams (Tufford and Marshall, 2002). The washing or erosion of contaminated sediments and particles is one of the main ways by which fecal coliform is introduced to streams, as the bacteria preferentially bind with sediment particles (Schoonover and Lockaby, 2006). As with other contaminants, this allows the bacteria to accumulate in benthic sediments. Leaking septic tanks, combined sewer overflows, and overwhelmed sewage distribution systems are also major contributors to urban stream bacteria concentrations (Higgins et al., 2005).

There is some controversy as to whether or not WWTPs are significant sources of fecal coliform bacteria. A study conducted near Houston, Texas, sampled effluent from WWTPs and concluded that the effluent was a significant source of fecal coliform to the bayou, especially during dry weather (Petersen et al., 2006). Another Houston, Texas study measured bacteria levels in WWTP effluent and determined the effluent was not a significant source in the Whiteoak Bayou (Petersen et al., 2005). While further research must be done to determine the actual impact of WWTP effluent on fecal coliform concentrations, there has been speculation that pathogenic organisms that enter a stream or water body in a viable-but-non-culturable state may be able to survive and reproduce in rich organic sediments (Petersen et al., 2005). As bacteria accumulates in benthic sediments and are fed by larger inputs of nutrients and organic matter (as discussed previously), the bed sediments may serve as a source of bacteria to overlying water (Petersen et al., 2005).

Petersen et al. (2005) determined that dry-weather storm sewer discharges were major sources of bacteria to nearby streams. Samples collected from storm sewer discharges revealed geometric means for E-coli and fecal coliform concentrations reaching 212 MPN/dL and 49 colony forming units (CFU)/dL, respectively. Thirty-nine percent of the E-coli-containing samples exceeded Texas water quality standards, while 28% of the samples exceeded the fecal coliform standards. The study concluded that increases in dry-weather storm sewer loads are likely a result of increased urbanization and development.

Rising bacteria levels in streams can be a severe threat to human health, as well as an upset to stream ecosystem functioning. The presence of fecal coliform bacteria is often associated with the presence of pathogens such as *Giardia, Shigella,* and *Salmonella.* A study conducted in 1970 reported that when water had fecal coliform concentrations higher than 2,000 CFU/100 mL, *Salmonella* was present with nearly 100% occurrence. Any of these pathogens, when ingested by humans, can cause intestinal illness or even death (Schoonover and Lockaby, 2005).

Algae

Research has shown that urbanization impacts algal communities primarily through changes in nutrient loads and light availability. Algal growth is commonly limited by nitrogen, phosphorus or light. Urbanization is associated with elevated stream nutrient levels (mainly nitrogen and phosphorus) and increases in light availability to streams through the removal of riparian vegetation. Thus, urbanization is a significant contributor to increases in algal growth in urban and the resulting decline in water quality via eutrophication (Busse et al., 2006).

Total and benthic chlorophyll-*a* concentrations in a stream are affected by the percentages of impervious surface and amount of urban areas in a watershed. Busse et al. (2006) reported that increases in urban development resulted in increases in chlorophyll-*a* concentrations, which were strongly correlated with increases in floating and benthic algae. Streams draining commercial sites were found to have the highest levels of total and benthic chlorophyll-*a*, floating and benthic algae and floating macroalgae when compared to rural, residential and undeveloped sites (Busse et al., 2006).

Biggs (2000) recommended a maximum of 30% filamentous algae cover to protect stream aesthetics, benthic biodiversity and habitat. Other researchers use chlorophyll-*a* concentrations to determine if a stream is impaired; some have suggested concentrations of chlorophyll-*a* as low as 15 mg/m^2 to prevent stream impairment. A study conducted on southern California streams revealed that streams draining developed sites consistently exceeded 30% algae cover and were classified as eutrophic (>70 mg/m^2), while all rural or reference streams were classified oligotrophic (<20 mg/m^2) (Busse et al., 2006).

Macroinvertebrates and fish

Aquatic fauna are usually confined by the geometry of the stream channel, making it more difficult for them to escape the spreading impacts of urbanization than terrestrial fauna (Wheeler et al., 2005). Urban streams are notoriously characterized by altered and impaired biotic communities. Studies conclude that even very low urban land cover levels (8-10%) cause significant changes in fish and macroinvertebrate communities (Roy et al., 2005; Wheeler et al., 2005).

Construction and erosion associated with urbanization introduces large amounts of fine sediments to streams. Resulting impacts on macroinvertebrates include reduced diversity and density, the abrasion, suffocation and shading of macrophytes, damage to respiratory structures, and reduction in habitat due to sediment filling interstitial spaces in stream beds (Wheeler et al., 2005). Increased stormflows from impervious surfaces displace organisms due to greater volumes, frequencies and velocities. The hydrologic, physical and chemical impacts of urbanization cause significant changes in the composition of macroinvertebrates assemblages, including: 1) lower taxonomic richness (Moore and Palmer, 2005); 2) a simplified, more homogeneous community structure that favors more pollution tolerant, hardy taxa (Morse et al., 2003); 3) shifts in the abundance of different functional feeding groups (decreases in the number of collectors, filterers and shredders, increases in the number of scrapers) (Roy et al., 2005), and 4) decreases in overall macroinvertebrate densities (Gresens et al., 2007).

Fish are also highly affected by urbanization. Larger amounts of fine sediments in streams clog the gills of fish, impair visibility, reduce prey abundance, and lower reproductive success (Wheeler et al., 2005). As the number of roads increase in developing urban areas, the number of culvert-type stream crossings increase. Culverts serve as barriers to fish movement and obstruct fish passages through high current velocities, shallow depths and vertical drops at outlets (Wheeler et al., 2005). Heavy metal concentrations, including lead, have been found in the body tissue of fish located in urban streams (Wheeler et al., 2005). Streams draining suburban areas were found to have more non-guarding species due to the fact that these species are more tolerant of altered flow regimes and increased sediment inputs present in suburban streams (Burcher and Benfield, 2006). Roy et al. (2007) concluded that increases in urbanization result in the reduction of fish richness, diversity, density, and abundance, especially of endemic and pollution sensitive species.

3.2 Traditional stormwater management

Stormwater has been an issue of concern since the emergence of ancient civilizations, around 3,000 B.C (Burian et al., 1999). The primary goals of early stormwater management were flood control and roadway drainage; however, in many cities, the stormwater system also served as a disposal method for waste. Open channels and ditches carried waste and runoff water away from cities to low-lying streams and rivers. Odor and aesthetic problems led to the covering of these channels and ditches and laid the groundwork for the underground stormwater and combined-sewer overflow systems that underlie many modern cities (Burian et al., 1999).

Until the 1960s, “the philosophy of stormwater management was to dispose of the water as quickly as possible from cities to the nearest receiving water” (Villarreal, 2005). Extensive underground piping networks were used to convey runoff from parking lots, roadways and buildings and discharge it into the closest stream or river. As the negative impacts of discharging stormwater runoff and wastewater into surface waters became apparant, the focus “shifted to include water quality concerns in addition to the traditional quantity concerns” (Burian et al., 1999). This new approach to managing stormwater emphasizes detention, retention and recharge (Niemczynowicz, 1999), and is referred to in this paper as ‘traditional stormwater management.”

3.2.1 Components of traditional stormwater management

Traditional stormwater management includes the curb-gutter-sewer system and is currently the conveyance system preferred by many municipalities (Li et al., 1998). The major components of this system are concrete curbs and gutters, drop inlets (catch basins), underground pipe networks and detention/retention basins. The majority of modern developments, both residential and commercial, utilize concrete curb and gutters to convey stormwater runoff from impervious surfaces (such as parking lots and roadways) to drop inlets (Li et al., 1998). These inlets are connected to extensive networks of underground pipes that carry the water either to existing surface waters or to large detention or retention basins.

A detention basin is an impoundment that collects and stores runoff and releases it through an outlet structure over an extended period of time. During a storm event, runoff ponds in the detention basin and is released slowly through the outlet structure to a receiving stream. While the water is ponded in the basin, gravitational settling is the predominant method of removing sediments and pollutants; therefore, the longer the water remains in the basin, the more removal occurs. However, the basin is designed to drain within 24-48 hours so that it remains dry during non-rainfall periods. Modifications to the traditional detention basin design include a shallow marsh to enhance pollutant removal through biological uptake and filtration or extra storage for high-volume storm events. Regardless of the design, the primary goals of detention basins are to reduce the peak flow of post-developed conditions to that of pre-developed conditions while providing water-quality treatment (VADCR, 1999).

Retention basins are the most common form of traditional stormwater management. Also called wet ponds, these function similarly to detention basins with the exception that they have a continuous pool of water between storm events. These basins also incorporate more wetland-type vegetation, thereby increasing the ability of the basin to remove pollutants through biological uptake and filtration. As with the detention basin, particulate pollutants are removed via gravitational settling. Retention basins offer more recreational and aesthetic benefits than detention ponds, and can also serve as wildlife habitat. Both retention and detention basins are most cost-effective when used to treat runoff from large drainage areas: their cost per acre treated is inversely proportional to the watershed size (VADCR, 1999).

3.2.2 Consequences

The perceived benefits of the traditional approach to stormwater management have led to the “extensive application of [the curb and gutter] system in both urban and suburban areas” (Li et al., 1998). While there are water quantity and quality benefits associated with the use of this system, there are many detriments as well.

Developments built prior to strict water-quality regulations typically do not use detention/retention basins to treat water before it is discharged into surface waters. Consequently, large amounts of sediment, pollutants and bacteria are emptied directly into streams and rivers and result in conditions such as those described previously in this paper (Li et al., 1998).

The use of detention/retention basins introduces another set of problems. VADCR (1999) states that sites with high permeability and high infiltration rates are not suitable for the placement of detention/retention basins and recommends the use of clay liners to reduce the potential for infiltration through the basin floor. Even without a liner, retention ponds are not viewed as a contributor to groundwater, as accumulated debris on the bottom of the pond impedes infiltration (USEPA, 1999h). The increase in urban-related impervious surfaces dramatically increases the amount of stormwater runoff that is produced during a precipitation event while decreasing the amount of water that can infiltrate into the ground and replenish the water table. The combination of increased runoff and decreased infiltration results in the lowering of the water table and decreased baseflow levels in streams (Li et al., 1998).

The basins effectively reduce peak flows by releasing stormwater over a longer period of time; however, the volume of water introduced to streams is unaffected. Developers in Virginia, USA, are only required to use the 2-year storm in calculating receiving channel adequacy (VADCR, 1999). Research has shown that basins designed according to the 2-year storm are inadequate in protecting the downstream channel from erosive forces. The use of smaller storms to size basins is recommended by USEPA (1999h). "It is becoming apparent that the increased total stormwater volume, longer duration of higher flows, and the synergistic effects of many detention systems within a region are creating significant problems," (Holman-Dodds et al., 2003) including in-channel erosion, the undercutting of banks and the armoring of stream beds due to higher flow rates and volumes (Paul and Meyer, 2001; Colosimo and Wilcock, 2007).

It has been well documented that water temperature in detention and retention basins can increase dramatically due to the exposure to sunlight and the shallow pool depth of the pool. Lieb and Carline (2000) reported temperature increases of up to 6.6ºC at a site downstream from a detention pond, a value that dramatically exceeds the 1.1ºC increase per hour required by the Clean Streams Law of Pennsylvania "for the maintenance of aquatic life in coldwater streams." The introduction of warm water to cold-water streams can be detrimental to biota, especially trout.

It may be convenient for municipalities to treat a large area with one basin; however, this imposes a dilemma when the basin fails or is not adequately improving the quality of the runoff. Upon failure or inadequate treatment, the entire volume of runoff from the drainage area is introduced to the receiving stream at a much lower quality than what is required for a healthy environment. An approach that incorporates a larger number of smaller management practices would be less detrimental to the stream if one of the practices were to fail, as each facility treats only a portion of the total runoff leaving the drainage area.

Although detention and retention basins offer peak flow reduction, flood control and some water quality benefits, they also cause many problems for the receiving stream and the water table. There is obvious need for improvements to the traditional approach to stormwater management: an approach is required that will include the necessary benefits for surface and ground waters without introducing a large number of detriments.

3.3 Low Impact Development: A new approach to stormwater management

The idea of low impact development (LID) arose in the 1990s as the negative impacts of traditional stormwater management became more apparent. Originally proposed by Prince George's County, Maryland, USA, the idea has slowly taken hold in many parts of the United States. The overall goal of this new approach is to "mimic the predevelopment site hydrology by using site design techniques that store, infiltrate, evaporate, and detain runoff" (Prince George's County, MD, 1999). While traditional stormwater management focuses on flood control by reducing peak-flow rates, LID addresses peak-flow rates in addition to reducing the total runoff volume (Dietz, 2007). The overall LID initiative calls for modified layouts for residential and commercial developments and changes in traditional zoning methods. This paper will focus solely on the stormwater management practices that have become associated with the LID concept: bioretention, porous pavement, constructed wetlands, gravel-based infiltration practices, vegetated swales, filter strips and buffers, sand filters and vegetated swales.

3.3.1 Bioretention

Bioretention cells, also called rain gardens, are composed of a porous media, mulch and vegetation. Water collects in the bioretention cell and infiltrates into the media, which is usually comprised primarily of sand. Soil fines and leaf compost can be added to the sand to manipulate the media infiltration rate and organic matter content. North Carolina State University's Stormwater Research Group recommends a mixture containing 85-88% washed, medium sand, 8-12% fines (clay and silt – can be in the form of topsoil), and 3-5% organic matter, which can be leaf compost, newspaper mulch, or another source of organic matter (Hunt et al., 2006a). If the in-situ soil is sandy loam or loamy sand it may be used as the bioretention media (VADCR, 1999); otherwise, the sand mixture can be produced by thoroughly mixing the appropriate amount of each constituent and filling a 'pit' to a minimum depth of three feet where the bioretention area is to be located (Winogradoff, 2001). The media is covered with a layer of mulch and the area is planted with pollution- and water-tolerant trees, shrubs and herbaceous species (Davis et al., 2001).

The primary goal of bioretention is to decrease surface runoff, increase groundwater recharge and remove pollutants from the stormwater entering the facility (Dietz, 2007). Bioretention areas are designed to remain dry between storm events, as the high infiltration rate of the media allows water to infiltrate quickly (VADCR, 1999). Pollutant removal occurs via filtration through the media, biological uptake by vegetation and microbial processes such as decomposition and biotransformation (Davis et al., 2006). As shown in Table 3.2, the majority of reported removal efficiencies from research studies demonstrate that bioretention effectively removes sediment and nutrients from stormwater. In addition, a study conducted by Dietz and Clausen (2005) reported that 98.8% of the water that entered a bioretention cell was retained through infiltration and evapotranspiration, with only 0.8% leaving the cell as untreated overflow.

Table 3.2. Average removal efficiencies for total suspended sediment (TSS), total nitrogen (TN), and total phosphorus (TP) for several peer-reviewed studies.

Study	**Average Pollutant Removal Efficiencies (%)**			**Hydrologic Reduction (%)**
	TSS	**TN**	**TP**	
Davis, et al. 2001			80	
Dietz and Clausen, 2005*		32	-110.6	98.8
Glass and Bissouma, 2005	98			
Hsieh and Davis, 2005*	91		63	
Hunt, et al., 2006b*	-170	40	-240	
Hunt, et al., 2006b*		40	65	
Weiss, et al., 2007*	85		72	

*Efficiencies based on reductions in mass, not concentrations.

Additional research performed by Hunt et al. (2006b) determined that using media with high phosphorus content results in phosphorus export from the bioretention area. By avoiding the use of a medium with high phosphorus content, a bioretention cell can reliably achieve high removal rates for total phosphorus. Designs can also be modified for limiting geologic conditions. Bioretention cells developed on sites with karst topography or low infiltration rates (such as clay soils) must be lined to prevent infiltration to the in-situ soil and incorporate an underdrain system to remove the water after it has passed through the media (VADCR, 1999).

There are some limitations regarding the use of bioretention. The size of the area draining to an individual cell should be no greater than 0.4 ha, and bioretention should not be used in areas where the seasonally high water table is less than 1.8 m from the bottom of the facility. Unstable soil strata, such as marine clay, and slopes greater than 20% make bioretention an unsuitable option as well (USEPA, 1999a; VADCR, 1999; USEPA, 2008).

The use of bioretention for stormwater treatment provides a natural-looking area that can be aesthetically beneficial to a site while also providing hydrologic and water quality benefits for stormwater runoff. There are many design modifications that allow bioretention to be used in a wide variety of topographic and geologic settings, and a considerable amount of research has been done to identify ways to improve upon the hydrologic benefits and pollutant removal efficiencies. "Despite certain problems with phosphorus export,…bioretention areas have proven to significantly reduce stormflow volumes and concentrations of many pollutants" (Dietz, 2007).

3.3.2 Permeable pavement

Permeable pavement, also known as porous pavement, is an alternative to traditional asphalt or concrete that allows water to pass through it. There are many different kinds of permeable pavement, including porous concrete, porous asphalt and interlocking grid pavers, which may be filled with grass, sand or gravel. Porous asphalt is created by removing the fines from the traditional asphalt mixture, which produces a pavement with interconnected voids and allows water to move through it (USEPA, 1999d). Porous concrete is similar to traditional concrete, however, the fine aggregates are removed and a uniform, open-graded coarse aggregate is mixed with Portland cement to create void space within the concrete (USEPA, 1999d). There are many types of interlocking grid-type pavers - web-type structures with voids that are filled with a permeable medium. Some are constructed of concrete, while others are made of plastic and are more flexible during installation on irregular surfaces (Booth and Leavitt, 1999). The medium filling the voids determines the system's infiltration rate and pollutant removal capabilities (Brattebo and Booth, 2003).

The use of permeable pavement systems in lieu of traditional asphalt or concrete has hydrologic, water quality, spatial, aesthetic and safety benefits. Using porous pavement instead of asphalt for parking lots and roadways minimizes the amount of impervious area in a watershed and effectively reduces both the volume and the peak flow rate of surface runoff during storm events (Bean et al., 2007). As water infiltrates through the pavement instead of leaving the site as runoff, porous pavement contributes significantly to groundwater recharge (USEPA, 1999d). The pavement also serves as a filtering device and successfully reduces the concentrations of many common stormwater pollutants (Dreelin et al., 2006). Table 3.3 shows the average removal efficiencies and hydrologic reduction from several different types of permeable pavements. With the exception of total nitrogen, the referenced studies show significant removal of sediment and nutrients, as well as considerable reductions in the amount of water leaving the site as surface runoff. All of the studies shown in Table 3.3 are compared to traditional asphalt when computing hydrologic reduction.

Table 3.3. Average removal efficiencies for total suspended solids (TSS), total nitrogen (TN) and total phosphorus (TP), as well as reductions in surface runoff, as compared to traditional asphalt.

Study	Pollutant Removal Efficiencies (%)			Hydrologic Reduction (%)	Type
	TSS	TN	TP		
Balades, 1995*	59				Reservoir structure
Dreelin,et al., 2006		-43	11	93	Grassy paver with underdrains
Gilbert, 2006*	90		69	72	UNI Eco-stone (12% voids)
Legret and Colandini, 1999*	59			97	Porous asphalt
Pratt, et al., 1995				63	Permeable concrete block pavement with reservoir structure – gravel sub-base
Pratt, et al., 1995				66	Permeable concrete block pavement with reservoir structure – blast furnace slag sub-base
Pratt, et al., 1995				53	Permeable concrete block pavement with reservoir structure – granite sub-base
Pratt, et al., 1995				55	Permeable concrete block pavement with reservoir structure – carboniferous limestone sub-base

*Efficiencies based on reductions in mass, not concentrations.

Permeable pavements have also shown to improve the safety of roadways during storm events by reducing spray generation and creating better skid resistance, but perhaps what makes these systems most attractive is the fact that "valuable land is not sacrificed to a single use – functional parking areas [can] also provide on-site stormwater control" (USEPA, 1999d; Dreelin et al., 2006). In addition, parking lots are the most favorable location for permeable pavements because they typically contribute a large percentage of the runoff that is generated in urban areas (Booth and Leavitt, 1999). Replacing several large impervious parking lots with permeable pavement can dramatically reduce the total amount of runoff leaving a watershed.

While permeable pavements seem to be an appealing alternative to impermeable parking lots and roadways, there are several restrictions and limitations regarding their use. The placement of porous pavement systems in areas with disturbed soils or soils that are easily moved by wind leads to clogging of the pavement, which severely reduces system functionality (Bean et al., 2007). The area where the pavement is to be installed should be relatively flat with field-verified permeability rates of at least 1.3 cm/hr (USEPA, 1999d). In addition, the site should allow at least 1.2 m between the bottom of the pavement and the top of the seasonally high water table to reduce the potential for groundwater contamination (USEPA, 1999d). Porous pavements should only be used on sites with light traffic; its use on high traffic areas and areas that experience significant truck traffic should be avoided (USEPA, 1999d).

Porous pavement systems require much more maintenance than traditional asphalt and concrete. Every-day traffic use, as well as snow removal and deicing procedures, deposit sediment and other particles on the pavement which build up and cause clogging. Clogging of the pavement surface drastically reduces the system infiltration rate, thereby decreasing the capability of the system to remove pollutants and decrease runoff volumes. It is recommended that the pavement be inspected and cleaned at least four times per year, which involves using a vacuum sweeper truck to remove sediments and spraying the surface with a high-pressure water hose to re-open the pores (USEPA, 1999d; Bean et al., 2007).

The installation and maintenance of permeable pavement systems are considerably more expensive and labor-intensive than traditional asphalt and concrete pavements. The costs to purchase materials and install them are 25-300% more than traditional asphalt and the installation is more complicated and time-consuming. The cost of maintenance can also be significant, as a vacuum sweeper truck and high-pressure washing system must be purchased to perform the required routine maintenance. However, if the cost of drainage facilities that are no longer needed due to reduced surface runoff is considered, the total project costs may be lower than traditional asphalt pavement. In addition, maintenance costs can be reduced if municipalities share equipment and maintenance responsibilities (Booth and Leavitt, 1999).

Research studies indicate consistent hydrological benefits of porous pavement regardless of the type or brand, and the majority of studies report significantly lower concentrations of measured pollutants in water that infiltrates through the pavement when compared to water that runs off of traditional asphalt (USEPA, 2000a; Bean et al., 2007). Research has also been done on many different types of pervious pavement systems and the results have lead to improvements in the design and application of these systems. Porous pavement located on sites with low permeability can utilize underground reservoirs and underdrains to collect and convey treated water to another facility or surface water body (USEPA, 1999d). A strict maintenance schedule can eliminate concerns of pavement clogging and failure and reduce repair and upkeep costs (Bean et al., 2007). With appropriate design modifications, proper installation and adequate, preventative maintenance, permeable pavement can be an attractive and beneficial alternative to traditional paving options.

3.3.3 Vegetated swales

Vegetated swales, also called grassed swales, are earthen channels planted with erosion-resistant, flood-tolerant grasses designed to provide water quality enhancement for stormwater as it passes through the swale. Although the primary function of a vegetated swale is stormwater conveyance, it provides both hydrologic and water quality benefits as well. Swales are designed so that water flows through them at a low velocity which allows some of the water to infiltrate into the subsoil, thereby reducing the overall volume of runoff leaving a site. Due to low velocities and dense vegetation, sedimentation and filtration processes also occur in the swale and aid in the removal of particulate pollutants. The use of curb and gutters and smooth-walled pipes in the traditional approach to stormwater management does not allow for velocity reduction, infiltration or pollutant removal. Vegetated swales could be a very suitable alternative for conveying stormwater to surface waters or additional stormwater treatment facilities (VADCR, 1999).

The majority of infiltration-oriented stormwater management practices recommend in-situ soils have a minimum infiltration rate to ensure that the practice functions properly. Soils should be at least as permeable as a silt loam soil with an infiltration rate of at least 0.7 cm/hr to be appropriate for the implementation of a vegetated swale. Soils that cannot establish dense vegetation cover, are eroded easily, or are wet/poorly drained should not be used for a vegetated swale. The slope of the swale should be relatively flat to prevent high flow velocities; however, the slope should be steep enough to ensure positive flow along the entire length of the swale. Swales should not receive runoff from areas that generate highly-contaminated runoff, and should be at least two feet above the seasonally high water table to prevent groundwater contamination. Additionally, vegetated swales should not receive runoff from drainage areas greater than two hectares, as it is imperative that the flow velocity within the swale remain low enough to encourage sedimentation and filtration of particulate pollutants. Grasses within the swale should be very dense and kept to a minimum height of ten centimeters to provide adequate filtration and aid in slowing the flow velocity (VADCR, 1999).

Numerous studies have been conducted on the water quality benefits offered by vegetated swales. While the removal efficiencies for nutrients vary considerably between studies, as shown in Table 3.4, vegetated swales consistently show good results for the removal of total suspended solids. With the exception of the study conducted by Yousef et al. (1987) the majority of the referenced studies show significant total phosphorus removals and moderate total nitrogen removals. Backstrom (2002) reported that 54% of the water entering the swale did not exit the swale due to infiltration, evapotranspiration or biological uptake. The studies conducted by Barrett et al. (1998) show significant exportation of bacteria from the swale, suggesting vegetated swales should not be used when the primary water quality concern is pathogens or bacteria.

Table 3.4. Average removal efficiencies for total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP) and bacteria, as well as the average reduction reported when comparing inflow and outflow of a vegetated swale. All removal efficiencies are based on reductions in mass, not concentration, and none of the studies incorporated check dams into their design.

Study	Pollutant Removal Efficiencies (%)				Hydrologic Reduction (%)
	TSS	TN	TP	Bacteria	
Backstrom, 2002	70				54
Backstrom, 2003	89				
Barrett, 2005	75				
Barrett, et al., 1998	89		55	-136	
Barrett, et al., 1998	87		45		
Rushton, 2001	83	58	26		
Yousef, et al. 1987		51	63		
Yousef, et al. 1987		41	42		
Yu, et al., 2001	94		99		
Yu, et al., 2001	48	20	50		
Yu, et al., 2001	67	14	29		

The primary water-quality concern for vegetated swales highlighted by research is the strong potential for the exportation of nutrients when inflow nutrient concentrations are low and the resuspension of sediment and particulate pollutants during high flow velocities (Barrett et al., 1998; Backstrom, 2003). An alternative design that has been suggested to prevent sediment resuspension is the incorporation of a small sediment forebay at the beginning of the swale (USEPA, 2008). The sediment forebay traps the majority of large-sized sediments before they enter the swale and makes it easier to remove trapped sediments. In locations with inappropriate soils or where groundwater contamination is a concern, the swale design can be modified to include a porous, engineered media (50% sand, 20% leaf mulch, 30% topsoil) and a gravel underdrain system to collect water after it has infiltrated through the media (VADCR, 1999). This modified design, commonly called a water quality swale, offers greater pollutant removal capabilities than a traditional vegetated swale and can make the swale a viable option in what would otherwise be an unsuitable location (VADCR, 1999). Check dams may also be strategically placed along the length of a traditional swale to slow flow velocities, encourage infiltration, and offer greater pollutant removal efficiencies. For maximum pollutant removal, the total volume that pools behind the check dams should equal the water quality volume for the contributing drainage area (VADCR, 1999).

Research has concluded that the use of vegetated swales as a stormwater conveyance method is an effective method of reducing surface runoff volumes and peak flow rates, as well as reducing the concentration and loads of pollutants from the runoff (Barrett et al., 1998). However, due to the variability of results regarding the nutrient and bacteria removal efficiencies of swales, it is strongly suggested that they be used in conjunction with other stormwater treatment practices, such as bioretention cells (USEPA, 1999g). Swales are cheaper than traditional piping methods of conveying stormwater and can offer hydrologic and water quality benefits as well, making them an attractive option for treating and transporting surface runoff (Barrett, 2005; USEPA, 2008).

3.3.4 Filter strips and buffers

A filter strip is a narrow piece of land planted with dense vegetation that is designed to filter sheet flow runoff. These pieces of land predominantly consist of grasses and legumes that remove sediment and pollutants through filtration, sediment deposition, infiltration and adsorption. The term ‘buffer’ usually refers to an area along a shoreline, wetland or stream. While these BMPs function similarly to filter strips, they are designed differently. A buffer ideally consists of three lateral sections: a stormwater depression area, a grass filter strip and a forested region. Each zone performs a specific role that is crucial to the overall function of the buffer. As water ponds in the stormwater depression area, particulate matter is removed via gravitational settling and water volume is reduced by infiltration. When the depression area is full, water overflows into the filter strip region of the buffer where it is filtered by dense vegetation and is given another opportunity to infiltrate or be taken up by plants. The forested area provides the final chance for infiltration and biological uptake and serves to further remove particulate matter and pollutants via filtration by vegetation (VADCR, 1999; USEPA, 2008).

Filter strips and buffers are most effective when they receive runoff as sheet flow; concentrated flow tends to form channels and cause erosion within the BMP. To assure that runoff enters the area as sheet flow, it is recommended that the contributing drainage area be limited to two hectares and the water travel no more than 45 m before reaching the BMP. These practices work best in permeable soils with high infiltration rates (greater than 1.3 cm/hr) and should be located in areas with relatively flat topography (5% or less). Additionally, soils should be able to establish dense covers of vegetation without the application of fertilizer and should not have high clay content (VADCR, 1999).

Research has shown filter strips and buffers effectively remove sediment and nutrients from stormwater runoff. Table 3.5 summarizes the findings by numerous studies that assessed the effectiveness of these practices in improving water quality. Some of these studies (Young et al., 1980, Dillaha et al., 1988) evaluated the performance of these BMPs when used to treat agricultural and feed lot runoff; results produced by these studies were very similar to those produced by BMPs used to treat urban stormwater. With the exception of the grass buffer studied by Dillaha et al., 1989, filter strips and buffers consistently produced high, positive removal rates for sediment, nutrients and bacteria. Studies performed by Dillaha et al. (1988), Dillaha et al. (1989), Coyne et al. (1998) and Mickelson et al. (2003) showed there is a strong correlation between the removal rates for sediments and nutrients and the width of the BMP: the wider the strip/buffer, the higher the removal rate. While the removal rates vary somewhat among the studies presented in Table 3.5, it can be concluded that filter strips and buffers are effective practices when used to enhance the quality of stormwater runoff.

Table 3.5. Average removal efficiencies for total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP) and bacteria for filter strips and buffers.

BMP	Study	Pollutant Removal Efficiencies (%)				Notes
		TSS	TN	TP	Bacteria	
Grass Buffer	Dillaha, et al., 1989*	56		-105		Width: 4.6 m
Grass Buffer	Dillaha, et al., 1989*	80		78		Width: 9.1 m
Grass Buffer	Schwer and Clausen, 1989*	95		89		Width: 26 m
Vegetated filter strip	Asmussen et al., 1977*	98				Dry antecedent conditions
Vegetated filter strip	Asmussen et al., 1977*	94				Wet antecedent conditions
Vegetated filter strip	Coyne, et al., 1995*	99			67	Width: 9.0 m
Vegetated filter strip	Coyne, et al., 1998*	96			75	Width: 4.5 m
Vegetated filter strip	Coyne, et al., 1998*	98			91	Width: 9.0 m
Vegetated filter strip	Daniels and Gilliam, 1996*	65				
Vegetated filter strip	Deletic and Fletcher, 2006*	69	46	57		
Vegetated filter strip	Dillaha, et al., 1988*	81	67	39		Width: 4.6 m
Vegetated filter strip	Dillaha, et al., 1988*	91	74	52		Width: 9.1 m
Vegetated filter strip	Fasching and Bauder, 2001	70				
Vegetated filter strip	Han, et al., 2005*	65				
Vegetated filter strip	Mickelson, et al., 2003*	70				Width: 4.6 m
Vegetated filter strip	Mickelson, et al., 2003*	87				Width: 9.1 m
Vegetated filter strip	Robinson, et al., 1996*	85				7% grade
Vegetated filter strip	Robinson, et al., 1996*	85				12% grade
Vegetated filter strip	Young et al., 1980*	79	84	83	69	Width: 24 m; accepts feed lot runoff

*Efficiencies based on reductions in mass, not concentrations.

Although the study performed by Deletic and Fletcher (2006) produced high average removal results for nutrients and sediment, they concluded that the performance of filter strips is highly variable and tends to decrease with increased flow rates. Therefore, if the practice is designed such that it receives large amounts of runoff at high flow rates, it may not produce high removal rates. Han et al. (2005) ascertained that the effectiveness of filter strips may fluctuate seasonally if the vegetative cover within the practice varies with the season. Additionally, the efficiency of these BMPs is highly dependent on the amount and density of vegetation; if weather conditions or the BMP location prevent the establishment of dense, hardy vegetation then the performance of the filter strip will suffer (VADCR, 1999). Lastly, to achieve maximum pollutant removal rates, a filter strip should be at least 7.5 m wide. This criterion demands large amounts of land, making this BMP unattractive in highly urban areas and areas where land is in high demand.

While filter strips and buffers are effective in removing sediment, nutrients and bacteria, the large amount of land required for maximum pollutant removal rates and the variability that had been demonstrated in research studies make them a less attractive option for stormwater treatment. The USEPA (2008) recommends that buffers and filter strips be used in combination with other treatment practices to maximize flow reduction and the improvement in water quality. If used as suggested by the USEPA (2008), filter strips and buffers could contribute greatly to pollutant and sediment reductions of runoff when used in conjunction with other LID strategies or when implemented around surface water bodies to supplement regional stormwater management approaches.

3.3.5 Constructed wetlands

Constructed wetlands mimic the hydrologic and ecologic processes of natural wetlands while also enhancing the quality and reducing the quantity of stormwater runoff (USEPA, 2008). These systems are built in areas where natural wetlands do not occur and while often created to offset the destruction of natural wetlands, they have recently become a popular stormwater management tool used to combat the impacts of urbanization on the quantity and quality of runoff (VADCR, 1999). The primary benefits of wetlands include the conveyance and storage of stormwater, the reduction of flood flows, the reduction in stormwater velocities and peak flow rates and the modification and/or removal of pollutants (VADCR, 1999; Kao et al., 2001).

Constructed wetlands are designed to have multiple regions with varying water depths, including deep pools and channels, low- and high-marsh zones, and semi-wet zones. The variety of depths throughout the wetland allow for greater diversity in plant and animal species and each region serves a specific function with regard to water quality enhancement and quantity control. The deep pool and channel zones, which range from 0.5 m to 2 m in depth, serve as a means to lengthen the flow path within the wetland and provide opportunities for the gravitational settling of particulate matter. Marsh zones contain a wide variety of wetland plants, including submerged and emergent species, and provide habitat for wildlife. Plants are an important component of wetlands, as they facilitate sedimentation and decrease water velocities by obstructing flow, act as a filtration system for particulate matter, provide biological uptake of nutrients and dissolved pollutants, and serve as food and habitat for wildlife. The semi-wet zone remains dry between runoff events but is wet during periods of rainfall and serves as temporary storage of stormwater to aid in the reduction of the peak flow rate and runoff volume. Plants located in this region grow well in dry conditions but can tolerate brief periods of inundation. The size of the semi-wet zone determines the size storm that can be treated and controlled by the wetland: large semi-wet zones allow the storage and slow release of larger runoff volumes and provide higher pollutant removal efficiencies than small semi-wet zones (VADCR, 1999).

Wetlands are intended to remain wet at all times and are therefore required to have a constant source of baseflow, even during dry periods. In areas that experience little rainfall or do not have a high water table, the continuous baseflow requirement results in the need for a large drainage area. Minimum drainage areas of 4-10 ha are recommended, but an analysis of the individual site is necessary to ensure the drainage area is large enough to provide the required baseflow. The in-situ soil requirements are similar to those for a wet pond: wetlands located in soils with high infiltration rates or in areas of karst topography must use impermeable liners to prevent the infiltration of water. Longer hydraulic detention times and flow paths within wetlands result in high pollutant removal efficiencies; therefore, larger wetlands are recommended if water quality enhancement is a primary goal. Additionally, the majority of the wetland is designed to be relatively shallow. These two constraints result in wetlands with large surface areas - usually 2-5% of the size of the contributing watershed (VADCR, 1999; Carleton et al., 2001; USEPA, 2008).

Constructed wetlands are considered one of the most effective practices for removing pollutants from stormwater runoff (USEPA, 2008). The many different physical and chemical processes that occur within the system, such as gravitational settling, biological uptake, filtration, decomposition, and chemical transformations, allow for considerable reductions in pollutant concentrations and loads (Birch et al., 2004). Table 3.6 summarizes several research studies conducted on the water quality enhancement capabilities of constructed wetlands used for stormwater treatment. Studies conducted by Martin (1988) and Weiss et al. (2007) produced similar results regarding TSS reductions; however, removal efficiencies for TN and TP varied considerably. The discrepancy between Adler et al. (1996) and the other two studies could be because the Adler study was a bench-scale study used to mimic the natural processes of a wetland. Taking all three studies into consideration, constructed wetlands can be expected to provide average TSS, TN and TP removal rates of approximately 67%, 32% and 51%, respectively, based on reductions in concentrations.

Table 3.6. Average removal efficiencies of a constructed wetland for total suspended solids (TSS), total nitrogen (TN) and total phosphorus (TP).

Study	Pollutant Removal Efficiencies (%)		
	TSS	TN	TP
Adler et al., 1996		42	95
Martin, 1988*	54	20	15
Weiss et al., 2007	68		42

*Efficiencies based on reductions in mass, not concentrations.

Wetlands also provide flood attenuation and downstream channel erosion control by temporarily storing stormflows and releasing them over an extended period of time (USEPA, 1999f). In addition, they offer aesthetic and habitat benefits and enhanced diversity of animal and plant life (Grayson et al., 1999; USEPA, 1999f). The maintenance requirements of constructed wetlands are considerably less than infiltration practices such as bioretention and porous pavement and are essentially the same as retention ponds (USEPA, 1999f ; USEPA, 2008).

Although constructed wetlands offer several water quality and quantity benefits, there are also disadvantages to their use. A wetland constructed with a contributing drainage area that is too small to provide constant baseflow results in a BMP that does not perform its intended functions and may be a threat to water quality (VADCR, 1999). Unfortunately, the large amount of area required for an effective constructed wetland often renders it an unattractive option for highly urban areas or where land is valuable (VADCR, 1999). Several design alternatives to the traditional wetland design exist that minimize the amount of land required for the wetland to function properly, such as pocket wetlands and pond/wetland systems (USEPA, 1999f). However, these designs still require significantly larger drainage areas than other stormwater BMPs and can be a threat to groundwater quality due to the required intersection with the water table to provide sufficient baseflow (USEPA, 1999f).

During the construction of the wetland, measures are taken to prevent water from infiltrating into the in-situ soil; consequently, constructed wetlands do not serve as a source of groundwater recharge, which is a considerable disadvantage in urban areas with low water tables (USEPA, 2008). As with retention basins, the shallow standing water of a wetland leads to the increase in water temperatures. The discharge of warmer water can be detrimental to cold water streams and have negative impacts on downstream biota. Furthermore, constructed wetlands are used to treat large drainage areas. This regional approach to stormwater management can treat substantial volumes of stormwater runoff at one time, but does not address the impacts of urbanization on smaller headwater streams in the contributing drainage area. Unless smaller, site-specific BMPs are implemented, these small streams can continue to degrade. Finally, many urban areas with constructed wetlands experience problems with undesirable waterfowl such as geese and ducks. Attracted by the habitat of the wetland, these species can quickly become a nuisance to residents, may threaten native species and pose as a threat to water quality through fecal deposition in the wetland (USEPA, 1999f).

While constructed wetlands are effective stormwater management practices for reducing runoff volumes and peak flow rates and removing pollutants, they have many disadvantages. Most of these drawbacks are similar to those of retention ponds and other BMPs associated with the traditional approach to stormwater management. Therefore, given that the need for low impact development strategies has become more apparent, alternative stormwater treatment practices appear more appropriate for addressing water quality and quantity issues associated with urbanization.

3.3.6 Gravel infiltration trenches

Infiltration trenches (ITs) are shallow, excavated trenches backfilled with a stone aggregate and can either be open-surface or underground facilities. Open-surface facilities receive stormwater via sheet flow while underground facilities accept runoff from pipes. These BMPs are designed to allow stormwater runoff to infiltrate through a porous, coarse aggregate and exfiltrate to the surrounding soils. The movement of water through the stone aggregate facilitates pollutant and sediment removal by means of filtration, while the collection of water in the bottom of the trench prior to exfiltration provides volume and peak flow rate reduction. Most ITs are designed without an outflow device and are sized to allow collected water to exfiltrate within 48 hours. Consequently, it is suggested that they only be used to treat areas 2 ha or less (VADCR, 1999).

ITs may only be implemented on sites with infiltration rates between 1.2 and 7.6 cm/hr and where soils contain less than 30% clay content. To prevent groundwater contamination, the bottom of the trench must be greater than 0.6 m above the seasonally high water table and ITs must not accept runoff from stormwater 'hot spots'. A stormwater hot spot is an area such as a gas station or highly industrial site that produces runoff with high concentrations of pollutants such as gasoline, motor oil or other chemicals. Additionally, these practices may not be used in areas underlain by karst topography (VADCR, 1999; USEPA, 2008).

Few data exist regarding the performance of gravel-based infiltration trenches; however, a small number of non-peer-reviewed studies performed by governmental organizations have indicated high removal rates for suspended solids, particulate pollutants and coliform bacteria (USEPA, 1999b). These types of BMPs are also beneficial for increasing groundwater recharge, replenishing the water table and raising baseflow in nearby streams (USEPA, 1999b). The linear shape of these facilities is ideal for retrofitting them in existing urban areas or locating them around the edges and in unused spaces on new development projects (USEPA, 2008). They can also be placed underground to preserve land in areas where space is limited and land is in high demand (VADCR, 1999).

The main concern associated with infiltration trenches is their high potential for failure: these BMPs tend to fail more frequently than other stormwater management practices (VADCR, 1999). A study conducted by the Maryland Department of the Environment concluded that 53% of infiltration trenches were not functioning as designed and 36% were partially or totally clogged (USEPA, 1999b). The majority of IT failures are attributed to clogging by sediment, oil and grease; therefore, it is strongly encouraged (and in some localities required) to incorporate pretreatment BMPs into the design of the IT (VADCR, 1999). Sediment forebays, grass filter strips or vegetated swales serve to remove a significant portion of particulate matter and hydrocarbons before they enter the trench and prevent them from diminishing the infiltration capacity of the media (USEPA, 2008). The size of the contributing drainage area greatly influences the amount of sediment and hydrocarbons entering the trench: ITs treating larger drainage areas tend to clog quicker and more frequently than those treating smaller drainage areas (USEPA, 2008).

The in-situ soil requirements for IT implementation often prevent them from being used: urban areas typically consist of clay-based fill soils that have been compacted to allow for drainage and development and the infiltration rates do not meet the minimum 1.2 cm/hr rate required for implementing infiltration trenches (Nelson et al., 2006). However, modifications to the original IT design can allow their use in urban areas as well as areas with karst topography. The incorporation of an impermeable liner on the bottom and sides of the trench and an underdrain system allow for the filtration of stormwater through the media but transport collected water to the existing storm sewer system instead of exfiltrating it (USEPA, 2008). Other modifications may be made to enhance pollutant removal: Substituting pea gravel for the top 30 cm of stone aggregate improves sediment filtering and maximizes pollutant removal. Adding a layer of organic matter or loam soil to the subsoil increases the removal of metals and nutrients (USEPA, 1999b).

Infiltration trenches are useful stormwater treatment practices, as their linear shape allows them to fit in small, unused areas of development and preliminary research results indicate good removal rates for sediment, bacteria and particulates. Design modifications may be used to expand the suitable applications for these BMPs. For example, areas with compacted or high-clay soils may employ ITs with an underdrain system. The maintenance burden and historically high failure rate should make developers leery of applying these practices; however, designs that incorporate pretreatment facilities and include a comprehensive maintenance plan may be strongly considered for treating small urban drainages areas.

3.3.7 Sand filters

Sand filters may be constructed above or below ground and typically consist of two or three chambers through which stormwater flows. As runoff enters the facility, it flows into the sediment chamber where it pools and particulate matter is removed via gravitational settling. The water pools to a certain level, usually 1 m, and flows over a submerged weir or through a perforated riser to the filtration chamber. The filtration chamber contains a bed of sand, usually a minimum of 0.5 m deep, underlain by a layer of gravel. Water percolates through the sand and gravel before being discharged via underdrain collector pipes which are connected to the existing storm sewer system. This second chamber uses filtration and adsorption to remove hydrocarbons, finer particles and some soluble pollutants. Some filters are designed with a third chamber, or clearwell, that collects the flow leaving the filtration chamber and discharges it to the storm sewer system or surface waters (USEPA, 1999e ; VADCR, 1999).

There are very few restrictions as to where sand filters may be applied. The majority of sand filters are not designed to interact with subsoils or groundwater; therefore, there are no infiltration rate or soil type requirements. It is recommended that the bottom of the filter be at least 0.6 m from the seasonally high water table; however, the filter design may be modified such that the chamber is located below the seasonally high water table. As the chambers are designed to be water-tight, there is no concern of groundwater contamination. Whereas most stormwater BMPs are recommended for watersheds with low percentages of impervious surfaces and low-density residential applications, sand filters require a high percentage of impervious surfaces. An impervious cover of at least 65% is recommended to reduce the amount of sediment introduced to the filter. In high-traffic areas or where aerial deposition of particulate matter is a problem, pretreatment BMPs such as vegetated swales, filter strips or sediment forebays should be included in the filter design (VADCR, 1999).

Perhaps the most important design constraint is the required elevation drop for the system to perform by gravity-controlled flow. The elevation difference between the inlet and outlet must be at least the height of the filter to ensure water flows through the system as intended (VADCR, 1999). Areas with flat terrain may use a pump system to control water flow through the system, but these have high maintenance requirements, increase the construction and maintenance costs of the BMP and are prone to failure. Barrett (2003) had significant problems with the utilization of pumps, as there was continuous clogging of the pump system and the “pumps failed repeatedly.”

There are several different designs that allow sand filters to be applied in a variety of situations and site conditions. Washington, D.C. sand filters, typically placed underground, are used to treat drainage areas that are 0.4 ha or less and that contain a large amount of impervious surface. Delaware sand filters are underground sand filters that treat drainages areas up to 2 ha. These filters are shallower than the Washington D.C. filter and therefore have lower maintenance and construction costs and are more easily applied in areas with high water tables or bedrock. The Austin sand filter emphasizes pretreating stormwater before it enters the filtration basin. In this type of filter, the sedimentation basin is designed to hold at least 20% of the WQV (preferably more if space and funding allows). No water enters the filtration basin without being held in the sedimentation basin for an extended period of time to allow particulate settling. These filters can accept runoff from drainage areas up to 20 ha and are typically designed as open-surface filters (VADCR, 1999; USEPA, 1999e).

Sand filters are well suited for areas with large amounts of impervious surfaces, such as commercial and industrial uses, and they are capable of treating runoff from stormwater hotspots without contaminating groundwater (VADCR, 1999). Underground filters can be placed under parking lots or buildings and are especially useful in ultra-urban areas where space is limited and land is expensive (USEPA, 2008). Surface sand filters can be positioned around the perimeter of a site to treat runoff in a manner that does not occupy much-needed land (USEPA, 2008).

In addition to being suitable stormwater management practices for highly urbanized and impervious areas, sand filters provide many water quality benefits. Research results produced by Barrett (2003) indicate these BMPs are effective in reducing sediment, nutrient and bacteria concentrations in stormwater runoff. Barrett (2003) studied an Austin sand filter with a sedimentation basin designed to hold the entire water quality volume. Total suspended solids, total phosphorus and fecal coliform bacteria concentrations were reduced an average of 90%, 39% and 65%, respectively. When inflow concentrations were high, the filter also showed excellent reductions in the concentrations of dissolved heavy metals. While total nitrogen concentrations decreased by 22%, nitrate concentrations were significantly higher in the effluent than in the influent.

Slight modifications to the filtration media may increase removal rates for various constituents. The addition of a peat layer in the filtration chamber may improve removal rates of nutrients and heavy metals by increasing microbial growth within the media. Additionally, sands with high iron (and possibly aluminum and calcium) content are expected to increase phosphorus removal within the filtration chamber (VADCR, 1999).

There are some disadvantages to using sand filters for stormwater treatment. These practices are very susceptible to clogging (and, subsequently, failure) when subjected to high sediment and hydrocarbon loads. This is of concern especially in watersheds with large amounts of pervious surfaces or in areas with significant deposition of sediment and particulate matter. It is recommended to include pretreatment BMPs in the designs of filters used in these areas or to consider other stormwater management practices (VADCR, 1999).

Sand filters are primarily designed to improve the quality of stormwater runoff; they do not provide runoff volume or peak flow attenuation. Additionally, they can only treat the water quality volume they were designed to treat: Any additional water does not receive adequate treatment and/or bypasses the system. Finally, these practices are, overall, more expensive than comparable stormwater management facilities. The majority of underground filters are considered confined spaces, which increases the cost of maintenance. Construction costs for open-surface and underground filters are also much higher than other structural BMPs (VADCR, 1999).

Sand filters are very effective practices for improving the quality of stormwater runoff in highly urbanized areas. While only a small number of research studies have been performed, the results from those studies indicate considerable reductions in the concentrations of nutrients, sediment and bacteria. While they tend to be more expensive than other stormwater BMPs, underground sand filters eliminate land acquisition costs and allow land to be used for purposes other than stormwater treatment, thereby making them economically viable options where land is expensive and in high demand. Surface sand filters are also viable options, as they are ideal for retrofit projects and can fit in small, unused spaces on developed sites. Overall, sand filters are excellent options for stormwater treatment in highly developed and impervious areas.

3.3.8 Vegetated roofs

Vegetated roofs, also known as green roofs, offer many environmental benefits over traditional asphalt or tin roofs by 1) providing insulation for buildings and reducing energy consumption; 2) increasing the roof life span by protecting it from ultraviolet (UV) rays and extreme temperatures; 3) contributing to the reduction of the urban heat island effect, and 4) filtering harmful air pollutants (VanWoert et al., 2005). In addition, green roofs can also offer dramatic reductions in runoff volumes and peak flow rates, and potentially improve the quality of water leaving the roof.

Vegetated roofs typically consist of four layers: impermeable liner, drainage layer, growth medium, and vegetation. The impermeable liner is placed on top of the roof, under the drainage layer and serves to protect the roof from intruding roots and to keep water from reaching the underlying structural components. The drainage layer is highly permeable and consists of a pre-fabricated drainage mat or plastic/geotextile drainage material that channels water to the roof edge. The expanded slate aggregate growth medium is lightweight, low-density, and is usually a mixture of Stalite, or an equivalent, sand and organic matter. Hardy vegetation covers the roof to intercept and evapotranspire precipitation and to provide shade. A porous expanded polypropylene (PEPP) vegetative support above the growth medium is optional; however this layer can increase the retention and detention capabilities of an extensive roof and provide additional thermal insulation (DeNardo et al., 2005; Carter and Rasmussen, 2006).

Two types of green roofs exist: Intensive roofs contain growth medium layers of at least 15cm and are generally designed to be accessible by the public for recreation. These types of roofs can support large shrubs and trees, as well as public facilities such as picnic tables and furniture. Extensive roofs have growth medium layers less than 15cm thick and are not accessible for public use. Intensive roofs are more expensive to construct and maintain, but provide aesthetic and recreational benefits that extensive roofs do not. Extensive roofs are more easily implemented on existing buildings, as they normally do not require additional construction or structural reinforcements. They also are designed to be low maintenance and are less expensive to construct than intensive roofs (USEPA, 2008).

One key requirement governing the construction of vegetated roofs is the building must be able to hold the weight of the roof's components when they are fully saturated. Most flat-roofed buildings are capable of withstanding the additional weight of a retrofit extensive green roof without any additional structural reinforcements or building modifications. However, intensive roofs are much heavier and require more support than traditional or extensive roofs. Vegetated roofs may be installed on slopes up to 20% with no negative impacts on their performance (USEPA, 2008).

Several research studies have been conducted to determine the hydrologic benefits of vegetated roofs in urban areas. The results of these studies consistently concluded that extensive vegetated roofs are very effective in reducing total runoff volumes and peak flow rates when compared to traditional, non-vegetated roofs. Carter and Rasmussen (2006) determined that an extensive roof in Athens, Georgia, USA, retained an overall average of 78% of the precipitation that fell on the roof, and retained over 90% of precipitation for all storms that produced less than 1.27 cm of rainfall. The roof also reduced peak flow rates and produced a lag time 18% greater than a traditional asphalt roof. The results produced by studies summarized in Table 3.7 support these findings.

Table 3.7. Hydrologic reductions for extensive vegetated roofs.

Study	Volume Reduction (%)
VanWoert et al., 2005	83
Villarreal, 2007	52
DeNardo et al., 2005	45
Kohler et al., 2002	70
Moran, 2004	63
Berndtsson et al., 2006	49

Very few studies of vegetated roofs have included an evaluation of their water-quality benefits. The studies that have been performed have produced conflicting results as to improvements vegetated roofs make in the quality of runoff leaving a roof. Moran (2004) found that TP concentrations were much higher in runoff leaving a vegetated roof than of that leaving a non-vegetated roof. Additionally, the concentrations of TN were higher in green roof runoff than in traditional roof runoff for the majority of rain events; however, this study used composted daily manure on the roof, which could be the reason for higher outflow concentrations of nutrients. Due to the volume reduction attained by the vegetated roof, the TP and TN mass loads were highly variable and no conclusions could be drawn when compared to traditional roofs. Berndtsson et al., 2006 concluded that extensive green roofs are significant sources of potassium and phosphate, with the primary source of the phosphate being the fertilizer applied to support the vegetation. Two of the four roofs studied reduced runoff TN concentrations: the other two acted as sources and increased TN concentrations. Conversely, Kohler et al. (2002) reported significant retention of nitrate and phosphate, with average concentration reductions of 80% and 67.5%, respectively.

There are several issues of concern regarding the use of vegetated roofs for stormwater quantity and/or quality control. Carter and Rasmussen (2006) discovered that once the drainage layer and growth medium became saturated with water, the roof behaved very similarly to a traditional roof. Correspondingly, this study determined that an inverse relationship exists between the depth of rainfall and the amount of precipitation retained by the roof, as well as between the depth of rainfall and the peak flow reduction attained by the roof. VanWoert et al. (2005), Villarreal (2007) and Moran (2004) confirmed these results. In comparing extensive roofs in humid climates with those in temperature climates, Kohler et al. (2002) noted that decreased evaporation during colder months in temperate climates significantly affects the retention and detention capabilities of vegetated roof systems.

The variability in data from studies evaluating water quality of vegetated roof runoff suggests that more research should be performed before implementing these systems with the primary goal of water quality improvement. However, it is unquestionable that vegetated roofs provide considerable hydrologic benefits through the retention and detention of precipitation. The retention of at least 50% of precipitation could mean significant reductions in the amount of stormwater introduced to a city's stormwater system and ultimately to surface waters: A modeling study of Washington, D.C. found that if 20% of buildings 930m^2 or larger installed green roofs, a total of roughly 1.1 million cubic meters of stormwater would be prevented from entering the city's storm sewer system (USEPA, 2008). This amount of reduction in stormwater could reduce stormflow volumes and rates within urban streams and decrease the erosion of streambanks.

4. Methods

4.1 Site description

The study site, located at 37° 14' N, 80° 24'W in Blacksburg, Virginia (Figure 4.1), is situated in the Ridge and Valley Physiographic Province, between the Alleghany and Blue Ridge Mountains. On average, the site receives approximately 109 cm of rainfall per year and experiences mean daily maximum temperatures that range from 5°C in the winter to 28°C in the summer (NCDC, 2008). During the warmer months, rainfall primarily comes in the form of convective thunderstorms, which produce high intensity, short duration rainfall events (UVA, 2000). Winter months are dominated by frontal storms, which produce low-intensity, long-duration events (UVA, 2000). The

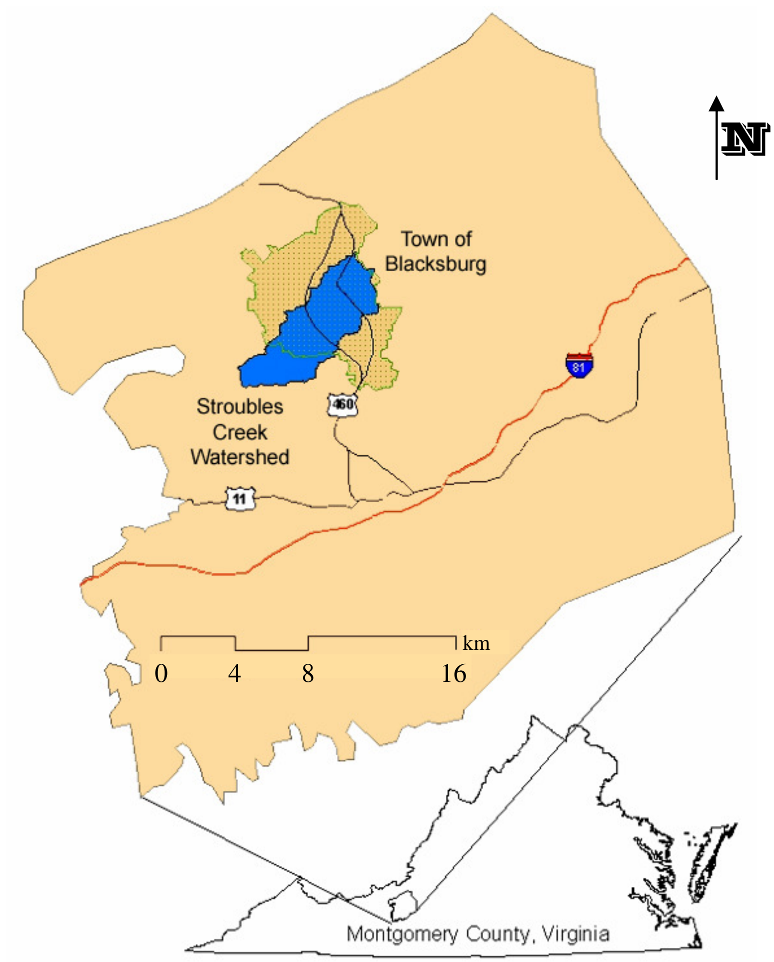


Figure 4.1. Location of the impaired section of the Stroubles Creek watershed in relation to the state of Virginia, Montgomery County and the Town of Blacksburg.

majority of data collected for this study was collected during winter months; however, some storm events were characterized by high-intensity, short-duration rainfall and are representative of summer-type thunderstorms.

Stroubles Creek, a tributary of the New River, was listed on the Virginia 303(d) list for both aquatic life (benthic macroinvertebrate) and bacterial impairments along an 8.0-km segment (VAW-N22R_STE04A00) between the Virginia Tech Duck Pond and the downstream confluence with Wall Branch. The 25-km^2 watershed corresponding to the impaired segment includes major portions of the Town of Blacksburg and the Virginia Tech campus and contains a significant amount of urban area. Approximately 46% of the upper Stroubles Creek watershed is urban/residential, while 28%, 21% and 5% of the watershed is forest, pasture and cropland, respectively.

A 2003 total maximum daily load (TMDL) study identified sediment as the leading cause of the benthic macroinvertebrate impairment (Mostaghimi et al., 2003). Construction and streambank erosion due to increased urban storm flows were cited as major sediment sources within the watershed. A subsequent TMDL implementation plan developed in May 2006 called for the implementation of retrofit stormwater management practices within the Town of Blacksburg and on campus to reduce sediment and high flow volumes in the creek (Yagow et al., 2006). Based on current urban development and growth patterns, it was estimated that all of the forested and agricultural land within the Blacksburg portion of the watershed will be eliminated by 2046, thus making it essential that BMPs be evaluated as methods of mitigating the impacts of urbanization on surface water quality.

Two innovative BMPs, a bioretention cell (BRC) and an infiltration trench with CU-Structural Soil™ (ITSS) were constructed at the Blacksburg Aquatic and Community Centers (Figure 4.2) to treat runoff from the parking lots and to serve as research and demonstration projects. Existing stormwater management at the site consisted of traditional curb and gutter and dry detention ponds, which discharged runoff to an unnamed tributary of Stroubles Creek.

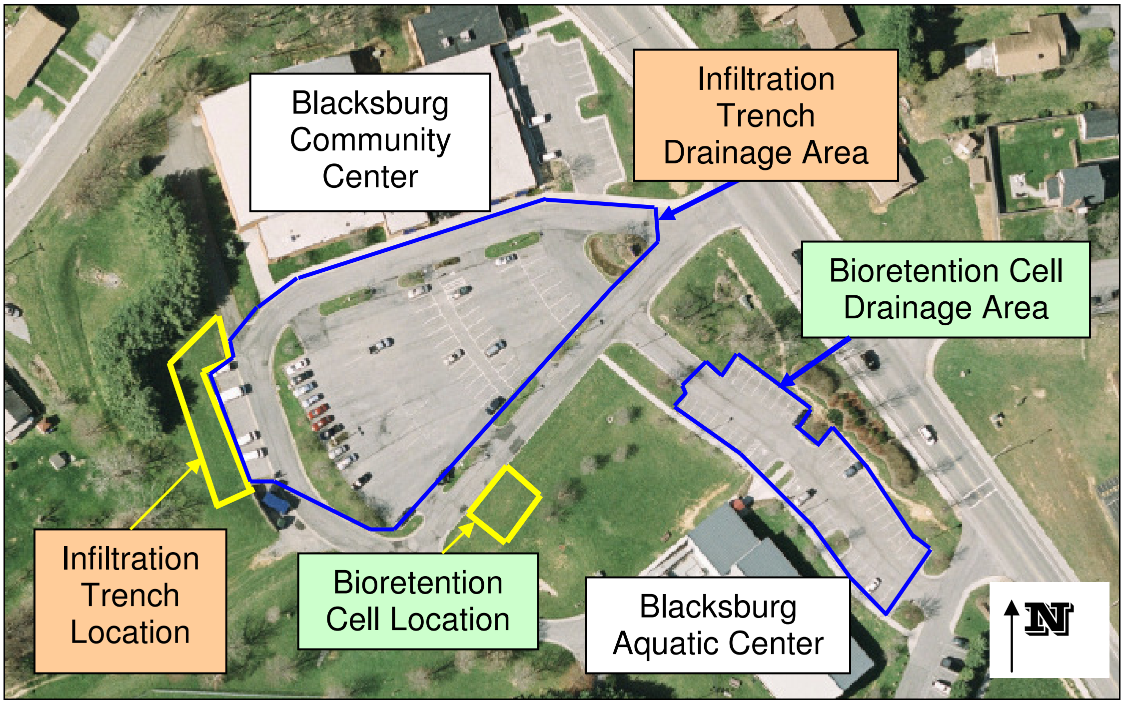


Figure 4.2. Best management practice locations in relation to their drainage areas and the Blacksburg Aquatic and Recreation Centers.

4.2 BMP design

The BRC and ITSS were designed to hold the first 13 mm of runoff from a 0.16-ha and a 0.73-ha asphalt parking lot, respectively. Additionally, both BMPs were designed to match the pre-development peak flow rates of a 2-yr and a 10-yr, 24-hr storm event. Observations of significant sediment deposition in the parking lot gutters and drop inlets draining to the ITSS led to the inclusion of a sediment forebay upstream of the ITSS. Due to underlying karst geology, extended ponding of water within the BMPs was not recommended; therefore, the BMPs were designed with a clay liner on the bottom of the BMPs and underdrain system.

The ITSS, Figure 4.3, is 27.0 m long, 3.7 m wide and 1.3 m deep and is filled with CU-Structural Soil™. CU-Structural Soil™ was developed by the Urban Horticulture Institute at Cornell University to provide urban tree root growth area within the gravel subgrade layers under paved surfaces, such as parking lots or sidewalks. It consists of approximately 85% #357 stone and 15% clay/loam soil held together with Gelscape® hydrogel. Gelscape® hydrogel is a potassium propenoate-propenamide copolymer

(Amereq Corp., New York, NY, USA) designed to force the soil to adhere to the stone in order to promote water and nutrient retention while maintaining high porosity.

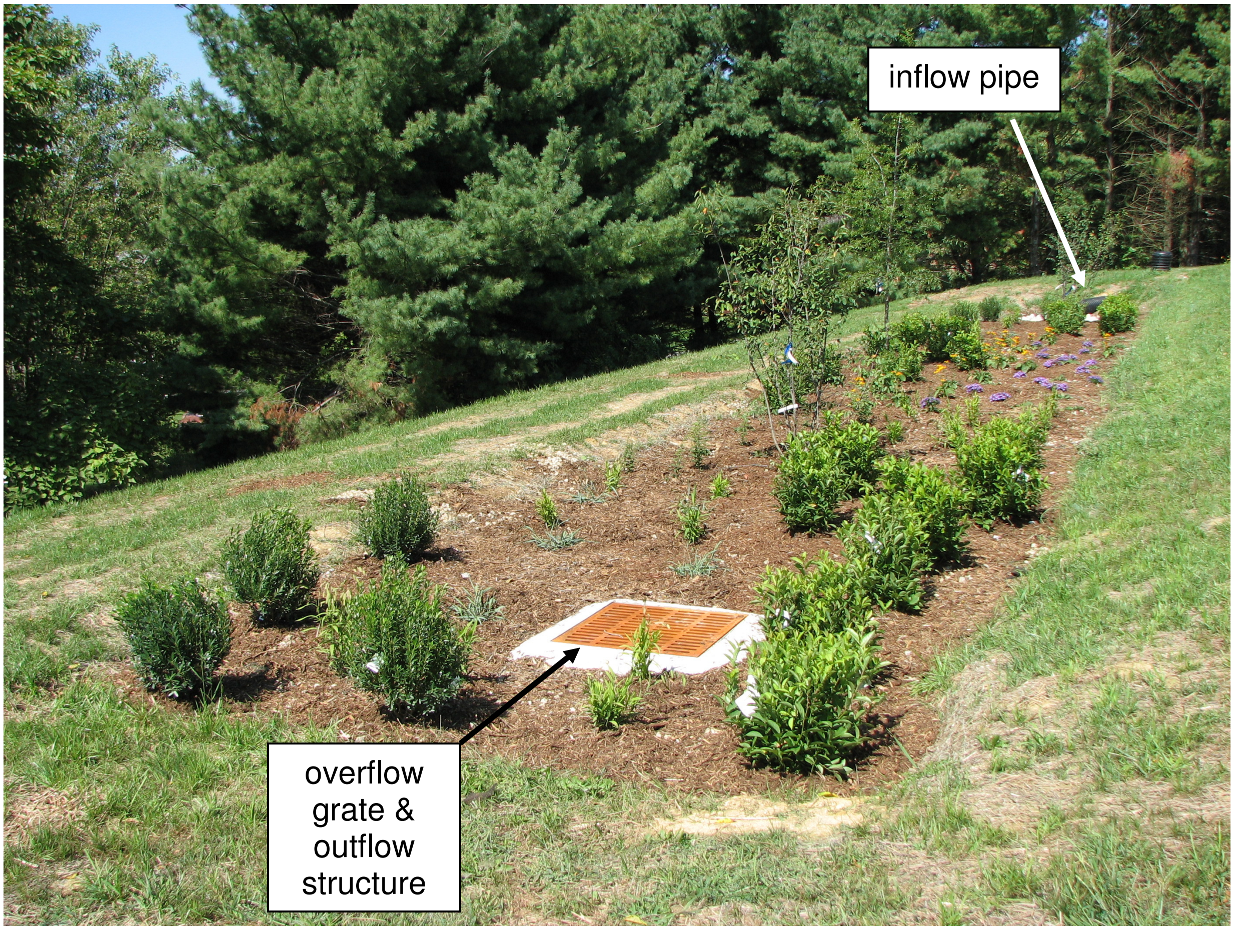


Figure 4.3. Structural soil infiltration trench that drains a 0.73-ha parking lot in Blacksburg, VA.

A 15-cm clay liner was constructed on the bottom of the ITSS by compacting in-situ clay soil with a rammer. The ITSS design included an underdrain system shown in Figure 4.4, consisting of two sets of two parallel, 10-cm high-density polyethylene (HDPE) perforated pipes covered by #57 stone and filter fabric to prevent clogging by fines. Infiltrated water is directed to the outlet structure, which connects to an existing dry detention basin. A 1-m layer of CU-Structural Soil™ overlies the drainage layer. The entire BMP is lined with LINQ GTF 130EX nonwoven filter fabric (LINQ Industrial

Fabrics, Inc.: Summerville, SC, USA) to prevent intrusion of the in-situ soil into the trench and clogging of the gravel bed. A 10-cm mulch layer covers the CU-Structural Soil™ and is underlain by filter fabric to prevent suspended solids from clogging the soil media. An overflow structure (connected to the existing storm sewer) drains water that ponds on the surface of the BMP in excess of 10 cm as well as water from the underdrain system. Hardy native perennials, shrubs, and trees were planted in the CU-Structural Soil™ to promote biological uptake and processing of pollutants and water and to provide a favorable environment for the growth of beneficial heterotrophic and autotrophic microorganisms (Appendix A).

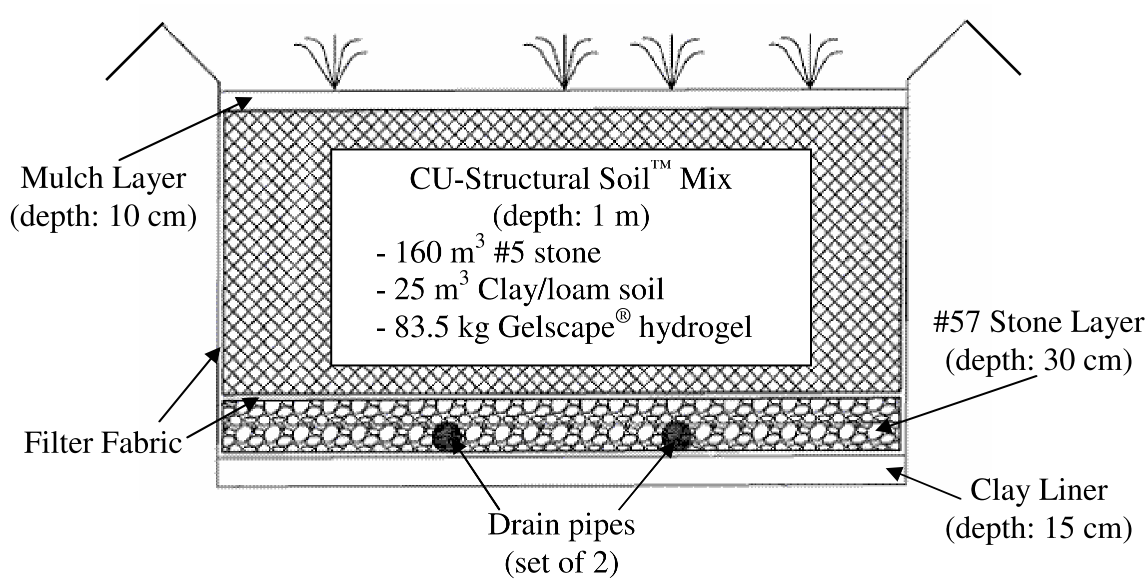


Figure 4.4. A cross-section of the CU-Structural Soil™ infiltration trench.

Filled with a mixture of 88% washed medium sand, 8% clay and silt fines, and 4% leaf compost, the BRC (Figure 4.5) is 4.6 m long, 7.6 m wide and 1.8 m deep (Hunt et al., 2006a). These media were not compacted and were overfilled to allow settling. The drainage layer, located 30 cm above the bottom of the BMP, consists of two sets of two parallel, 10-cm perforated pipes, covered with #57 stone and wrapped in filter fabric to prevent clogging by fines. These underdrains connect to an outflow structure and then to an existing dry detention pond. The 30-cm ponding depth at the bottom of the

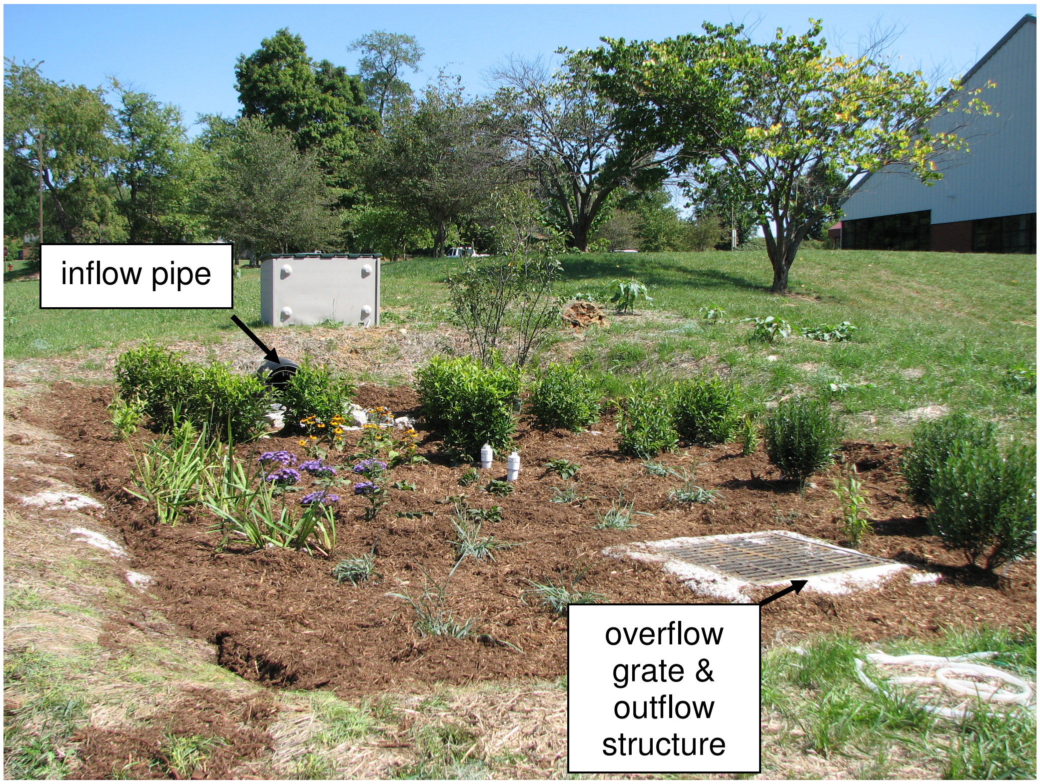


Figure 4.5. A bioretention cell located in Blacksburg, VA that drains a 0.16-ha parking lot.

BRC was included to promote denitrification. A 15-cm compacted clay layer prevents water from infiltrating into the subsoil and the bottom and sides of the BMP are lined with filter fabric to prevent the surrounding soil from intruding into the cell and clogging the media. The media are covered with 10 cm of mulched wood chips to encourage plant growth and a variety of hardy native perennials, shrubs and trees were planted to maintain infiltration rates and promote pollutant removal. Water ponded in excess of 10 cm overflows into the outlet structure, which is connected to the existing storm drainage system. A cross-section of the bioretention cell is presented in Figure 4.6.

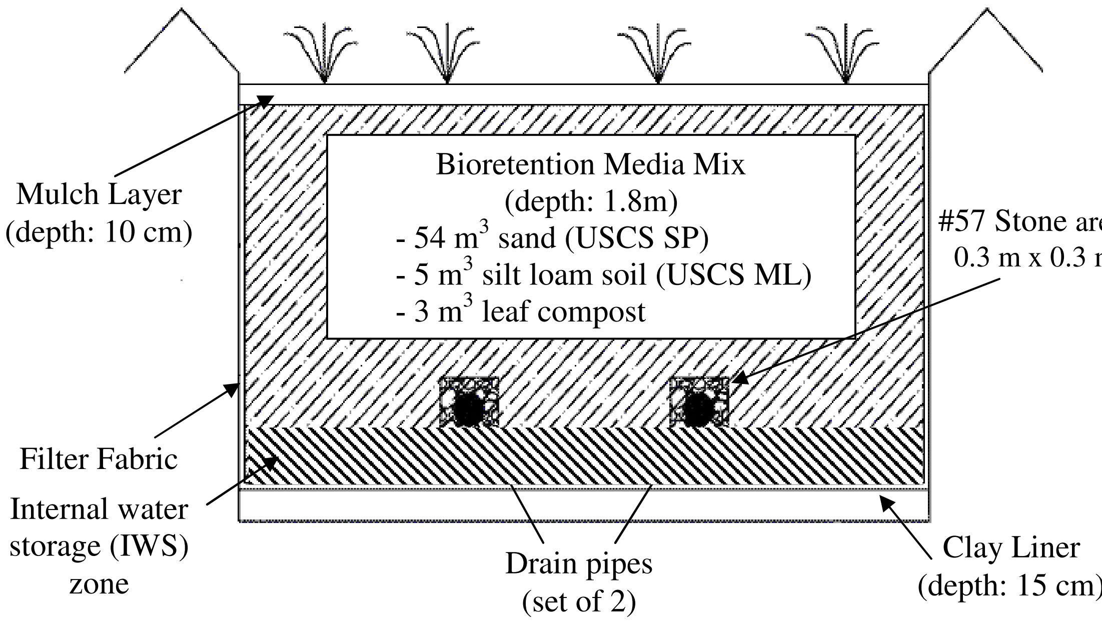


Figure 4.6. Cross-section of bioretention cell.

4.3 Monitoring

Independent runoff events were defined as storms having a minimum of six hours between inflow events; otherwise, all samples were considered representative of a single event. A tipping-bucket rain gage, located approximately 0.4 km from the study site, measured precipitation depth and intensity. Due to equipment malfunction on February 7, 2008, rainfall was not recorded at this location until March 28, 2008. Precipitation data during this time period were obtained at a nearby weather station operated by the National Oceanic and Atmospheric Administration and located at the Virginia Tech Airport, approximately 5.46 km from the study site. This station records precipitation data every twenty minutes.

Thelmar compound v-notch/rectangular weirs and bubble levelers (Thel-Mar, Brevard, NC, USA) were installed in the inflow and outflow pipes of each BMP (Figure 4.7). ISCO 6700 samplers (0.3 mm accuracy; Teledyne Isco, Inc., Lincoln, NE, USA) (Figure 4.8) with bubbler-level flow modules recorded water levels every minute and were programmed to begin sampling when water flowed over the weir crest. The ISCO samplers were programmed to take a discrete sample of approximately 1 L following every 2.8 m^3 of runoff. Flows below 1.2E-5 L/s were not recorded.

Two sets of nested piezometers were installed in each BMP to observe water movement through the system. Each set includes a piezometer that extends to the bottom of the BMP and one that extends 0.9 m above the bottom of the BMP. The piezometers were constructed of 5-cm diameter PVC pipe with an end cap (Figure 4.9). Holes 0.64 cm in diameter, at an approximate spacing of 1.9 cm, were drilled to a height of 10 cm above the end cap. Unvented Onset Hobo Model U20 pressure transducers (0.3 cm accuracy; Onset Computer Corp., Bourne, MA, USA) recorded total pressure at 1-min. intervals (Figure 4.10). Barometric pressure data were recorded at the Heth Farm (4.8 km from the site) at 5-min. intervals by a Vaisala PTB101B analog barometer (0.15hPa accuracy; Vaisala Oyj, Vantaa, Finland) and were used to correct the piezometer data to determine water level within the BMPs.

Figure 4.7. Thelmar weir, bubbler level and ISCO intake tube installed in the inflow pipe of the bioretention cell.

Figure 4.8. ISCO 6700 sampler installer at the inflow pipe of the infiltration trench.

Figure 4.9. Uphill piezometer set for the structural soil infiltration trench.

Figure 4.10. Hobo U20 pressure transducer used in the piezometers.

4.4 Laboratory analyses

Samples taken within an individual storm event were composited to produce a single influent and a single effluent sample for each BMP for each runoff event. Each composite sample was analyzed for fecal coliform bacteria (FC), *Escherichia coli* (E-coli) bacteria, total nitrogen (TN), total phosphorus (TP) and suspended sediment concentration (SSC). While it is recommended by the USEPA to use a grab sampling technique for samples to be analyzed for bacteria (USEPA, 2002), safety and time constraints required the use of automated samplers for sample collection. Fecal coliform and E-coli concentrations were determined using the membrane filtration procedure (Clesceri et al., 1998; USEPA, 2000). TN and TP concentrations were analyzed using Hach methods 10071 and 8190, respectively (Hach, 2002). Suspended sediment concentrations were determined using ASTM Method D 3977-97 (ASTM, 2000). For two runoff events, each individual sample taken during the runoff event was analyzed for the constituents discussed above. For four BRC events and two ITSS events, the composite samples were also analyzed for nitrate, nitrite and ammonia concentrations using Hach methods 8171, 8507 and 10023, respectively (Hach, 2002).

Stormwater runoff samples were stored in acid-washed plastic bottles at 4°C prior to laboratory analysis. Samples were analyzed within the holding times recommended by USEPA (2002), which are summarized in Table 4.1. However, the holding time used for E-coli and fecal coliform differs from the 6 hours suggested by USEPA. Due to funding and personnel shortages, it was not feasible to meet this criterion; therefore, the 24-hr holding time recommended by Clesceri et al. (1998) was used.

Table 4.1. Holding times for individual laboratory analyses. (NARA, 2008)

Parameter	Holding Time
Bacteria	24 hours
Suspended Sediment	7 days
Total Phosphorus	28 days
Total Nitrogen	28 days
Nitrate and Nitrite N	48 hours
Ammonia-N	28 days

One duplicate was run for every 20 samples for each test performed, and one sample spiked with a known concentration (quality control standard – "QCD") was run for every set of samples. The acceptable ranges for the values of duplicates and QCDs for each of the individual tests are summarized in Table 4.2. If the duplicates and/or QCDs did not fall within the specified range, the test was repeated for the entire set of samples until the values were in compliance.

Table 4.2. Acceptable limits for analyzed parameters (TARP, 2003)

Parameter	Acceptable Range for Quality Control Standard	Acceptable Range for Duplicates (Relative Percent Difference)
Bacteria	Not Specified	Not Specified
Total Phosphorus	90-110% of recorded value	20%
Total Nitrogen	90-110% of recorded value	28%
Suspended Sediment Concentration	75-125% of recorded value	25%
Nitrate and Nitrite N	90-110% of recorded value	45%
Ammonia-N	90-110% of recorded value	52%

Samples that resulted in an 'underrange' reading were recorded as half the lowest detectable value. Values assigned when a sample concentration was below the detectable limit are shown in Table 4.3.

Table 4.3. Concentration values recorded for samples returning a 'nondetect' reading.

TN (mg/L)	Ammonia (mg/L)	Nitrite (mg/L)	Nitrate (mg/L)	TP (mg/L)	FC (CFU/100 mL)	EC (CFU/100 mL)
0.25	0.01	0.001	0.05	0.01	0.5	0.5

Samples of the sand, topsoil and leaf compost were collected as they were mixed to create the bioretention media. The Gelscape® hydrogel was sampled when applied to the stone used in the ITSS treatment media, and a sample of mulch was taken when it was spread on the BMPs. A composite sample of potting soil was created by taking subsamples of the planting media from several of the plants placed in each of the BMPs. Each of the media components were tested for total nitrogen, total phosphorus and Mehlich-III P using methods published by the American Society of Agronomy and Soil Science Society of America [SW 846-6010B for TP, MSA Part 2 (1996); Dumas Method for TN, Page (1982)]. Samples that were not homogenous, such as the mulch, were ground to create a mixture representative of the overall sample before being analyzed.

4.5 Data analyses

Precipitation data collected by the tipping bucket rain gage were used to determine storm length, average and maximum rainfall intensity, duration of preceding dry weather and total precipitation for each storm event. Pressure data recorded by the HOBO pressure transducers were corrected using the barometric pressure and converted to centimeters of water.

Water-level (head) data, monitored via the bubbler levels and flow modules, were used to calculate flow rates and total flow volumes for each storm event and BMP, using a rating curve developed from the manufacturer-provided weir rating table. Table 4.4 summarizes the head ranges for each curve section as well as the equation and R^2 value for the fitted line. Water levels recorded by the flow module were used to calculate flow rates using the appropriate regression equation.

Table 4.4 Weir rating curve regression equations and R^2 values.

Head (ft)	Trendline Type	Equation	R^2
0.016 – 0.082	Power	$y = 3.6455x^{2.5716}$	0.9975
0.083 – 0.121	Power	$y = 258.53x^{4.2309}$	0.9920
0.122 – 0.154	Linear	$y = 0.9854x - 0.087$	0.9987
0.155 – 0.226	Linear	$y = 1.1947x - 0.1209$	0.9984
0.227 – 0.259	Linear	$y = 1.4604x - 0.1822$	0.9990
0.260 – 0.292	Exponential	$y = 0.026e^{7.7912x}$	0.9984
0.293 – 0.364	Linear	$y = 2.4826x - 0.4762$	0.9997
0.365 – 0.607	Linear	$y = 2.2015x - 0.3771$	1.0000

Total mass loads for each storm were determined by multiplying the concentration of the flow-weighted composite sample by the total flow. For events for which samples were analyzed individually, concentrations were multiplied by the flow volume for each time interval preceding the sample to determine the mass load for each interval. Percent removal calculations were performed using total mass loads. In addition, the findings and conclusions reported hereafter refer to total mass loads, not concentrations, unless otherwise noted. Finally, peak-flow rates were identified for individual storm events as the largest flow rate obtained during the entire event. If the storm had multiple peaks in flow, the peak-flow rate was taken as the largest peak during the event.

4.6 Statistical analyses

The total outflow mass load for TN, TP, SSC, FC, EC for each storm was subtracted from the total inflow mass load to determine the change in runoff pollutant mass attributable to each BMP. Similarly, the total outflow volume was subtracted from the total inflow volume. The data were checked for normality using the Shapiro-Wilks test (Dalgaard, 2002). All data were non-normal. A one-sided, nonparametric Wilcoxon Signed Rank Test was used to test for significant changes in TN, TP, SSC, FC, and EC mass loads, as well as runoff volume and peak flow rate through the BMPs. The nonparametric Spearman's ρ Correlation test was used to investigate correlations between precipitation, flow, and pollutant removal rates (Dalgaard, 2002).

An alpha value of 0.05 was used for all statistical tests to determine significant differences. A value was considered an outlier in a dataset if it exceeded the most extreme data point within that dataset that did not exceed 1.5 times the interquartile range (difference between the 75^{th} and 25^{th} percentile). All statistical analyses were performed using the statistical software R, version 2.6.2 (Dalgaard, 2002).

5. Results and Discussion

5.1 Precipitation

Monitoring of the infiltration trench started October 23, 2007 and monitoring of the bioretention cell began on November 25, 2007. Due to limited funding for BMP assessment, monitoring of both BMPs was discontinued March 20, 2008. During this time period, a total of 34 precipitation events occurred, with 29 of these storms producing inflow into one or both of the BMPs. An average of 1.0 cm of rainfall fell per storm, with an average intensity of 5 mm/hr. Total rainfall depth and duration data for each storm are shown in Figure 5.1. Table 5.1 indicates which BMPs experienced inflow and/or outflow for each storm event. Not applicable (n/a) indicates an equipment malfunction that prevented data collection.

The study site is located in the Southwest Mountain Climate Region and, as discussed in Section 4.1, receives the majority of winter precipitation from low intensity, long duration frontal storms. Summer precipitation comes primarily from convective thunderstorms that produce high intensity, short duration events. Due to the majority of the study period taking place during the winter, most of the monitored storms resulted from frontal systems and few displayed the characteristics of convective thunderstorms. Thus, the monitored runoff events were the result of rather uniform storm events that are characteristic of only part of the annual precipitation pattern. This lack of short-duration, high-intensity precipitation must be taken into account when reviewing the results of this study, as the results may not be representative of precipitation events occurring in the spring or summer.

When compared to the 30-yr monthly averages, the rainfall amounts received during the study period were much lower, as shown in Figure 5.2. However, this lack of rainfall is representative of the weather patterns experienced during 2007, as many parts of the United States of America, the study site included, suffered a severe drought. A report issued by the Virginia Department of Environmental Quality on October 22, 2007 stated that 'exceptional drought conditions [persisted] in Southwest Virginia' and rainfall amounts received during the preceding year were well below the normal range (VADEQ-DMTF, 2007). A status report issued on March 25, 2008 stated that precipitation deficits had not improved since October, but the severity of the drought throughout Virginia was slightly reduced (VADEQ-DMTF, 2008).

The drought potentially had numerous effects on the BMP performance in reducing flow and improving stormwater quality. Due to the drought, there were longer periods of dry weather between storm events, which likely increased the time for pollutant accumulation on the parking lots and increased inflow pollutant concentrations. Water-starved plants, dry treatment media and parched surrounding soil could have increased the flow reduction capabilities of the BMPs, producing higher flow reductions and pollutant removal rates than would be observed in years with normal rainfall amounts. The extended drought also could have increased runoff infiltration within the ITSS sediment forebay, decreasing the number of storms producing inflow to the infiltration trench. Perhaps most importantly, the drought resulted in fewer precipitation events and a smaller data set during the study period than would be expected based on the 30-yr average.

The total precipitation, duration, average rainfall intensity, peak rainfall intensity and the amount of time since the last precipitation event were determined for each monitored storm event. These variables were tested for correlation with the percent mass removal for all measured constituents (TN, TP, SS, FC, EC). It was determined that none of the storm characteristics listed above were significantly correlated with the percent mass removal of any constituents; thus, there was little evidence that the features of an individual storm event affected the BMP pollutant removal efficiencies.

Table 5.1. A summary of inflow/outflow occurrence for monitored storm events. A check mark indicates data was collected

Storm	Date	Bioretention		Infiltration Trench	
		Inflow	Outflow	Inflow	Outflow
1	10-24-07	n/a	n/a	✓	✓
2	10-25-07	n/a	n/a	✓	✓
3	11-9-07	n/a	n/a	×	×
4	11-15-07	n/a	n/a	×	×
5	11-26-07	✓	×	×	×
6	12-03-07	✓	×	×	×
7	12-15-07	n/a	n/a	✓	✓
8	12-21-07	✓	×	×	×
9	12-22-07	×	×	×	×
10	12-23-07	✓	×	×	×
11	12-28-07	✓	✓	n/a	n/a
12	12-30-07	✓	×	×	×
13	01-05-08	✓	×	×	×
14	01-08-08	✓	×	×	×
15	01-10-08	✓	×	×	×
16	01-11-08	✓	×	×	×
17	02-01-08	✓	✓	×	×
18	02-04-08	✓	×	×	×
19	02-06-08	✓	×	×	×
20	02-06-08	✓	×	×	×
21	02-13-08	✓	×	✓	✓
22	02-18-08	✓	×	×	×
23	02-23-08	✓	×	×	×
24	03-04-08	n/a	n/a	n/a	n/a
25	03-07-08	✓	×	✓	✓
26	03-08-08	×	×	×	×
27	03-14-08	✓	×	✓	✓
28	03-15-08	✓	×	×	×
29	03-19-08	✓	✓	✓	×

* Not applicable (n/a) indicates an equipment malfunction that prevented data collection

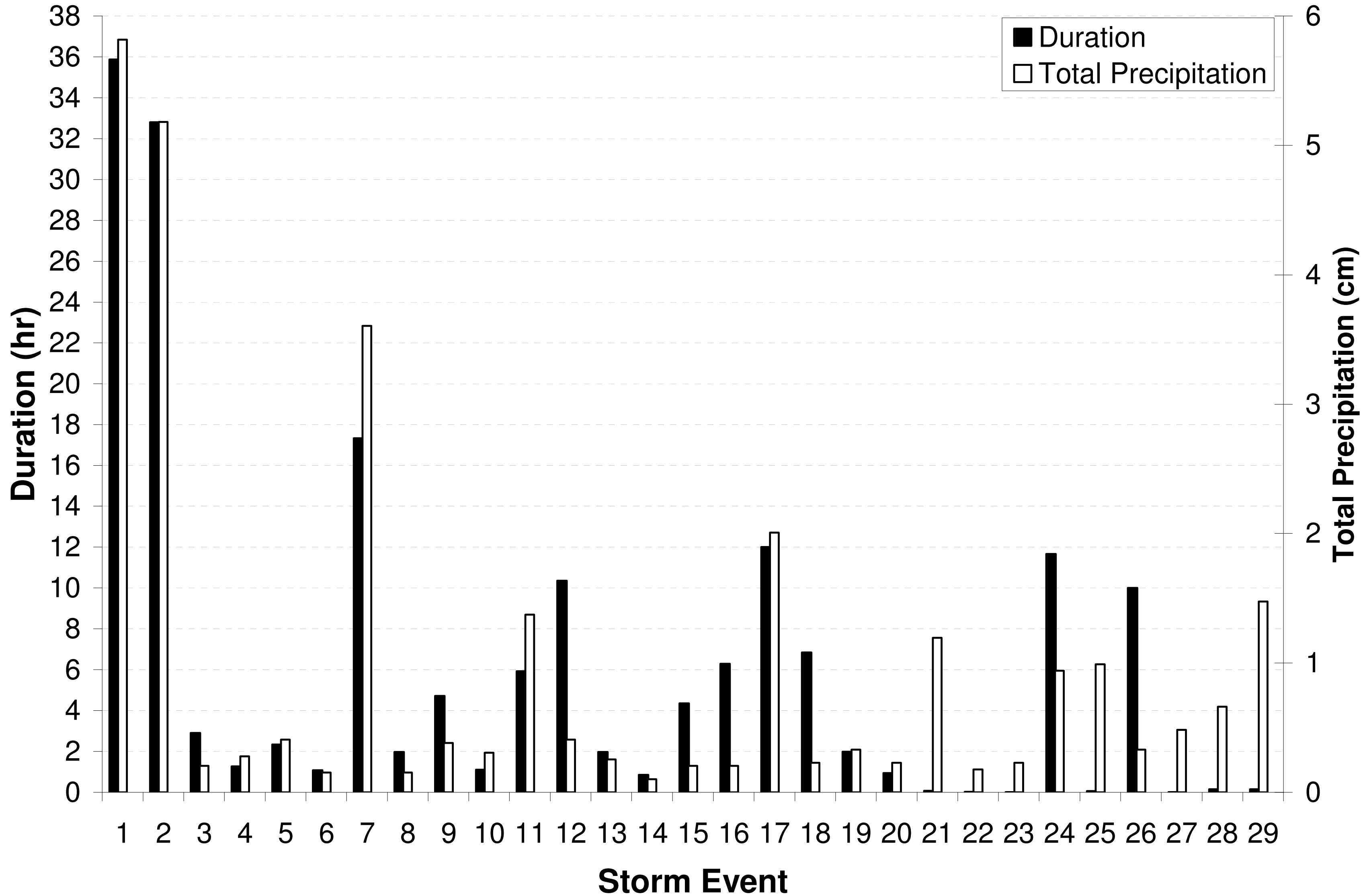


Figure 5.1. Storm duration and total precipitation of monitored storm events.

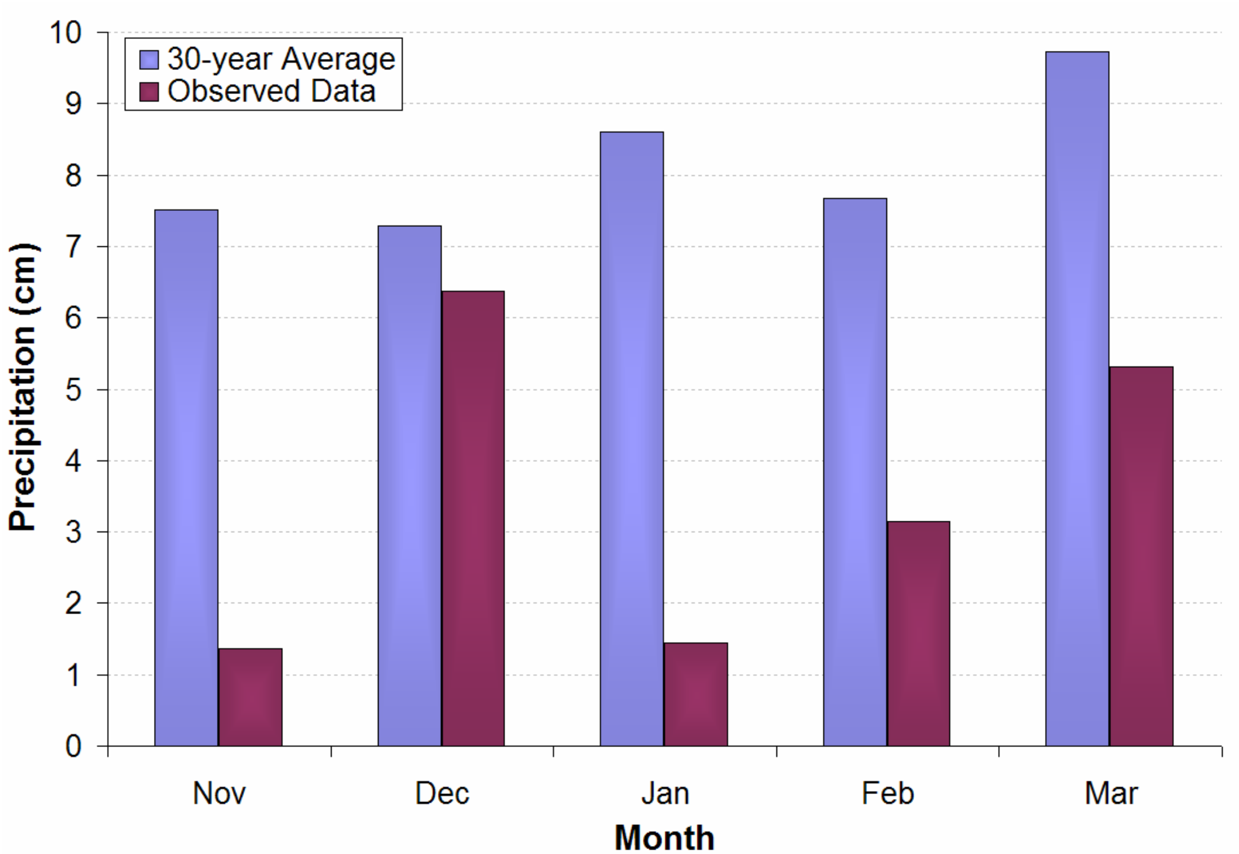


Figure 5.2. A comparison of the 30-yr average precipitation and the observed precipitation for Blacksburg, VA for each month within the study period (Nov. 2007 – Mar. 2008).

5.2 BMP Hydrology

The following section discusses the hydrology of the bioretention cell and the structural soil infiltration trench in regards to data collected during the five month study period. Vertical bar graphs are used to describe concentration data, while horizontal bar graphs are used to describe mass data.

5.2.1. BRC: Flow Volume

Of 23 monitored precipitation events, 21 produced inflow to the BRC, but only 3 produced outflow: storms 11, 17 and 29. The design capacity of the BRC was approximately 25,500 L. Inflow volumes ranged from less than 1 L for storm 13 to over 9,700 L during storm 11. For the three storms that generated outflow, the outflow volumes ranged from a minimum of less than 1 L to a maximum of 468 L during storms

29 and 11, respectively. Figure 5.3 summarizes the inflow and outflow volumes for the BRC for individual storm events. The inflow volume generated by storm 13 and the outflow volume from storm 29 were both less than 1 L and too small to be seen clearly on the graph. Several storms did not generate outflow (5, 6, 8, 10, 12, 13, 14, 15, 16, 18, 19, 20, 21, 22, 23, 25, 27, 28).

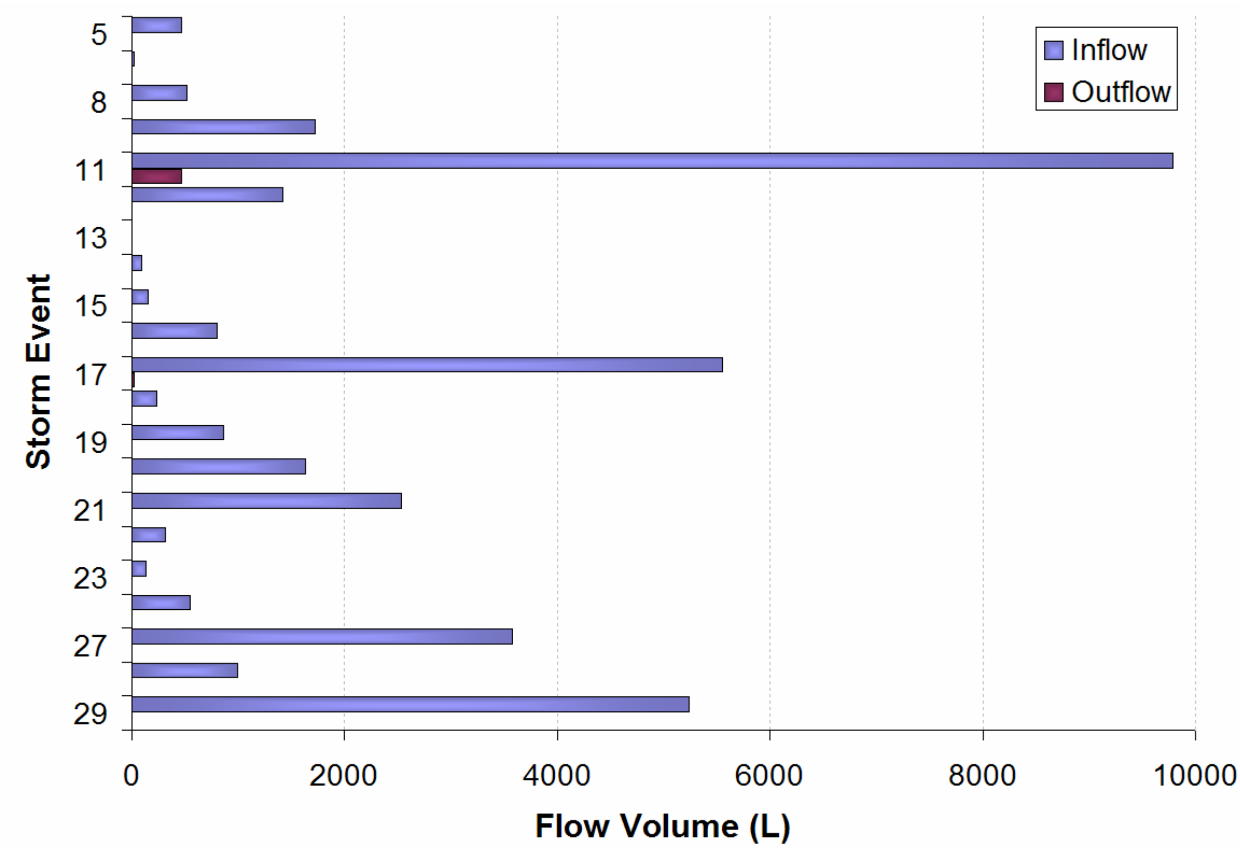


Figure 5.3. Inflow and outflow volumes from the bioretention cell for individual storm events.

The mean inflow volumes were 1,743 L and the median inflow value was 800L. The majority of water that entered the BMP was treated by infiltrating through the BRC media: less than 1% left as surface overflow.

The only monitored precipitation event that produced overflow was storm 29. This storm was characteristic of a convective thunderstorm, producing large amounts of rainfall in a very short time period: the storm produced 1.5 cm in 0.13 hr (11.3 cm/hr), generating maximum inflow rates for the BRC of 12.6 L/s. The existing mulch layer and underlying sand were raked smooth and new mulch was applied on March 13, 2008. The storm occurred on March 19, 2008 and the high inflow velocities cut a path directly through the middle of the BMP to the overflow grate. Little runoff infiltrated. The new mulch was loose and did little to slow down the inflow. Additionally, the plants in the BRC had not grown over the winter months and were not yet big enough to block the incoming water and create a longer flow path from the inflow pipe to the overflow grate. Water level data recorded by the piezometers were analyzed and it was determined that there was no treated outflow produced during this storm event; only untreated overflow left the system.

Figure 5.4 displays a cumulative hydrologic budget for the BRC. The plot takes into account the loss of water through overflow and outflow, as these are the only monitored pathways for water loss from the BMP; therefore, the amount of water shown in Figure 5.4 is hypothesized to have left the cell via exfiltration or evaporation or was stored in the media or in the IWS zone of the BMP. Since the study period occurred primarily during the winter months and the vegetation was planted at the beginning of the study period, evapotranspiration was considered negligible.

During the study period, a total of 36,596 L entered the BMP, while only 492 L exited the BMP, producing a cumulative flow reduction of 98.7%. The median flow reduction, when based on individual storms, was 100%. When only the three storms that produced outflow were analyzed, the median percent flow reduction was 99.6%. Statistical analyses verified that the amount of water entering the BMP was significantly greater than the amount leaving the BMP ($p = 2.384\text{E-}7$). Statistical analyses also identified a negative correlation between inflow volume and percent reduction in flow volume ($\rho = -0.597$, $p = 0.00336$). Larger storms have a greater chance of producing outflow and, thus, have a lower flow reduction percentage.

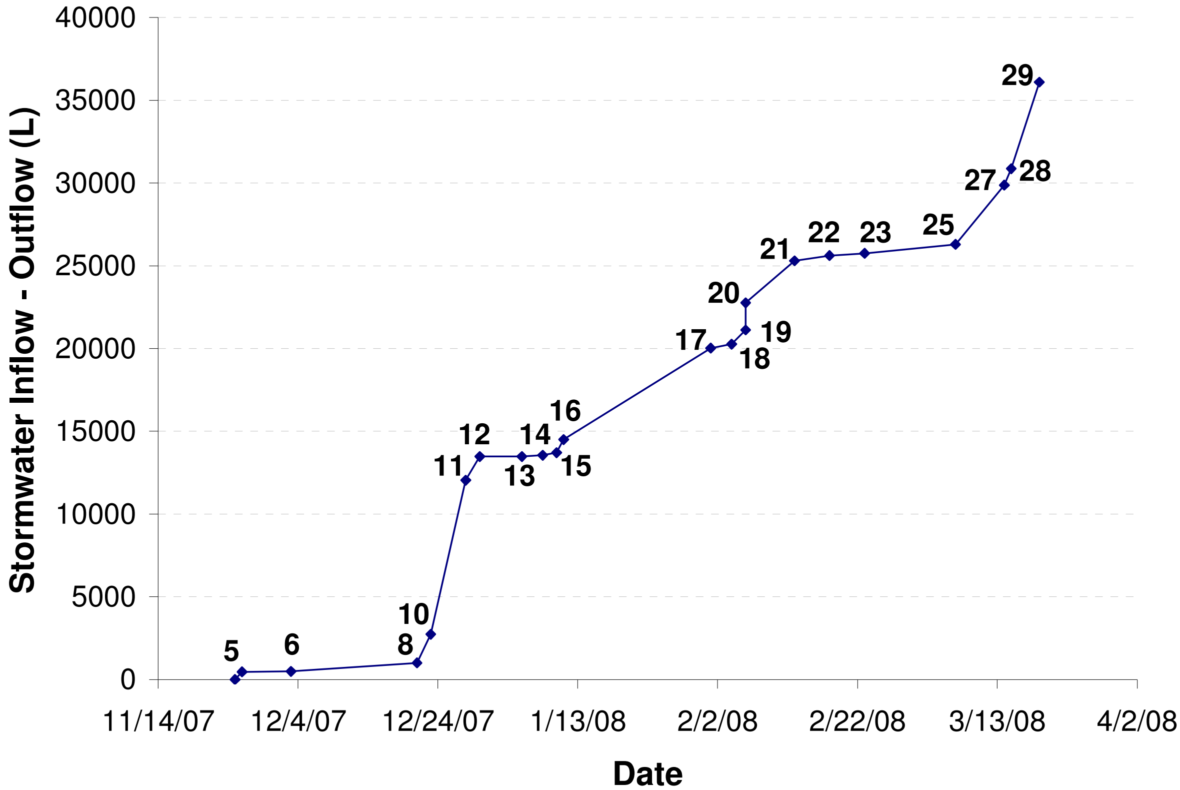


Figure 5.4. Cumulative runoff plot for the bioretention cell. Point labels indicate storm number.

During BMP construction, a bedrock outcropping was encountered in the northeast corner of the bioretention cell; the bedrock was drilled away, and construction continued as planned. The bottom of the cell was lined by compacting in-situ clay to a depth of 15 cm; however, the sides of the cell were not lined. The soil surrounding the BMP was primarily fill dirt put in place when the Aquatic Center was constructed in 1992; the fill dirt consisted mostly of clay and was filled with cracks. It is likely that water was rapidly lost through sides of the BMP via cracks in the fill dirt and/or through cracks in the bedrock, thus causing significant reductions in outflow volumes. Considering the bedrock outcropping was located in the highest part of the BMP and the area was suffering from a severe drought, cracks within the surrounding soil were the most likely conduit for the runoff.

Figure 5.5 displays water levels as recorded by the HOBO pressure transducers. The ‘uphill piezometer’ is located approximately 1/3 of the distance between the inflow pipe and the overflow grate, while the 'downhill piezometer' is located approximately 2/3 of the distance between the pipe and the grate. Both are on the centerline of the BMP and extend to the bottom of the BRC (approximately 1.83 m).

Figure 5.5 shows the movement of water within the BRC for storm 11, which occurred on December 28 and 29, 2007. Analyses of the graph and personal observation of the BMP during multiple storm events provided useful information regarding BRC hydrology. As stormwater entered the bioretention cell it typically infiltrated rapidly in front of the inflow pipe, as opposed to flowing over the bed of the BMP and then infiltrating into the media. The graphs of the uphill and downhill piezometer water levels are similar, but separated by approximately 30 min. This suggests water moved rapidly to the bottom of the BMP and pooled before moving horizontally along the bottom of the BMP.

As shown in Figure 5.5, runoff from storm 11 filtered through the treatment media within approximately 2 hours, leading to an estimated vertical hydraulic conductivity of 11.8 cm/hr, and pooled to a height of 38 cm in the uphill part of the BRC and 40 cm in the downhill part of the BRC. The actual hydraulic conductivity was much higher than the design value of 5 cm/hr. The higher hydraulic conductivity is likely due to the fact that the BRC media were not compacted, but instead allowed to settle over time. The actual hydraulic conductivity will probably decrease over time as the media consolidates. Outflow via the underdrains did not begin until water reached a height of 38 cm, and outflow ceased when water levels within the BMP dropped below 26 cm. Although the BRC was designed to include a 30-cm IWS zone, Figure 5.5 shows water levels within the BMP continued to drop below 30 cm, indicating water was rapidly exfiltrating into the surrounding soil.

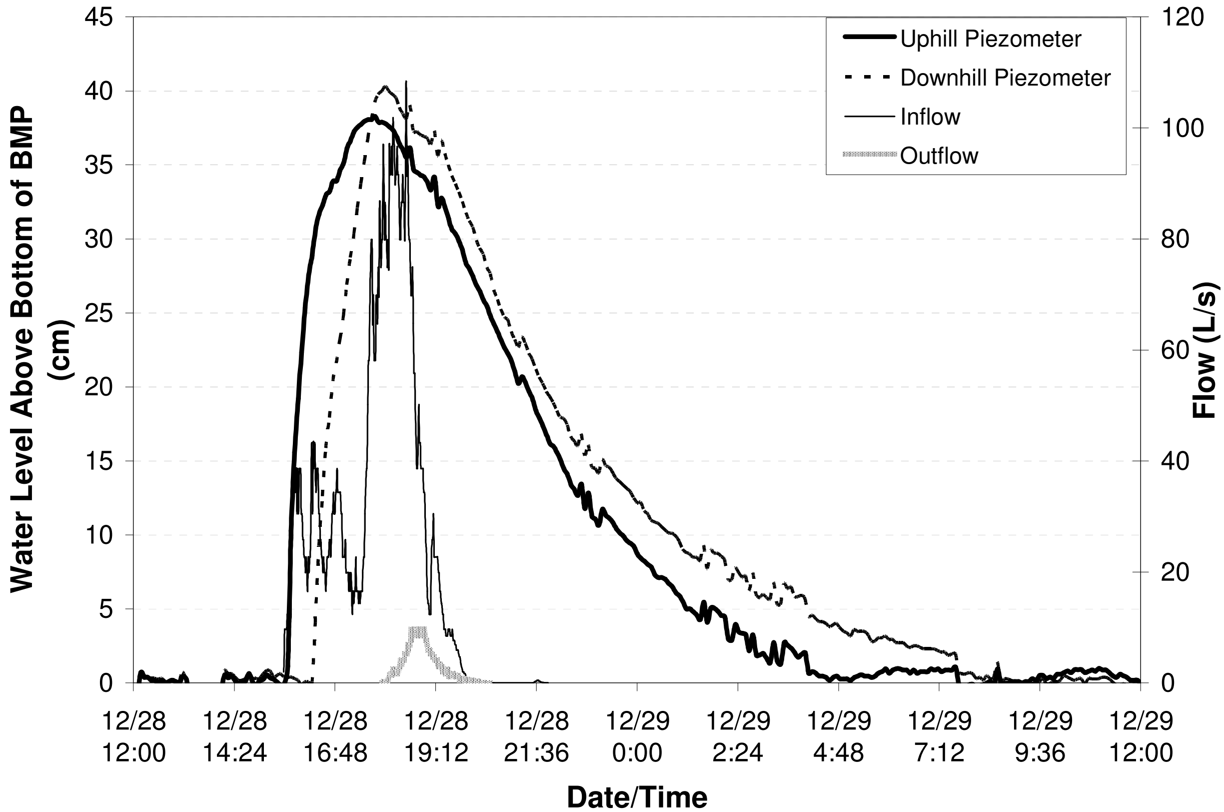


Figure 5.5. Water levels within the bioretention cell, as well as inflow and outflow rates during storm 11 on December 28/29, 2007.

Results from the BRC are similar to findings by other research studies. A study performed by Dietz and Clausen (2005) documented a 98.8% reduction in storm volumes for a bioretention cell in Haddam, CT. This study was conducted on soils classified as loamy sand and was designed primarily to infiltrate water, unlike the BRC. Hunt et al. (2006b) performed a hydrologic analysis of a bioretention cell constructed in high-clay soils which was designed with an IWS zone and an underdrain system. This design was a much closer representation of the BRC in this study, as the primary BMP design function was stormwater treatment, not exfiltration. Their study reported an average flow reduction of 78%, which is somewhat lower than the results from the BRC, but still higher than would be expected in clay subsoils.

5.2.2. BRC: Peak Flow Rate

As few runoff events produced outflow, there were few data to analyze regarding peak flow rate reduction. Peak inflow rates for the BRC ranged from less than 1 L/s for storm 13 to 13 L/s for storm 29, with a mean of 1.5 L/s and a median of less than 1 L/s. For storms that generated outflow, peak rates ranged from 0.01 L/s for storm 17 to 0.2 L/s for storm 11. The median percent reduction of peak flow rate was 100% (99.3% considering only the three storms that produced outflow). For all storms monitored during the study period, inflow peak flow rates were significantly higher than outflow peak flow rates (p = 2.148E-5).

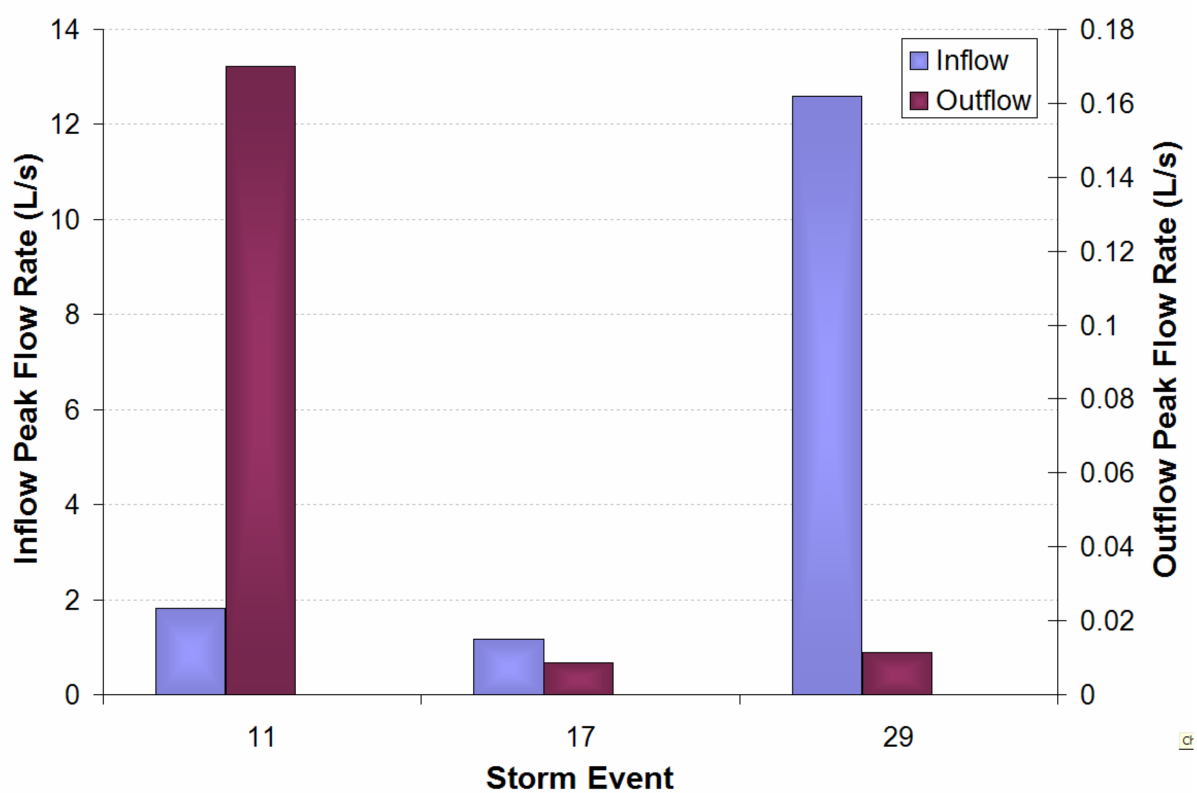


Figure 5.6. Inflow and outflow peak flow rates for storms that produced outflow from the bioretention cell. Note the difference in scale for the secondary axis for outflow.

An important aspect of BMP performance is the treatment of frequent, small storm events. As there was a lack of outflow for the majority of monitored storms, and consequently a 100% flow volume and peak flow reduction, an excellent overall reduction in peak flow rate was achieved. Even for larger storms that generated outflow, the BRC successfully reduced peak flow rates by 96%. This result indicates the media was well chosen, as it allows for rapid infiltration of water at the surface of the BMP, but still controls the rate at which water enters the underdrains.

5.2.3. ITSS: Flow Volume

Of the 27 monitored storms, only seven had the necessary combination of total precipitation, rainfall intensity and storm duration to create an inflow event for the infiltration trench. The total inflow and outflow volumes generated by these storms are summarized in Figure 5.7. Inflow volumes ranged from 939 L in storm 29 to 81,621 L in storm 2. Outflow volumes ranged from a minimum of 0 L in storm 29 to 72,289 L in storm 2. Mean inflow and outflow volumes were 25,567 L and 20,488 L, respectively. The median inflow volume was 6,522 L, while the median outflow volume was 530 L. There were no outliers identified in the data.

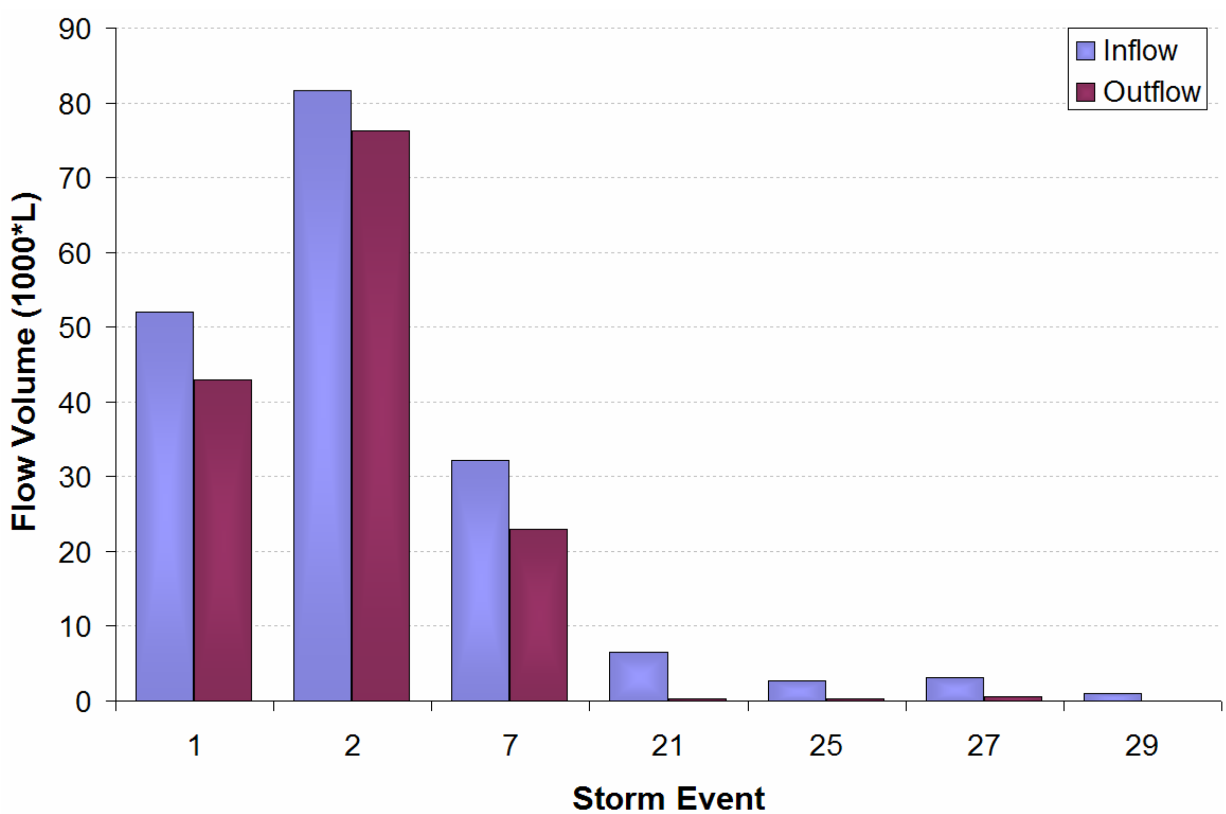


Figure 5.7. Total inflow and outflow volumes for the structural soil infiltration trench.

The lack of flow into the ITSS is due to the inclusion of a sediment forebay upstream of the ITSS. Due to the lack of soil consolidation in the forebay and the low soil moisture content, infiltration rates in the sediment forebay were very high. As a result, a large storm event was required to fill the sediment forebay and introduce water into the ITSS. Thus, there are few monitoring data available for the ITSS.

For storms 21, 25 and 27, a tarp was placed in the sediment forebay to act as a liner and prevented water from infiltrating into the sediment forebay. The tarp was used to facilitate data collection. These three storms were smaller than the other 4 storms that produced inflow to the ITSS and probably would not have produced inflow to the BMP if the tarp had not been used. The flow reduction for these three events was higher than the three preceding events, most likely due to the smaller inflow volume. This could also be the cause for a larger overall mean and median flow reduction.

The ITSS had much lower flow reductions that the BRC and, overall, only slightly reduced the volume of water entering the stormwater drainage system. There were no bedrock outcroppings encountered during the construction of the infiltration trench, and the design did not include an IWS zone. Thus there was less opportunity for water to exfiltrate through the sides of the ITSS. Although the sides of the ITSS are not lined, the bottom is lined with compacted clay (as is the BRC), and there were no cracks or bedrock outcroppings to facilitate the channeling of water into the surrounding subsoil. The flow volume reduction that did occur was likely due to water leaving the trench through the cracks in the fill dirt that forms the walls of the BMP. Therefore, the ITSS is functioning as designed.

The flow of water through the ITSS during storms 1 and 2 (October 24 and 25, 2007) is shown in Figure 5.8. Both piezometers referenced in Figure 5.8 extend to the bottom of the ITSS. The uphill piezometer is located in the centerline of the BMP approximately 9 m from the inflow and the downhill piezometer is located approximately 18 m from the inflow pipe, also in the centerline of the BMP. Water moved rapidly through the treatment media, as shown in the graph: spikes in inflow correspond with spikes in water levels at the uphill piezometer and spikes in outflow correspond with drops in water levels. Increases in downhill piezometer water levels occur a few minutes later than increases in uphill levels, and the increases are not as large, indicating that the majority of the water enters the underdrains before reaching the downhill portion of the BMP.

Based on inflow and outflow data collected during the study period, the actual hydraulic conductivity of the CU-Structural Soil™ was estimated to be 60 cm/hr. This hydraulic conductivity is much larger than the original design hydraulic conductivity of 38 cm/hr and much larger peak outflow rates were recorded for the ITSS than were expected.

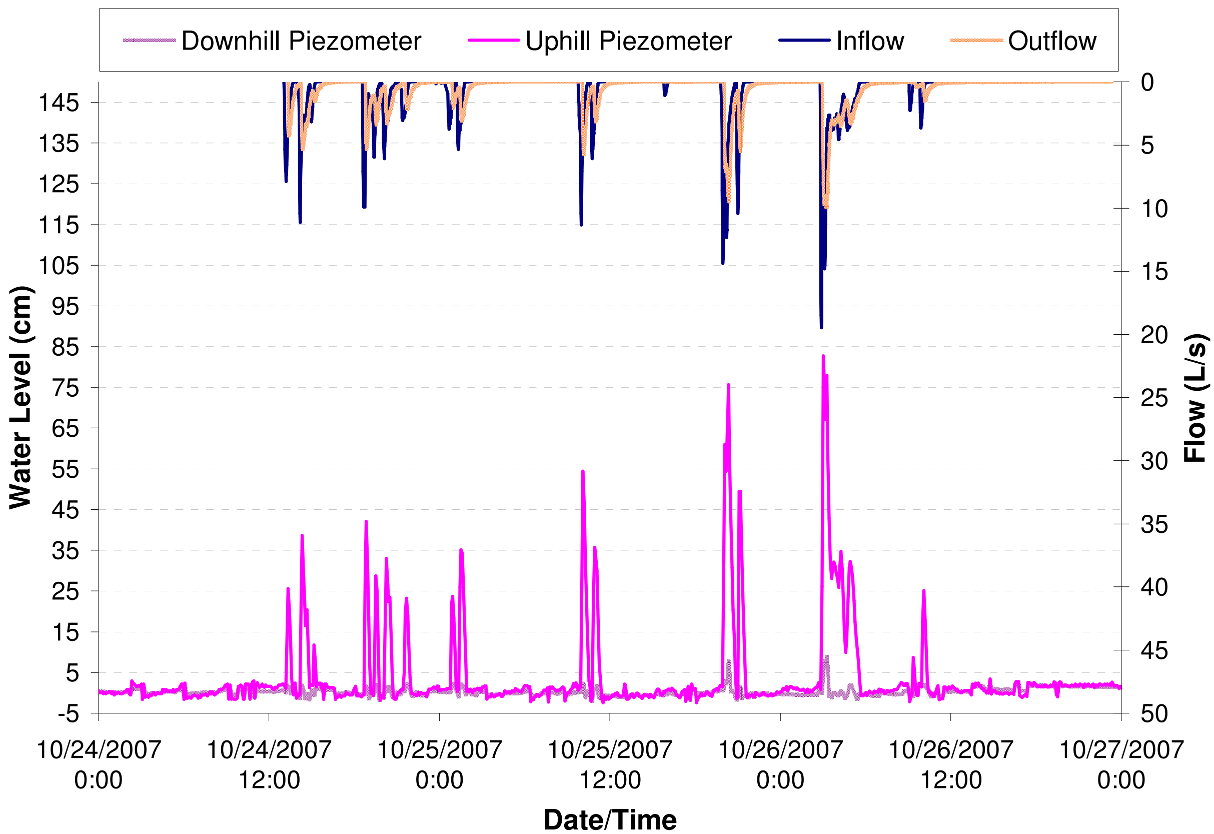


Figure 5.8. Water levels within the structural soil infiltration trench, as well as inflow and outflow rates during storm 11 on December 28/29, 2007.

The trees and plants within the BMP had not started to grow during the study period and therefore did not contribute to flow reduction within the ITSS. It is hoped that as the tree roots develop and the shrubs and perennials grow they will reduce flow volumes by reducing the pore space in the gravel and via biological uptake. Further monitoring is needed to determine the true role of the plants in the sequestration of pollutants and incoming water.

As with the BRC, any water that did not leave the ITSS as outflow was assumed to leave via exfiltration or evaporation; transpiration was assumed negligible since the study was not conducted during the growing season. All water that left the BMP as outflow did so via the underdrain pipes: there was no overflow during any of the storm events. Figure 5.9 shows the amount of water that entered the ITSS during the study period via inflow and left as outflow.

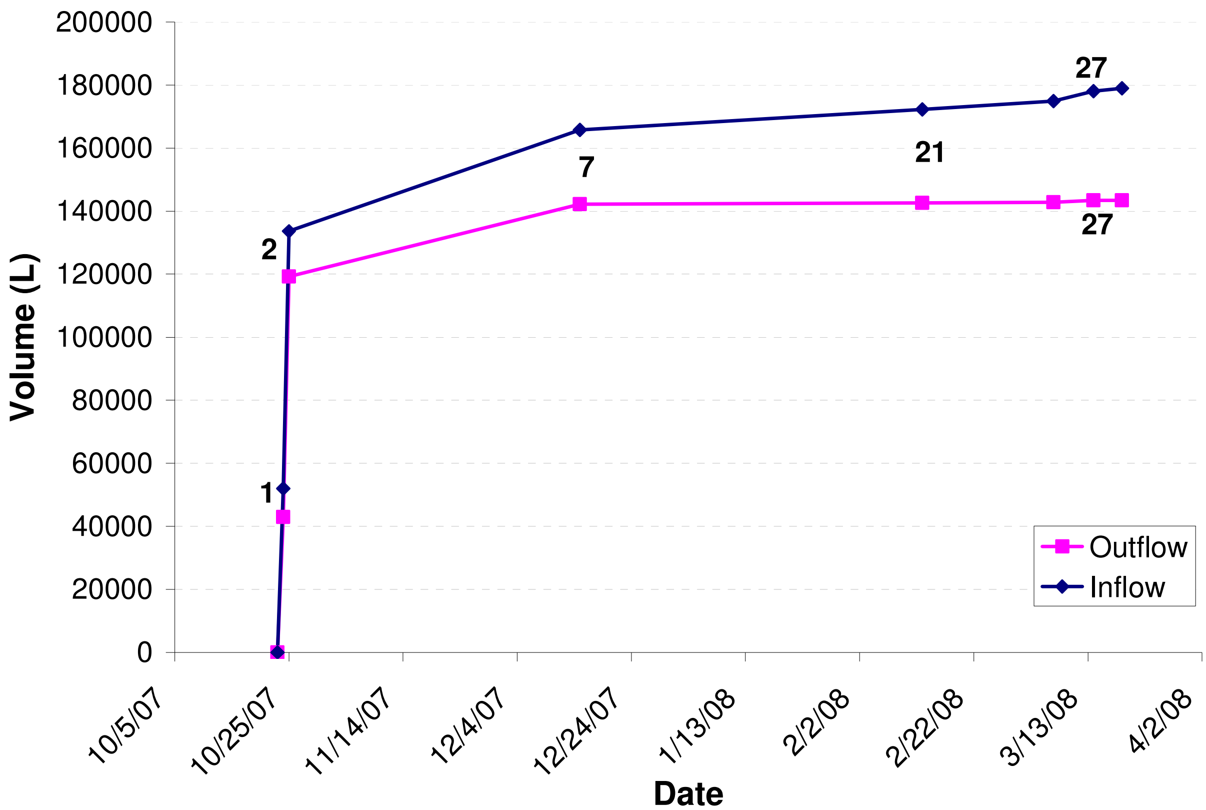


Figure 5.9. Cumulative inflow to and outflow from the structural soil infiltration trench. Point labels indicate storm events.

A total of 178,970 L entered the ITSS during the study period as inflow; 143,414 L left the BMP as outflow. Therefore, the cumulative percent reduction of flow volume was 20%. The median removal rate based on individual storm reductions was 83%. Statistical analyses verified that the inflow volumes were significantly greater than the outflow volumes ($p = 0.0078$).

There was a strong positive correlation between the amount of water entering the ITSS and the amount of water leaving via outflow ($\rho = 0.955$, $p=0.0008$). Higher inflow volumes resulted in higher outflow volumes. This is due to the lack of exfiltration and a design that did not include an IWS zone, as discussed previously, and is not considered a negative characteristic of the design. However, the percent reduction of volume was negatively correlated to the inflow volume (ρ= -0.893, p=0.0123): As the amount of water entering the BMP increased, the percent reduction of flow volume decreased. Consequently, the ITSS was less effective at reducing flow volumes for larger storm events.

There are no prior studies on the use of CU-Structural Soil™ for stormwater treatment practices and no peer-reviewed studies could be located that analyzed the hydrologic and water quality benefits of gravel-based infiltration trenches.

5.2.4. ITSS: Peak Flow Rate

Peak flow rates entering and exiting the ITSS are summarized in Figure 5.10. Storm 29 did not produce outflow; therefore, the outflow peak flow rate was not considered in the following analyses. Inflow peak flow rates ranged from 0.34 L/s (storm 21) to 19.54 L/s (storm 2), while outflow rates ranged from 0.17 L/s for storm 25 to 9.91 L/s for storm 2. Mean inflow and outflow peak flow rates were 7.44 and 3.55 L/s, respectively (Figure 5.11). The median inflow peak flow rate was 4.81 L/s and the median outflow peak flow rate was 2.83 L/s. There were no outliers in the dataset.

Statistical analyses verified that the inflow peak flow rates were significantly higher than the outflow peak flow rates (p = 0.0078) for all monitored storm events. The median percent reduction of peak flow rate was 62%. While significant, the reduction of peak flow rates by the ITSS could be improved, especially for larger storms. The rate at which outflow leaves the BMP is controlled by the size of the underdrain pipes, not by the infiltration rate of the media. A media with a lower porosity would force water to move through the ITSS more slowly and increase the reduction of peak flow rates. Another alternative would be the use of smaller underdrains or a fewer number of pipes. As for the current infiltration trench, the installation of restrictors or valves on the existing underdrain pipes could be a solution for reducing the rate at which water leaves the system.

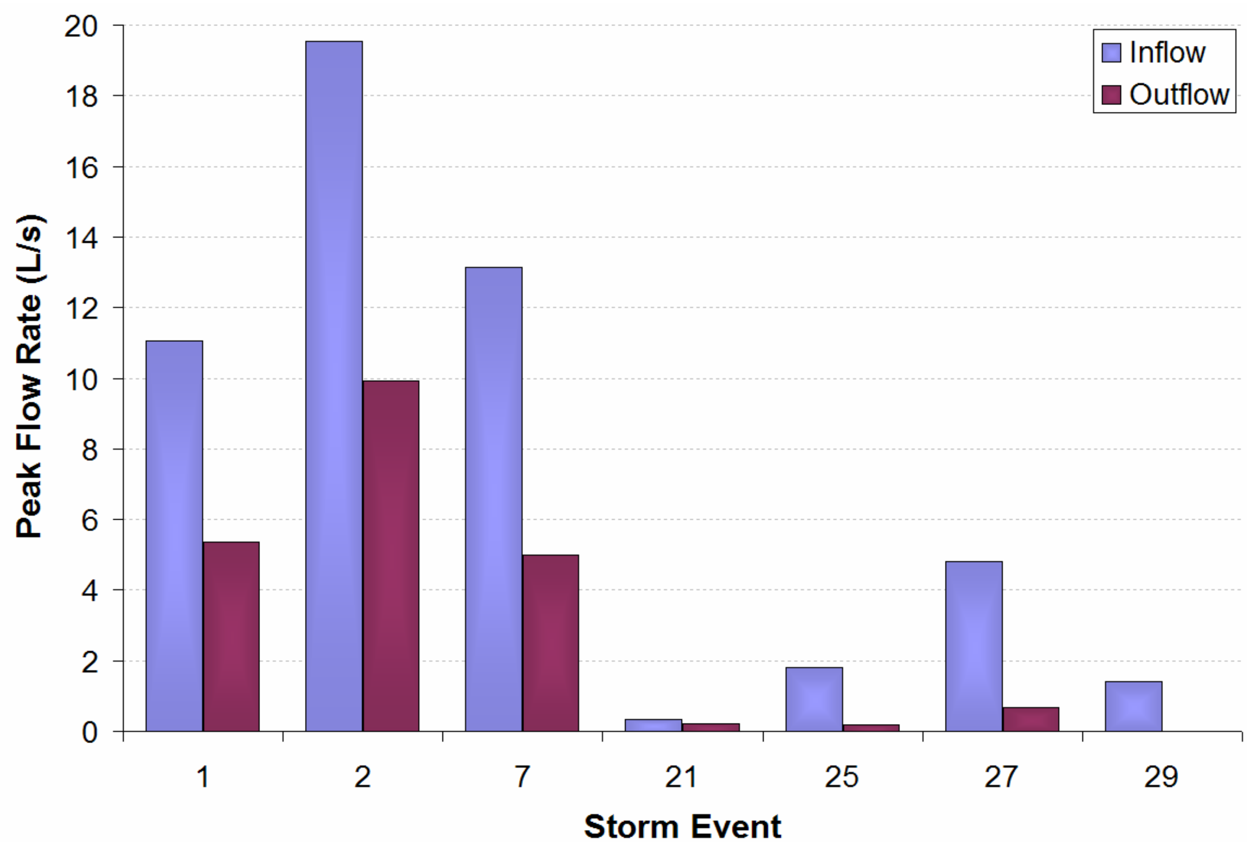


Figure 5.10. Peak inflow and outflow rates for the structural soil infiltration trench.

Several correlations were identified between peak flow rates and other flow variables. There was a strong positive correlation between the peak inflow rate and the outflow volume of the ITSS ($\rho = 0.90$, $p = 0.006$). There was also a positive correlation between the inflow volume entering the ITSS and the peak outflow rate leaving the ITSS ($\rho = 0.857$, $p = 0.0238$). A negative correlation was identified between the amount of inflow entering the BMP and the percent reduction in peak flow rates ($\rho = -0.786$, $p = 0.048$). These correlations provide several insights about the hydrology of the ITSS. Larger storms produce higher peak inflow rates as well as higher outflow volumes, and a higher peak inflow rate can be indicative of a higher outflow volume. Similarly, this suggests that large inflow volumes are representative of larger storms, which usually produce higher peak outflow rates than smaller storms. Additionally, the reduction in peak flow rates within the ITSS decreases as the size of the storm (and inflow volume) increase. Therefore, the BMP is more effective at reducing peak flow rates for smaller storms with less inflow volume.

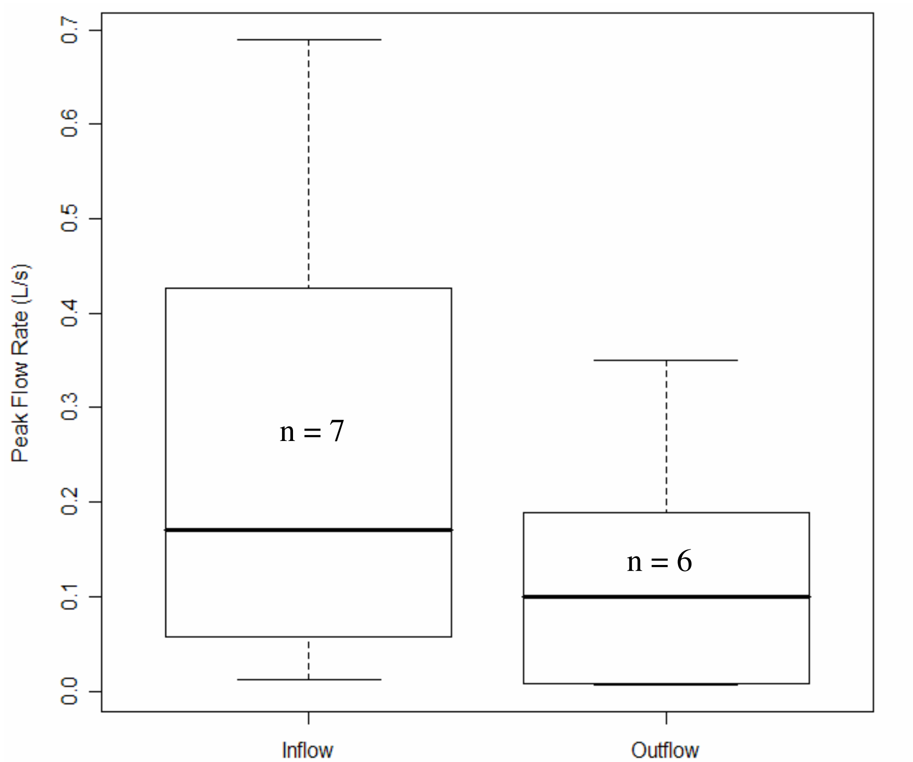


Figure 5.11. Inflow and outflow peak flow rates for the structural soil infiltration trench. The bold line in the middle of the box represents the median, while the top and bottom of the box represent the 25th and 75th percentiles, respectively. Whiskers of the boxplot extend to the most extreme data point which is no more than the range times the interquartile range from the box.

5.2.5. BMP Hydrology Summary

Due to the presence of the sediment forebay, the ITSS received outflow for a smaller number of storms than the BRC. The sediment forebay also drastically decreased the rate at which water entered the ITSS in comparison to flow rates entering the BRC. Due to large amounts of water leaving the BMP via exfiltration, the BRC significantly reduced flow volumes and peak flow rates, producing outflow for only three of 29 storm events. Peak flow rates and flow volumes were significantly reduced within the ITSS; however, the hydraulic conductivity of the treatment media was higher than originally designed, and the peak outflow rates were higher than expected. The use of flow restrictors and/or smaller underdrain pipes is recommended to further reduce peak flow rates in gravel-based infiltration trenches with underdrains.

5.3 BMP Impacts on Water Quality

The following section discusses the water quality impacts associated with the BRC and ITSS. During analysis, concentration values for events without outflow were designated 'not applicable' and were not included in mean or median calculations; for load values for events without outflow were designated 0, and were included in mean or median calculations. Therefore, all median and minimum values for constituent outflow loads for the BRC are 0. When testing for significance, the Wilcoxon Signed Rank Test did not include NA values in the statistical analyses; thus, the statistical analyses for BRC pollutant concentrations only analyzed concentration data for the three storms that produced inflow and outflow. A load value of zero was considered a valid data point, so all 21 storm events were included in statistical analyses of BRC loads. Similar techniques were employed for the ITSS as well.

5.3.1. BRC: Suspended Sediment

As summarized in Figure 5.12, inflow suspended sediment concentrations ranged from 26 mg/L for storm 8 to 593 mg/L for storm 21. Of the three storms that produced outflow, storm 29 had the highest SSC of 872 mg/L, while storm 17 had the lowest of 8.8 mg/L. Mean and median inflow concentrations were 197 mg/L and 166 mg/L, respectively, while mean and median outflow concentrations were 304 and 32.5 mg/l, respectively. Two outlying concentrations identified in the inflow dataset correspond with storms 20 and 21. The inflow and outflow concentrations were not significantly different, most likely due to a lack of outflows and the resulting small data set.

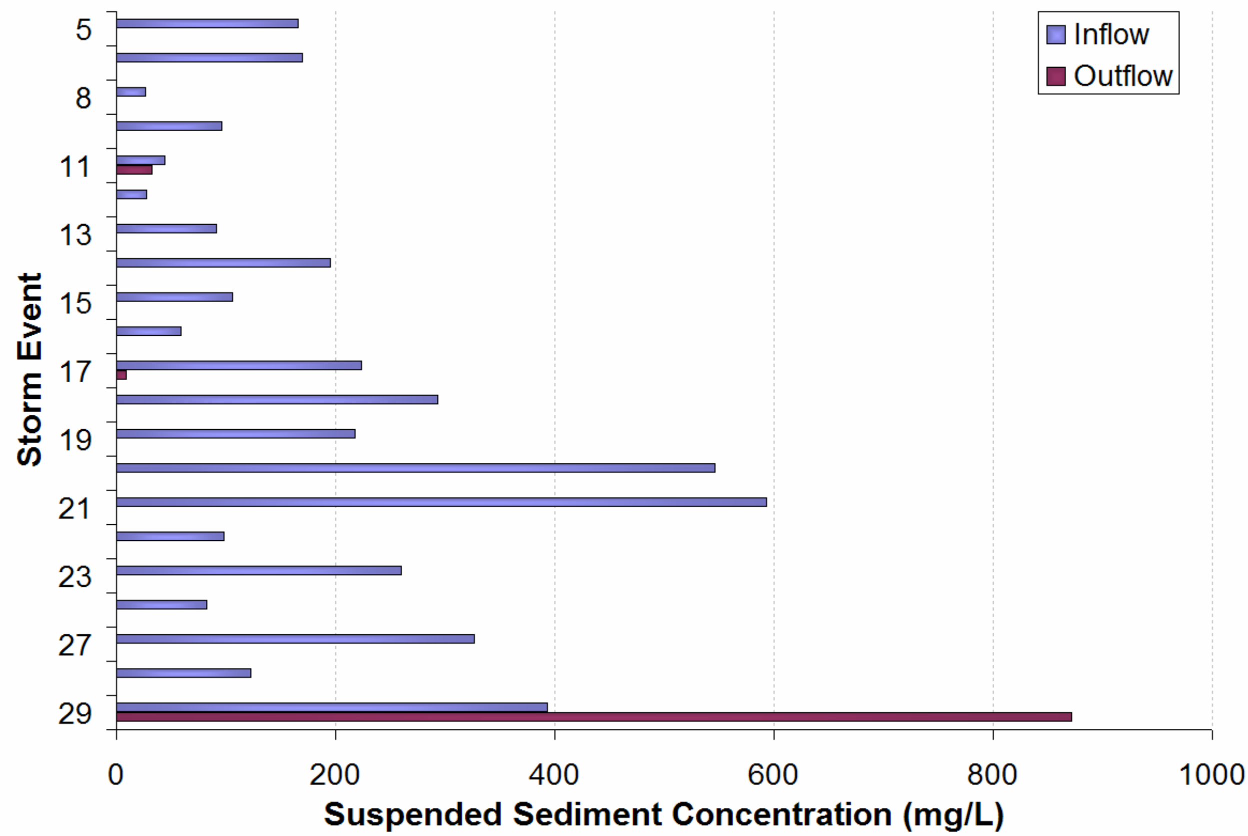


Figure 5.12. Inflow and outflow suspended sediment concentrations for the bioretention cell for each monitored storm event.

Total SSC inflow and outflow loads for the BRC were calculated for each storm event (Figure 5.13). These values ranged from 0.03 g (storm 13) to 3,867.0 g (storm 21) for inflow and 0.0 g to 15.2 g (storm 11) for outflow. Mean loads were 500.0 g and 0.8 g for inflow and outflow, respectively. The median inflow value was 68.5 g of sediment.

The highest suspended sediment outflow concentration and load occurred during storm 29, which was the only storm that produced outflow in the form of surface overflow. The occurrence of overflow was determined by the presence of mulch and debris on top of the overflow grate, indicating water ponded above the grate. No outflow occurred through the underdrains, as determined by an analysis of water levels within the BMP. The higher sediment concentration and load were likely due to a recent application of new mulch and the high inflow velocities, as described previously in section 5.2.1.

Storms 20 and 21 had high inflow suspended sediment concentrations as compared to previous storm events. These storms occurred on February 6, 2008 and February 13, 2008, respectively, amidst icy weather. The Town of Blacksburg treats their parking lots with a mixture of calcium chloride, magnesium chloride and rock salt. Town streets are treated with a mixture of aggregate and deicing chemical (to be discussed later). Increases in the amount of sediment and aggregate on the surface of the parking lots draining to the BMPs were noticed following icy weather. Therefore, the source of the suspended sediment increases during these storm events was likely the deicing mixture applied to the parking lots and/or aggregate that was tracked into the parking lot from the street.

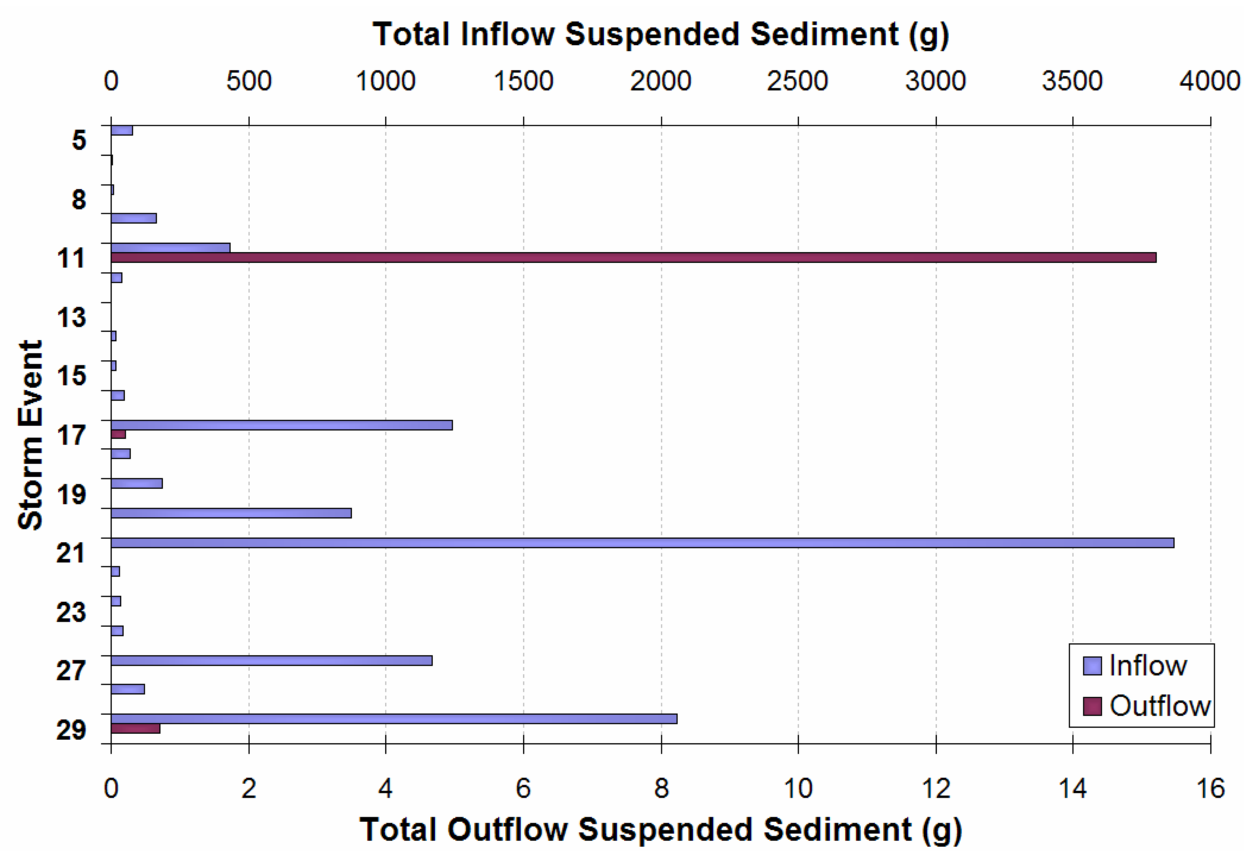


Figure 5.13. Inflow and outflow suspended sediment loads for the bioretention cell. Note the secondary y-axis for outflow loads.

A cumulative plot of sediment movement within the BRC throughout the study period is displayed in Figure 5.14. The plot takes into account sediment entering the BMP via inflow and leaving the BMP via outflow and/or overflow throughout the study period.

During the study period, a total of 10,105 g of suspended sediment entered the BMP via inflow, while only 16 g exited the BRC through outflow. Thus, the cumulative mass percent removal of suspended sediment by the BRC was 99.8%. The median SS removal rate per storm event was 100%. When only the three storms that produced outflow were considered, the average removal rate dropped slightly to 99.9%.

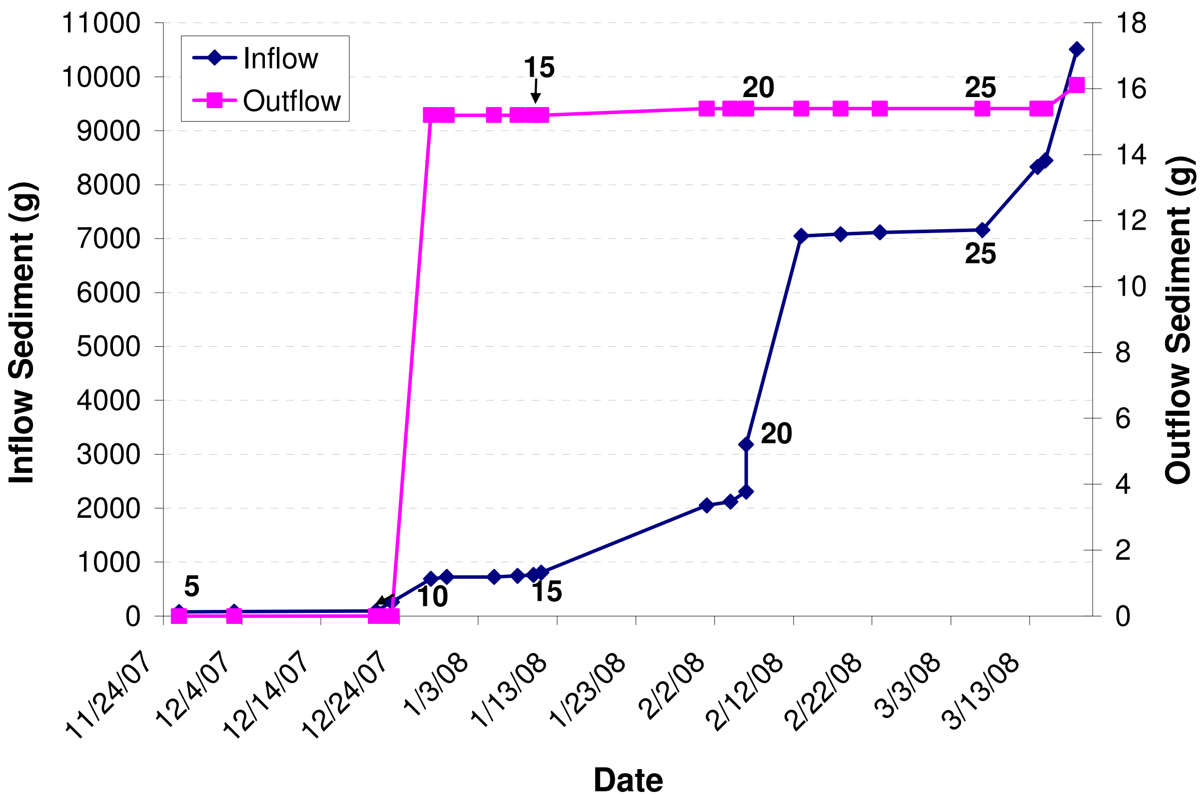


Figure 5.14. Cumulative sediment budget for the bioretention cell.

Statistical analyses confirmed that the total mass of sediment entering the BRC was significantly greater than the total mass leaving the BRC through outflow (p = 2.384E-7). The percent mass removal was negatively correlated with inflow volume (ρ =

-0.647, p = 0.00114); therefore, the percent reduction in suspended sediment declines as the inflow volume increases. This finding is unsurprising as higher inflow volumes would likely be more turbulent and would be more likely to result in surface overflow. There were no significant correlations of percent mass removal to either the inflow suspended sediment concentration or load.

In a study of a bioretention facility located in the parking lot of the Navy Yard, Washington, DC, Glass and Bissouma (2005) measured a 98% reduction in total suspended solids, which is similar to the 99% reduction in SS found in this study. Overall, the BRC substantially reduced the amount of suspended sediment entering the existing stormwater management system.

5.3.2. BRC: Total Nitrogen

Inflow total nitrogen concentrations ranged from below the detection limit (storm 11) to 7.2 mg/L (storm 17; Figure 5.15); outflow concentrations ranged from below the detection limit (storm 11) to 5.8 mg/L (storm 17). Mean and median values were 2.7 mg/L and 2.2 mg/L for inflows, respectively. Outflow mean and median values were 3.8 and 5.3 mg/L, respectively. Outlying values for inflow concentrations were identified as those generated during storms 17 and 19. The inflow and outflow concentrations of total nitrogen were not significantly different, although this result was likely affected by the small set of outflow events (n = 3).

Figure 5.16 summarizes the total mass of nitrogen that flowed in and out of the BMP during each storm. Inflow load values ranged from 0.001 g for storm 13 to 40 g for storm 17; the maximum outflow load was 0.13 g (storm 17). Mean inflow and outflow loads were 4.43 g and 0.012 g, respectively. The inflow median value for total nitrogen was 1.29 g; three outliers identified for inflow loads correspond with storms 17, 21 and 27.

Storm 17 produced a high inflow concentration and load of TN for the BRC. The source of this high concentration is unknown. Storm 29 had an unusually high outflow TN concentration, as this is the storm that produced overflow. The high concentration is most likely due to the application of new mulch six days prior to the storm, as discussed previously.

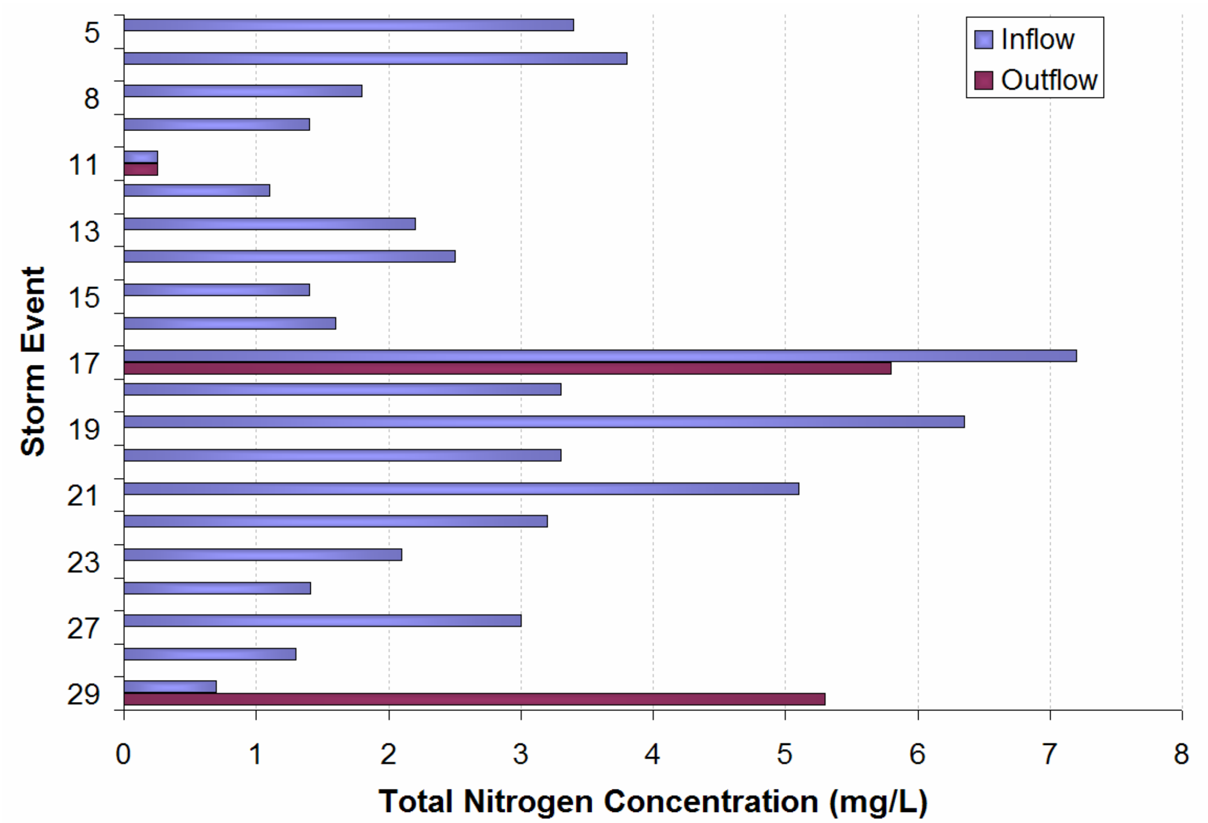


Figure 5.15. Total nitrogen inflow and outflow concentrations for the bioretention cell.

Table 5.2 summarizes the amount of nitrogen attributable to each media component. While it is recognized that a certain amount of nitrogen is contributed by living plant material, the amount was considered small when compared to the amount supplied by the media. While the nitrogen concentration of the sand is fairly low, 87% of the media was sand; thus, the sand contained the greatest fraction of nitrogen within the BRC. While the leaf compost was added as a carbon source, it was also a significant source of nitrogen within the BMP. Figure 5.17 summarizes the percentage of nitrogen contributed by the various components of the BMP at the beginning and end of the study period. This figure shows that the mass of nitrogen entering the BRC during the study period represented a fraction of a percent of the overall nitrogen balance.

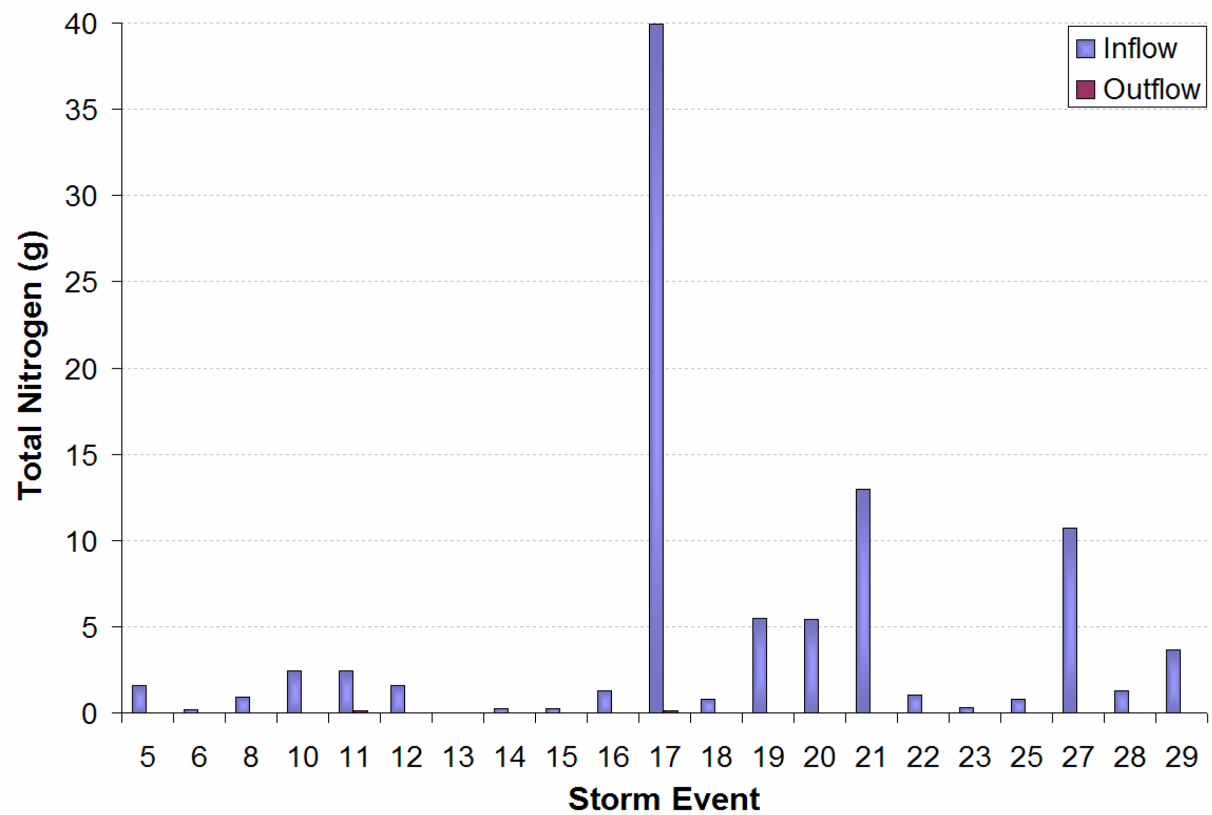


Figure 5.16. Total nitrogen inflow and outflow mass for all storms producing flow events for the bioretention cell.

Table 5.2. Total nitrogen concentrations and mass for each media component present in the bioretention cell during the study period.

	Sand	**Mulch (Appl. 1)**	**Mulch (Appl. 2)**	**Leaf Compost**	**Top Soil**	**Potting Soil**
Concentration (mg/kg)	1660	4720	4720	13,470	594	2270
Total Mass (kg)	165.65	11.99	4.28	62.32	5.39	0.26

Mulch was a sizeable contributor of TN, but the difference between the relative contribution at the beginning of the study period and the end of the study period was surprising. A mulch layer was applied to the BRC before monitoring commenced, and a ‘refresher’ layer was applied in March, 2008, toward the end of the study period. The second application of mulch, which is common practice for bioretention cells, increased the percent contribution of TN for mulch by approximately 1.5%. If a new layer of mulch is applied every year each layer adds approximately 4.3 kg of TN, the amount of TN in the BRC in 10 years due to mulch could be approximately 22%. It is important to note that not all of the nitrogen in the leaf compost and mulch would be in a labile form, as some organic forms are refractory.

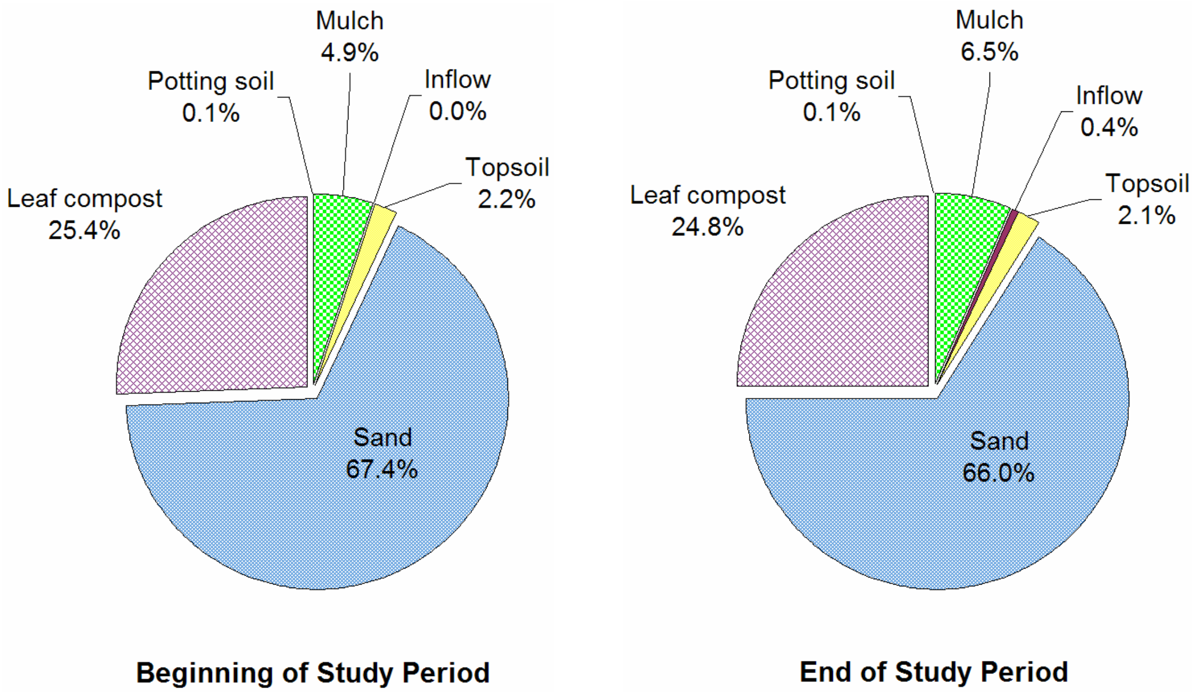
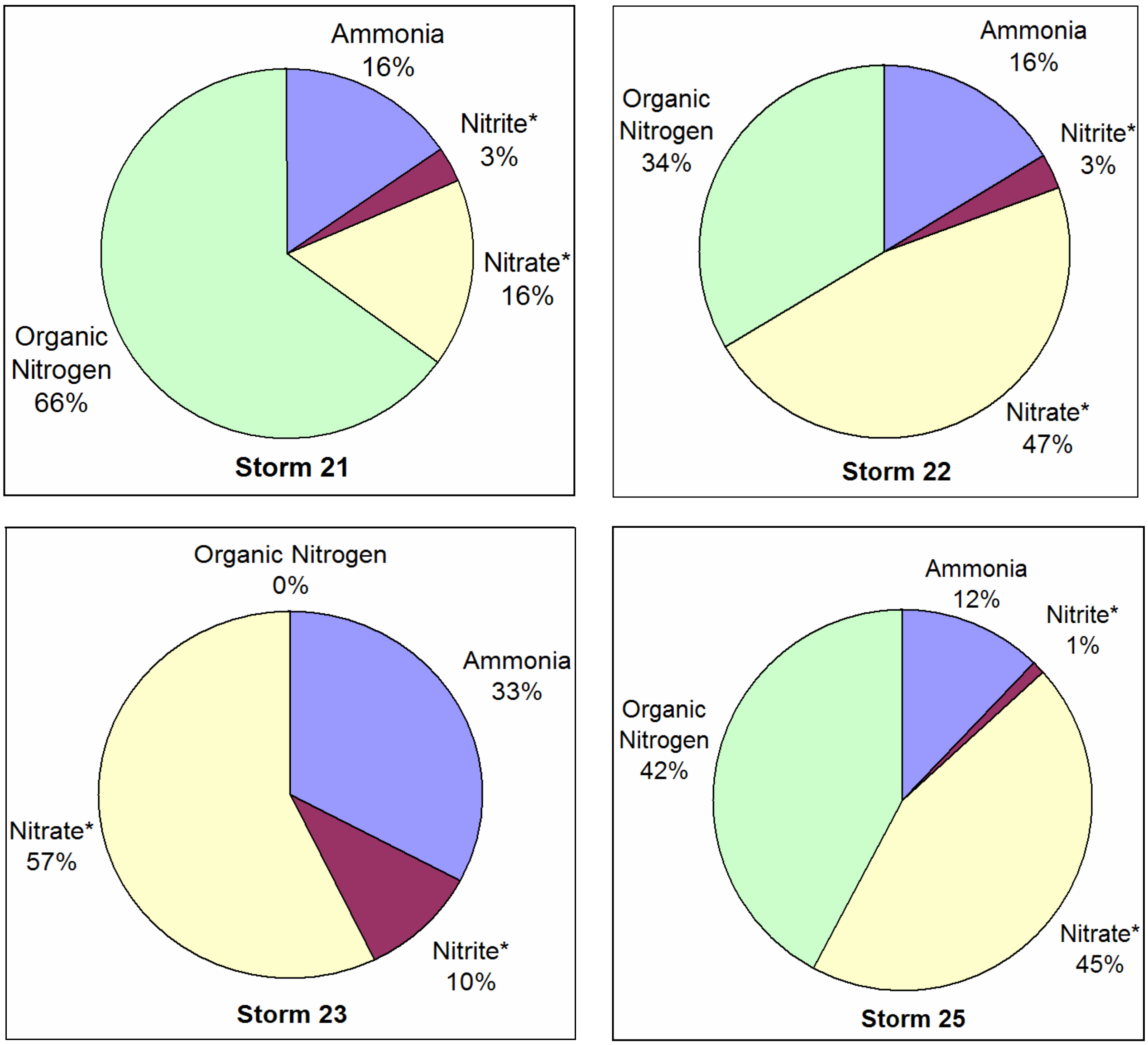


Figure 5.17. Relative contribution of media components to the total nitrogen mass balance within the bioretention cell at the beginning and end of the study period.

An analysis of the dominant nitrogen species in the runoff can give an indication of possible nitrogen sources; therefore, ammonia, nitrite and nitrate concentrations were analyzed for BRC inflow for several selected storm events. Organic nitrogen was determined as the difference between total nitrogen and the sum of ammonia/ammonium, nitrite, and nitrate. Figure 5.18 summarizes the contributing percentage by mass of each element in the nitrogen series for storms 21, 22, 23 and 25. A table of the mass and concentrations of each element may be found in Appendix B.

Four storm events were analyzed for ammonia, nitrite and nitrate to determine the TN composition. However, none of these storm events generated outflow. Nitrate accounted for an average of 41% percent of the BRC TN load, as compared to 0.6% for the ITSS. As nitrate is highly mobile anion, it is most likely to travel as a dissolved form. Therefore, the large amount of nitrate in the BRC inflow is most likely due to fertilization of a small grassy area that drains to the BMP, in addition to the parking lot. Town of Blacksburg maintenance crews apply fertilizer to both the grass and the trees within the area annually. This area also contains several trees that are maintained by the Town of Blacksburg and had new mulch applied during the study period (specific date unknown).



* Tests were performed on filtered sample due to high turbidity.

Figure 5.18. Inflow total nitrogen composition for the bioretention cell for storms 21, 22, 23 and 25, expressed in percentage by mass. Storms 21, 22, 23, and 25 occurred on February 13, 18 and 23, 2008 and March 7, 2008, respectively.

A cumulative mass balance for total nitrogen was performed for the BRC for the study period (Figure 5.19). During the study period, a total of 93.1 g of total nitrogen entered the BMP via inflow; 0.25 g exited via outflow, resulting in a cumulative total mass reduction of 99.7%. Individual storm reductions resulted in a median removal rate of 100% (99.7% for storms that only produced outflow). Statistical analyses concluded that the inflow mass of total nitrogen for the BRC was significantly greater than the outflow mass ($p = 2.384\text{E-}7$). The percent mass removal of TN within the BRC was not correlated to the concentration or the mass of inflow TN; however, the removal rate was negatively correlated with the inflow volume ($\rho = -0.661$, $p = 0.0015$), suggesting that the BRC is most effective at reducing nitrogen concentrations for smaller storms with smaller inflow volumes.

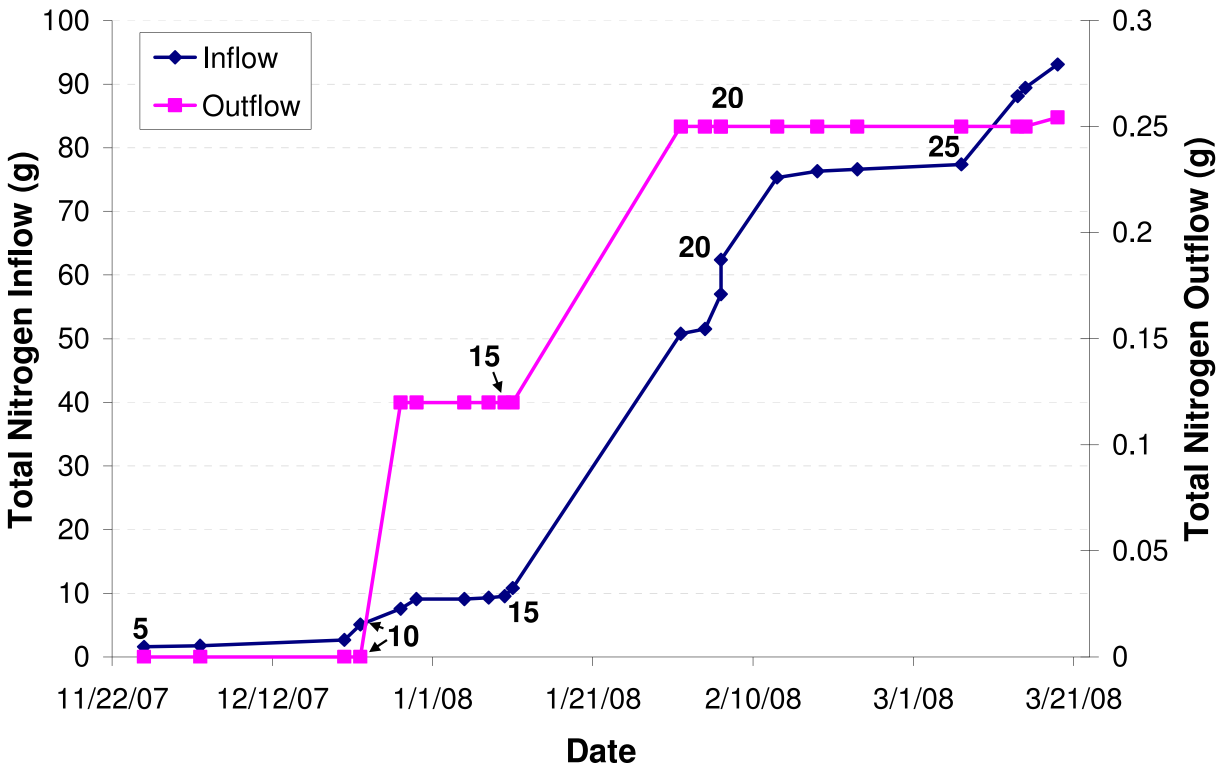


Figure 5.19. Cumulative total nitrogen (TN-N) inflow and outflow for the bioretention cell. Point labels specify storm events.

The 99% removal efficiency of the BRC was much higher that results reported by other studies. Dietz and Clausen (2005) reported a TN removal rate of 32%, while Hunt et al. (2006) reported a rate of 40%. The difference between the removal efficiency achieved in this study and those reported by other studies is most likely due to the extremely high flow reductions and the large number of storm events that did not produce outflow from the BRC.

5.3.3. BRC: Total Phosphorus

An overall summary of inflow and outflow total phosphorus concentration data is shown in Figure 5.20. Inflow concentrations ranged from a minimum of 0.1 mg/L (storm 11) to a maximum of 5.0 mg/L (storm 19). Outflow concentrations varied from 0.1 mg/L for storm 17 to 2.3 mg/L for storm 29. Figure 5.20 identifies the median values for inflow and outflow concentrations as 2.2 and 5.3 mg/L, respectively. Mean values were 2.7 and 3.8 mg/L for inflow and outflow, respectively. Figure 5.21 summarizes the inflow and outflow concentration values for each storm monitored within the study period. The inflow and outflow concentrations did not differ significantly.

The two outliers identified in the inflow concentration dataset for the BRC occurred during storms 19 and 20. As mentioned in section 6.2.3, icy weather was prominent prior to these two storm events. The deicing chemical Liquidow™ is occasionally applied to the parking lot as part of a rock salt and aggregate mixture using an application rate of 26.2 L/metric ton (Long, 2008). Liquidow™ is a 30-42% $CaCl_2$ solution containing 25 ppm phosphorus. Depending on the amount of chemical applied and the frequency of freezing precipitation, this may or may not be a significant source of phosphorus in stormwater runoff. If 190 L of Liquidow™ were applied to the parking lot in conjunction with 7 metric tons of rock salt and aggregate mixture, this would contribute approximately 4.7 g of TP.

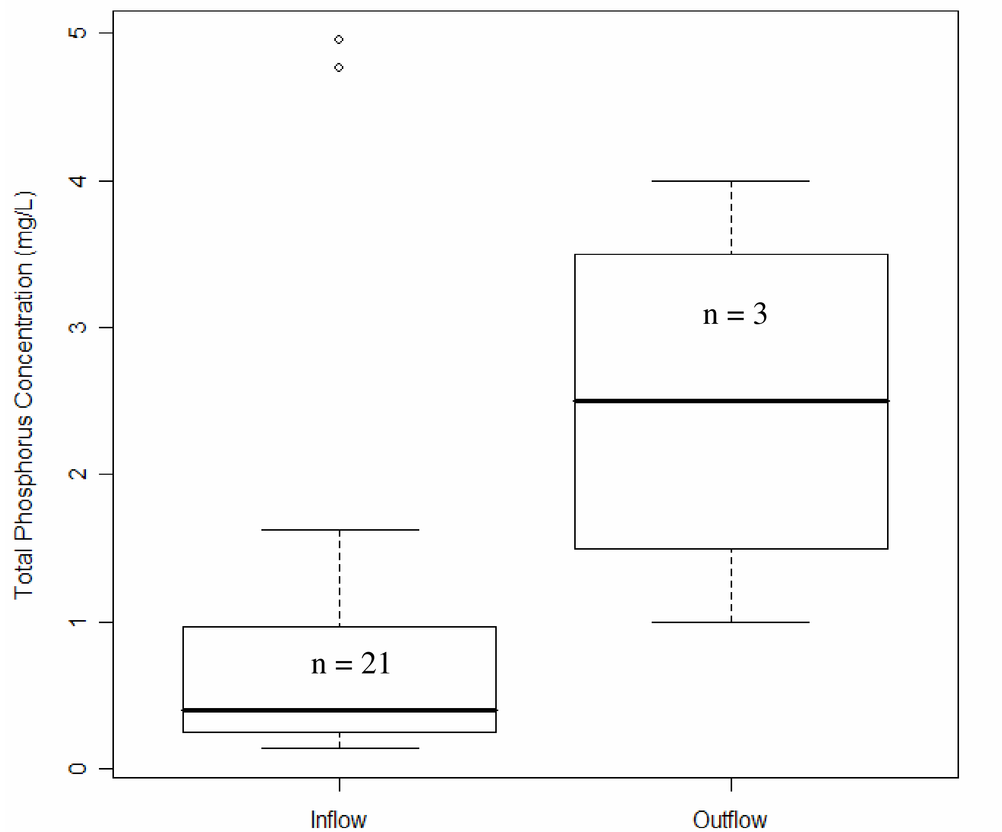


Figure 5.20. Boxplots of inflow and outflow total phosphorus concentrations for the bioretention cell. Only events that produced outflow from the bioretention cell are included in the outflow concentration plot (storms 11, 17 and 29).

Figure 5.22 displays the total mass of phosphorus that entered and exited the BMP during each storm event. Minimum and maximum inflow load for total phosphorus were 0.0001 g (storm 13) and 7.78 g (storm 20), respectively. The maximum outflow load during the study period was 0.086 g, which occurred during storm 11. Mean inflow and outflow values were 1.1 g and 0.004 g, respectively. The median inflow load was 0.2 g. One outlier was identified in both inflow and outflow values: both outliers correspond with the maximum load values.

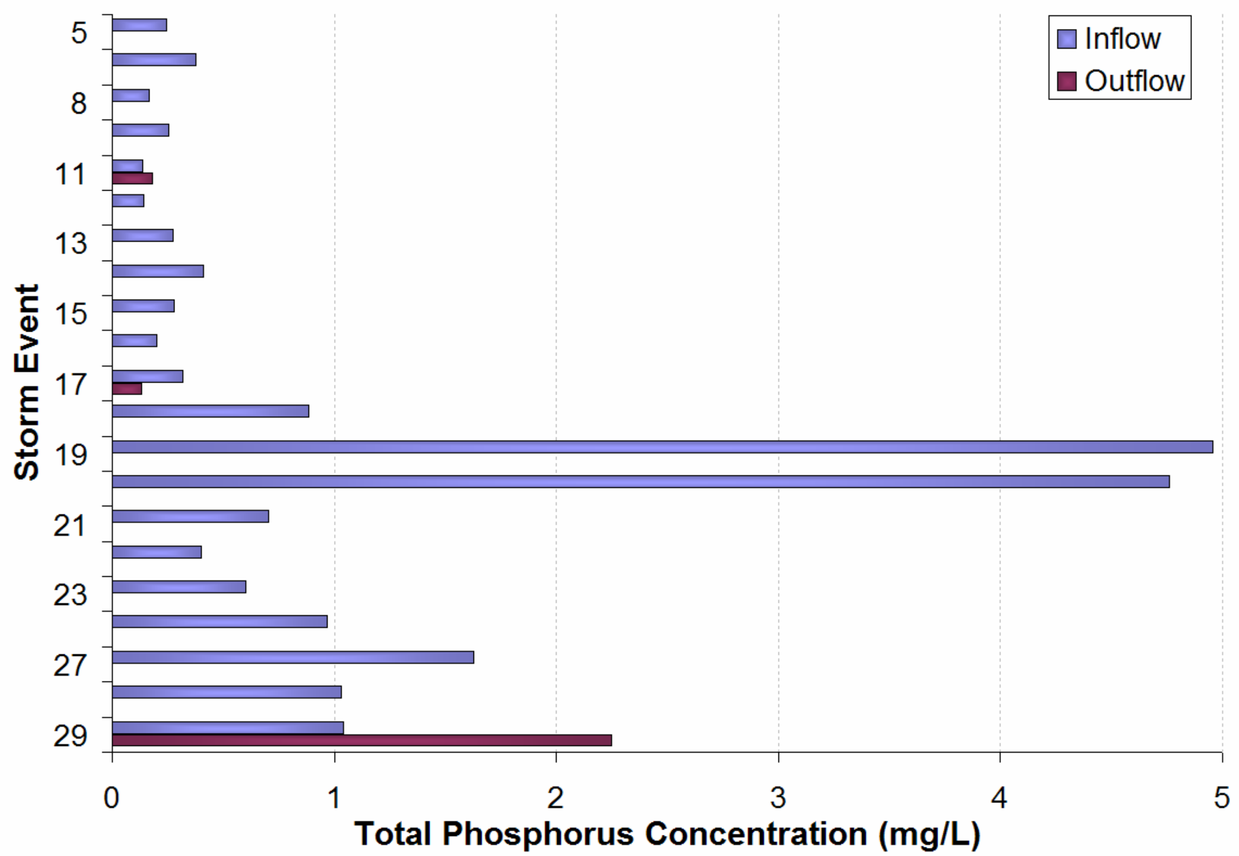


Figure 5.21. Inflow and outflow total phosphorus concentrations for the bioretention cell.

Storm 29 produced high concentrations of total phosphorus in outflow from the BRC. As discussed previously, this is most likely due to the newly-applied mulch and the large inflow velocities. Table 5.3 and Figure 5.23 summarize the mass of phosphorus present in each component of the BRC at the beginning and end of the study period. Leaf compost is the most significant source of TP in the BMP – due to the high concentration of TP in the compost - while topsoil is the second largest contributor. It is expected that the leaf compost and topsoil have the highest concentrations of TP, as phosphorus binds strongly with soil fines, but not sand particles. TP added as a result of stormwater inflow is negligible compared to the amounts contained in the other components of the BMP media.

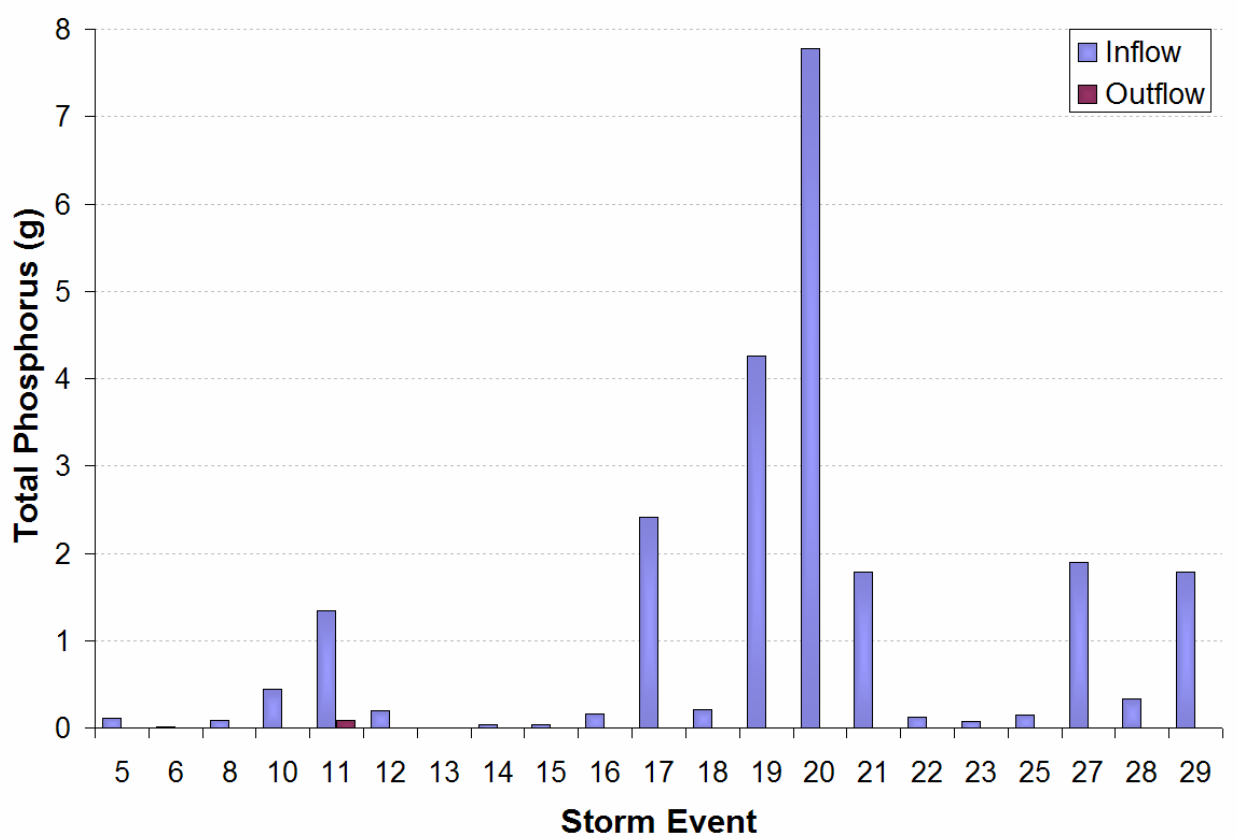


Figure 5.22. Inflow and outflow phosphorus load for the bioretention cell.

Surprisingly, mulch was a considerable contributor to the amount of TP in the BRC. According to Figure 5.23, a new mulch layer increased the percent contribution of TP by approximately 2%. A new mulch layer is commonly added to bioretention cells in the spring of each year; the old mulch layer is generally not removed due to labor, budget and time constraints. In ten years, approximately 27% of the TP within the BRC will be due to mulch, assuming each additional mulch layer adds approximately 0.2 kg of TP and no mulch is removed.

Table 5.3. Total phosphorus concentration and mass for each media component present in the bioretention cell during the study period

	Sand	Mulch (Appl. 1)	Mulch (Appl. 2)	Leaf Compost	Top Soil	Potting Soil
Concentration (mg/kg)	10	200	200	900	200	400
Total Mass (kg)	0.998	0.508	0.181	4.082	1.81	0.047

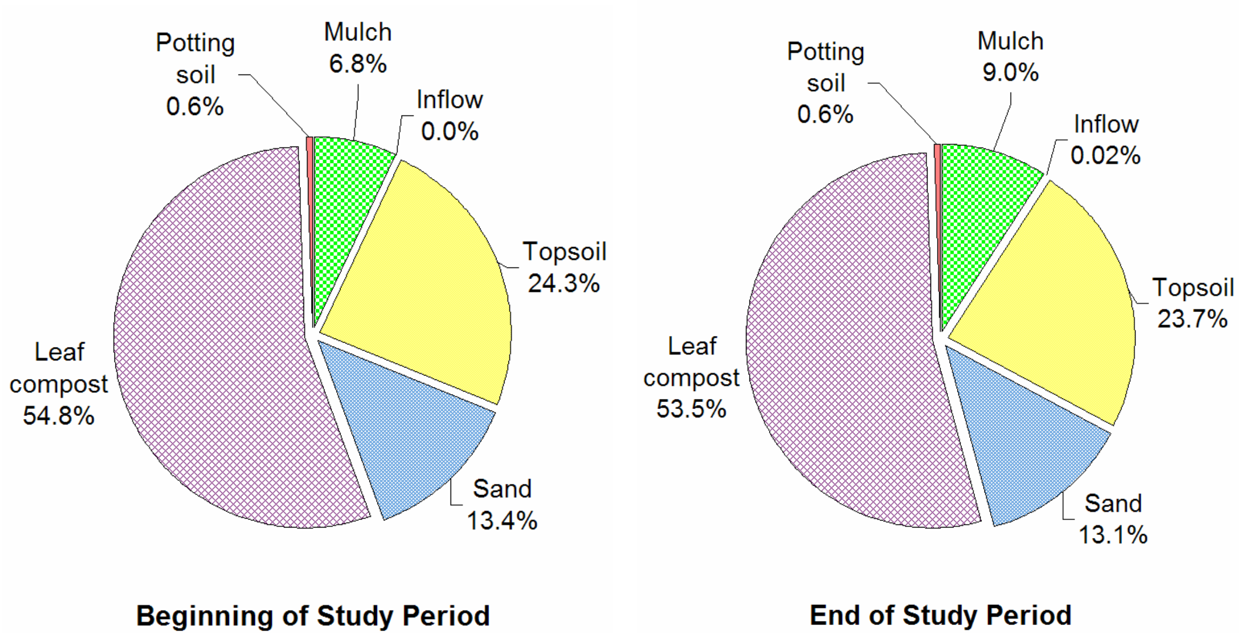


Figure 5.23. Phosphorus mass balance for the bioretention cell at the beginning and end of the study period.

To evaluate the potential of the bioretention media to store phosphorus, a Mehlich-III P test was conducted on all solid materials included in the bioretention media. A Mehlich-III P test value is representative of the amount of available phosphorus in the media. Certain ranges of Mehlich-P values correspond to levels of available phosphorus: very low, low, medium, high, etc (VADCR, 2005). Table 5.4 displays the Mehlich-III P value for each media component as determined by laboratory analyses, and the overall value based on the mass-weighted average of the media as a whole. Overall, the Mehlich-III value for the treatment media is very low (VL), as determined using the scale published by VADCR (2005).

Table 5.4. Mehlich-III P ranking for each media component in the bioretention cell, and the overall ranking for the treatment media.

Sand	**Mulch**	**Leaf Compost**	**Top Soil**	**Potting Soil**		**Overall Value**
Very Low	Medium	Very High	Low	High		Very Low

Hunt et al. (2004) showed that a relationship exists between the amount of available P in the treatment media and the TP removal efficiency of a bioretention cell. As the BRC treatment media was very low in available phosphorus, it is likely the BRC will continue to be a sink for TP for the near future.

A cumulative TP mass balance was calculated for the BRC. Figure 5.24 summarizes the cumulative amount of phosphorus within the BRC throughout the study period, accounting for TP entering the BMP via inflow and exiting in outflow.

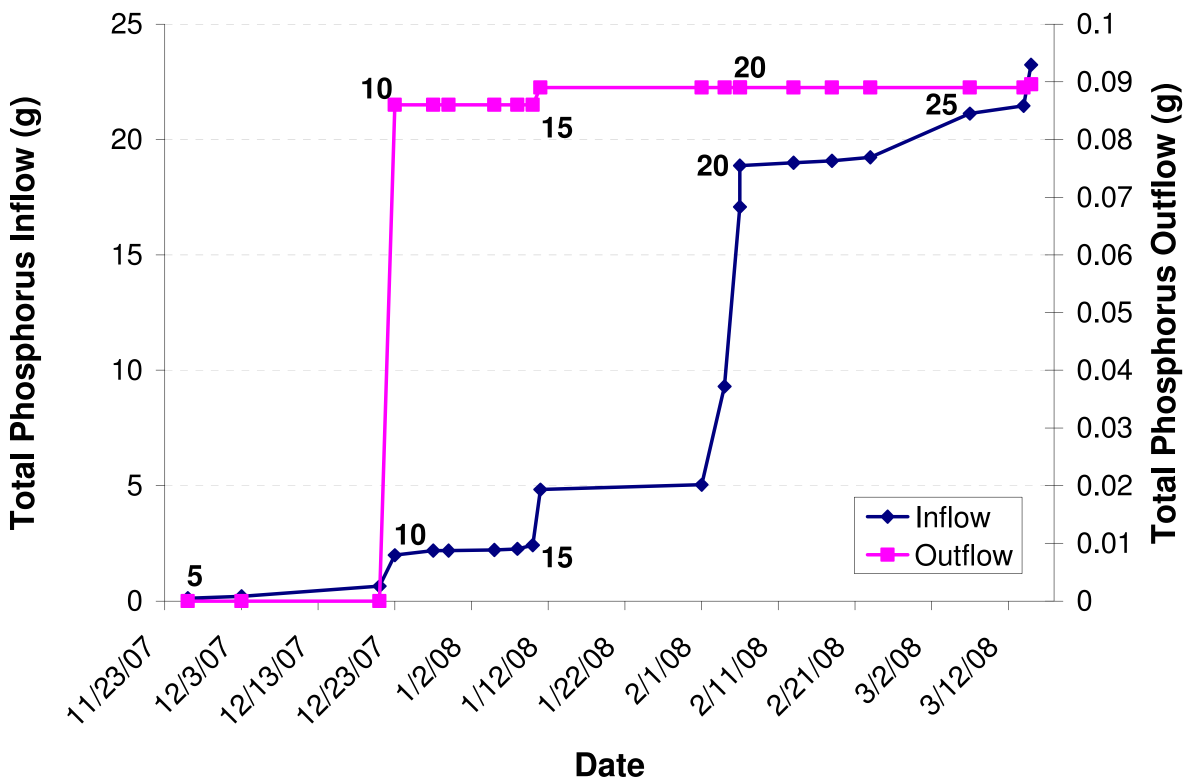


Figure 5.24. Inflow and outflow cumulative total phosphorus for the bioretention cell. Point labels indicate storm events.

The BRC greatly reduced the amount of TP entering the stormwater drainage system. In total, 23.24 g of total phosphorus entered the bioretention cell via inflow while only 0.09 g left via outflow. Therefore, the cumulative percent reduction for the BRC was 99.6%. The median removal rate for an individual storm was 100% (when only considering storms that produced outflow, this value dropped to 99.8%). Statistical analysis confirmed that the inflow mass load was significantly greater than the outflow mass load ($p = 2.384E\text{-}7$).

The efficiency of the BMP in reducing the mass of TP was not correlated to the inflow concentration or load; however, the percent mass removal was negatively correlated with the inflow volume ($\rho = -0.571$, $p = 0.009$), indicating reduced TP removal with increased inflow.

The TP removal rates reported by other research studies are lower than the rates reported in this study: Hunt et al. (2006) and Davis et al. (2001) reported TP load reductions of 66% and 80%, respectively. The difference between these average removal rates and the 99% produced in this study is most likely the lack of storms producing outflow. Additionally, Hunt et al. (2006b) concluded the amount of available phosphorus in the treatment media greatly influences the TP removal rate of the bioretention system. Other studies might have used a treatment media with a higher amount of available phosphorus than the BRC, which could account for the higher removal rate when compared to previous studies.

5.3.4. BRC: Fecal Coliform Bacteria

Inflow fecal coliform bacteria concentrations ranged from 15 colony forming units (cfu)/100 mL for storm 27 to 2700 cfu/100 mL for storm 8. Outflow concentrations had a minimum value of 10 cfu/100 mL for storm 29 and a maximum value of 500 cfu/100 mL for storm 17. Inflow and outflow median concentrations were 180 and 440 cfu/100 mL, respectively. The mean inflow concentration was 610 cfu/100 mL, while the mean outflow concentration was 316 cfu/100 mL. Concentrations for individual storms events are summarized in Figure 5.25. The inflow and outflow fecal coliform concentrations were not significantly different.

Surprisingly, the lowest fecal coliform outflow concentration occurred for the storm event that produced overflow: the runoff that did not pass through the treatment media of the BRC had lower FC concentrations than runoff that left the BMP via the underdrains. Additionally, both storms events that produced outflow (not overflow) had higher concentrations in the outflow than the inflow, while the storm that produced overflow had higher inflow concentrations than outflow. These seemingly contradictory results indicate that bacteria are likely either being harbored or regenerated within the treatment media of the BRC, the drainage pipes, or the outflow ISCO sampler.

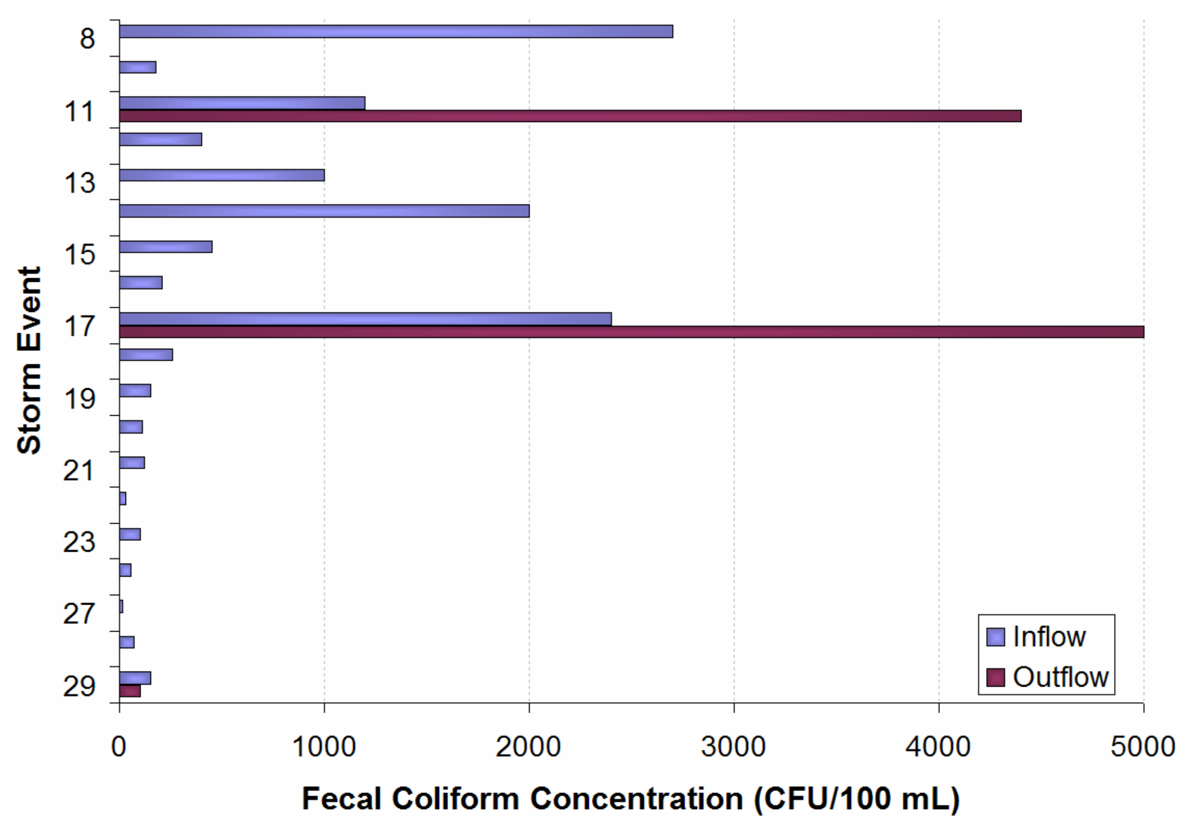


Figure 5.25. Inflow and outflow fecal coliform concentrations for the bioretention cell.

The water quality standards set forth by Virginia Department of Environmental Quality (VADEQ) state that the geometric mean of fecal coliform concentrations for two or more samples in a calendar month should not exceed 200 cfu/100 mL, which is denoted as ‘GM Standard’ in Figure 5.26. Additionally, it is stated that a single sample should not contain fecal coliform bacteria in a concentration higher than 400 cfu/100mL.

This concentration is shown on the figure as ‘SS Standard’. The observed inflow and outflow concentration data for the BRC are plotted on this figure as well, allowing comparison of the data to the state standards.

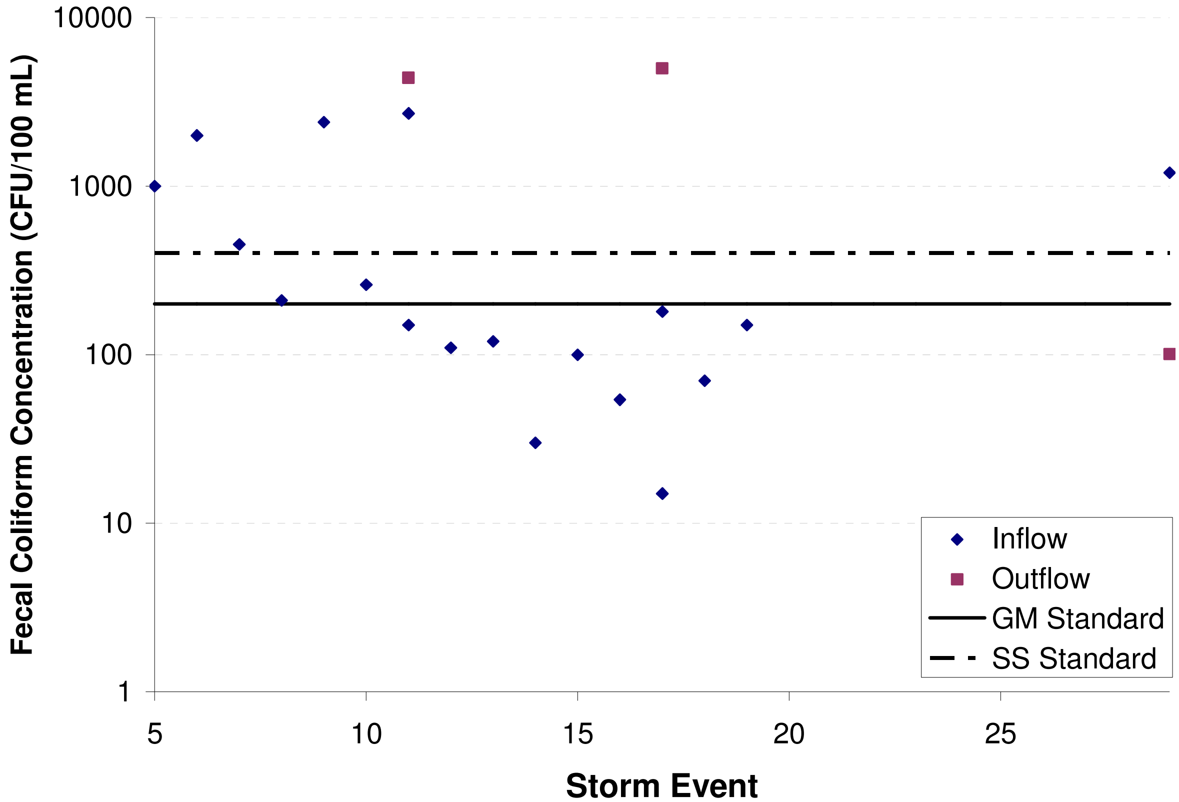


Figure 5.26. Inflow and outflow fecal coliform concentrations for the bioretention cell in reference to the EPA water quality standard for streams. The geometric mean (GM) standard and the single sample maximum (SS) standard are 200 cfu/100 mL and 400 cfu/100 mL, respectively, as shown on the plot.

Nine out of 19 (47%) inflow concentrations exceeded the VADCR geometric mean (GM) standard discussed in section 5.2.5; 66% of the outflow concentrations exceeded the standard. Six of the 19 (32%) inflow concentrations exceeded the single sample (SS) standard, while 66% of outflow concentrations were in violation of the SS standard. The only outflow concentration that did not exceed either of the standards was the concentration in the overflow that occurred during storm 29. Further investigation is required to isolate the source of fecal coliform bacteria.

Flow volumes were used to convert fecal coliform concentrations to a total number of colonies for each storm event. These results are shown in Figure 5.27. Inflow fecal coliform colonies ranged from 3.7E3 cfu for storm 13 to 1.3E9 cfu for storm 29; outflow number of colonies had a minimum value of 818 cfu and a maximum value of 2.06E7 cfu. Mean inflow and outflow values were 8.33E7 cfu and 1.14E6 cfu, respectively. The median inflow number was 1.74E6 cfu. Three outliers were identified for the inflow data and one outlier for the outflow data. The three inflow outliers correspond with storms 11, 17 and 19, and the outflow outlying data point is the load value for storm 11.

A mass balance was performed on fecal coliform within the BRC. The results are displayed in Figure 5.28. The cumulative plot shows the number of fecal coliform colonies that accumulated within the BMP throughout the study period, taking into account those that left via outflow.

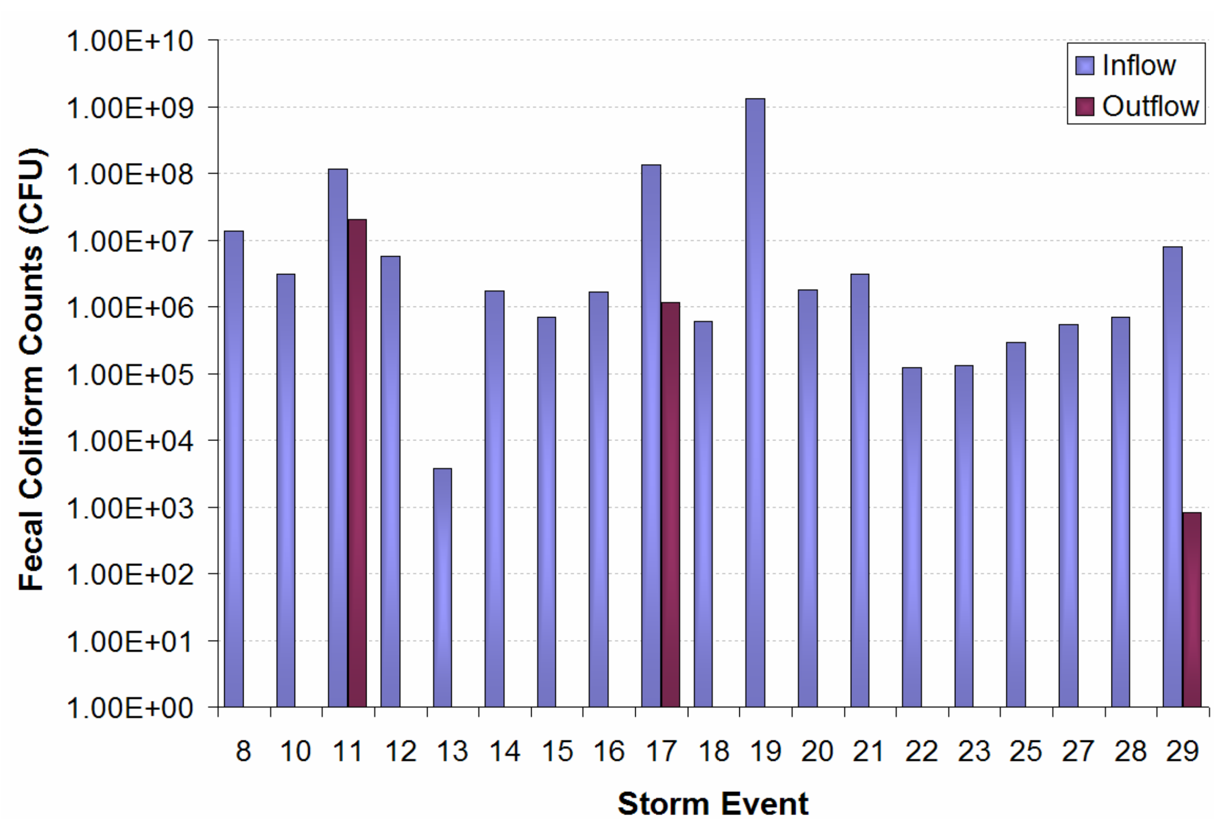


Figure 5.27. Fecal coliform counts for the bioretention cell. Note that the y-axis is on a logarithmic scale.

Approximately 1.58E9 fecal coliform colony forming units entered the BMP during the study period, while approximately 2.17E7 colony forming units left the BMP via outflow. Consequently, the cumulative removal percentage was 98.6%. The median removal rate for individual storm was 100%; when only the three storms that produced outflow were considered, the median removal rate was 99.1%. Statistical analyses confirmed that, overall, the total number of inflow colonies were significantly greater than the total number of outflow colonies ($p = 1.907E-6$); however, the outflow concentrations for the three storm events that produced outflow were still above state water quality standards.

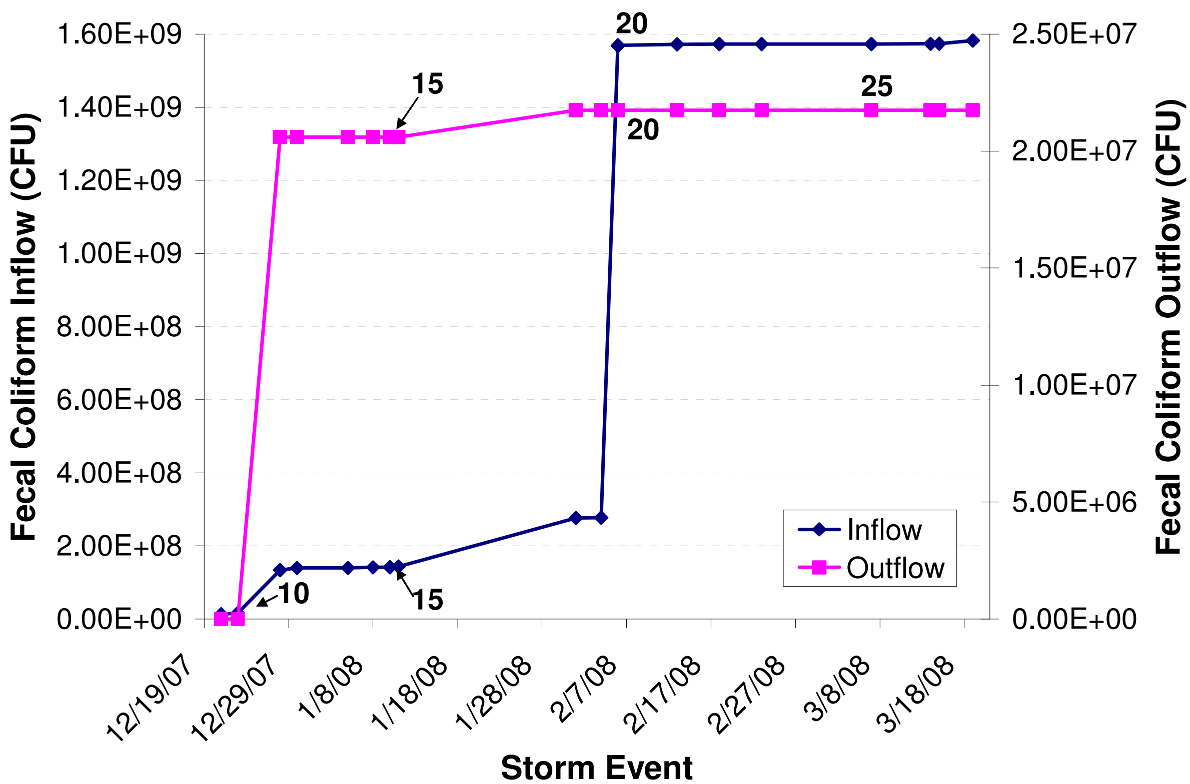


Figure 5.28. Inflow and outflow cumulative fecal coliform counts within the bioretention cell. Point labels indicate storm events.

Due to the high flow reduction for the BRC, the outflow fecal coliform counts were substantially lower than inflow counts for every monitored storm event, thereby greatly reducing the amount of FC bacteria entering the stormwater drainage system. The percent mass removal was negatively correlated with the inflow volume (ρ = -0.681, p = 0.0013), as well as the total inflow load (ρ = -0.568, p = 0.0112). There was no significant correlation between fecal coliform concentrations and suspended sediment concentrations.

Little information is available on reductions in bacteria counts due to BRCs; the study by Hunt et al. (2006) documented an average total load reduction for fecal coliform bacteria of over 90%. This result is similar to the 98% load removal found is this study.

5.3.5. BRC: Escherichia coli (E-coli)

E-coli inflow and outflow concentrations for the BRC ranged from 2 cfu/100 mL (storm 27) to 480 cfu/100 mL (storm 29), and 25 cfu/100 mL (storm 17) to 12,400 cfu/100 mL (storm 11), respectively. The concentration data for each individual storm is summarized in Figure 5.29. The median inflow concentration was 50 cfu/100 mL and the outflow median value was 103 cfu/100 mL. Mean concentrations were 92 and 4,176 cfu/100 mL, respectively. The identified inflow outlier corresponds to the maximum inflow concentration value, which was generated during storm 29. The inflow and outflow concentrations of E-coli bacteria were not significantly different, likely due to the small number of outflow events.

The inflow and outflow E-coli concentration data were multiplied by the corresponding flow volume to determine the total number of bacteria for each storm event. These data are shown in Figure 5.30. The maximum number of inflow colonies was 2.51E7 colony forming units for storm 29, and the minimum inflow number was 1.85E2 cfu for storm 29. Outflow counts ranged from 834 cfu (storm 29) to 5.8E7 (storm 11). Mean inflow and outflow counts were 2.38E6 cfu and 3.05E6 cfu, respectively; median values were 3.38E5 cfu for inflow and 0 cfu for outflow. Inflow counts identified as outliers correspond with storms 11, 19, 20 and 29. The outflow count outlier occurred for storm 11.

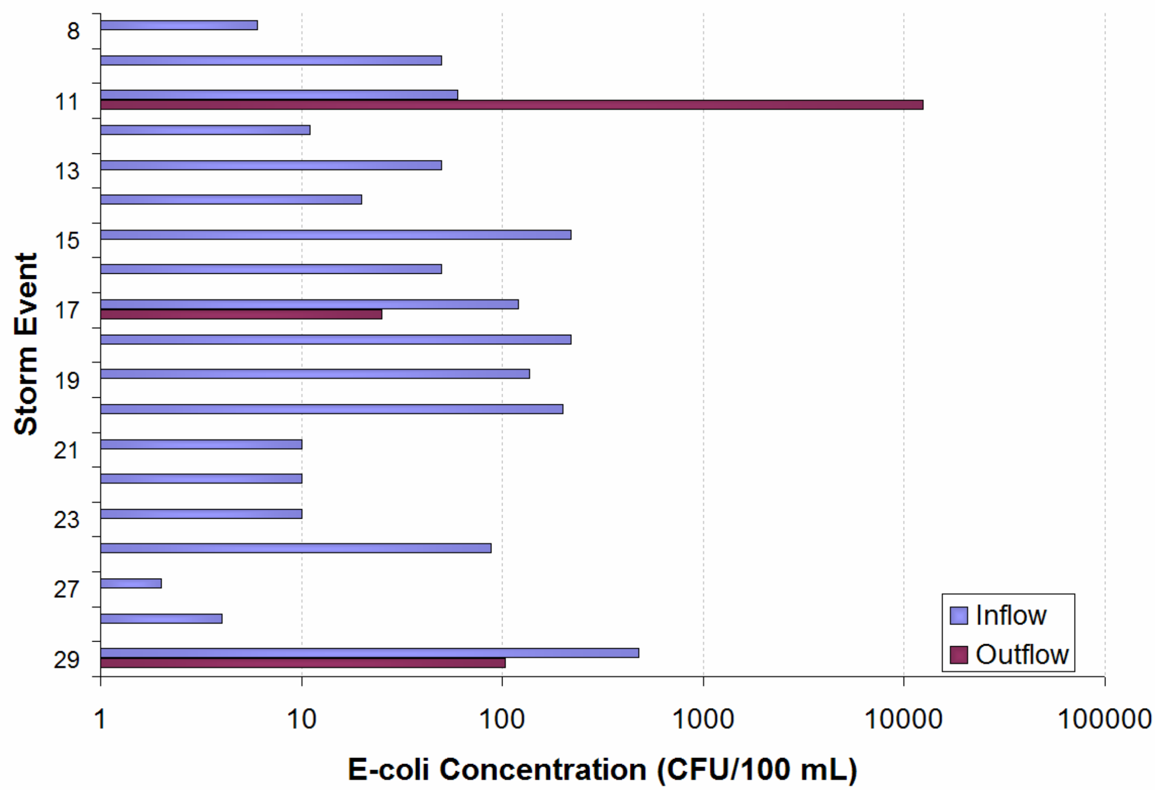


Figure 5.29. E-coli concentrations for the bioretention cell for monitored storm events. Note that the y-axis is on a logarithmic scale.

Unlike the fecal coliform data, the E-coli data showed no evident trends in concentration or colony reductions. Even with a high flow reduction for storm 11, the BRC still exported a large amount of E-coli. Overall, the BRC served as a significant source of E-coli to the stormwater drainage system, suggesting EC bacteria are being harbored or produced in the treatment media, the drainage system, and/or the monitoring system. As with the fecal coliform bacteria, further analyses must be conducted to determine the source of the E-coli.

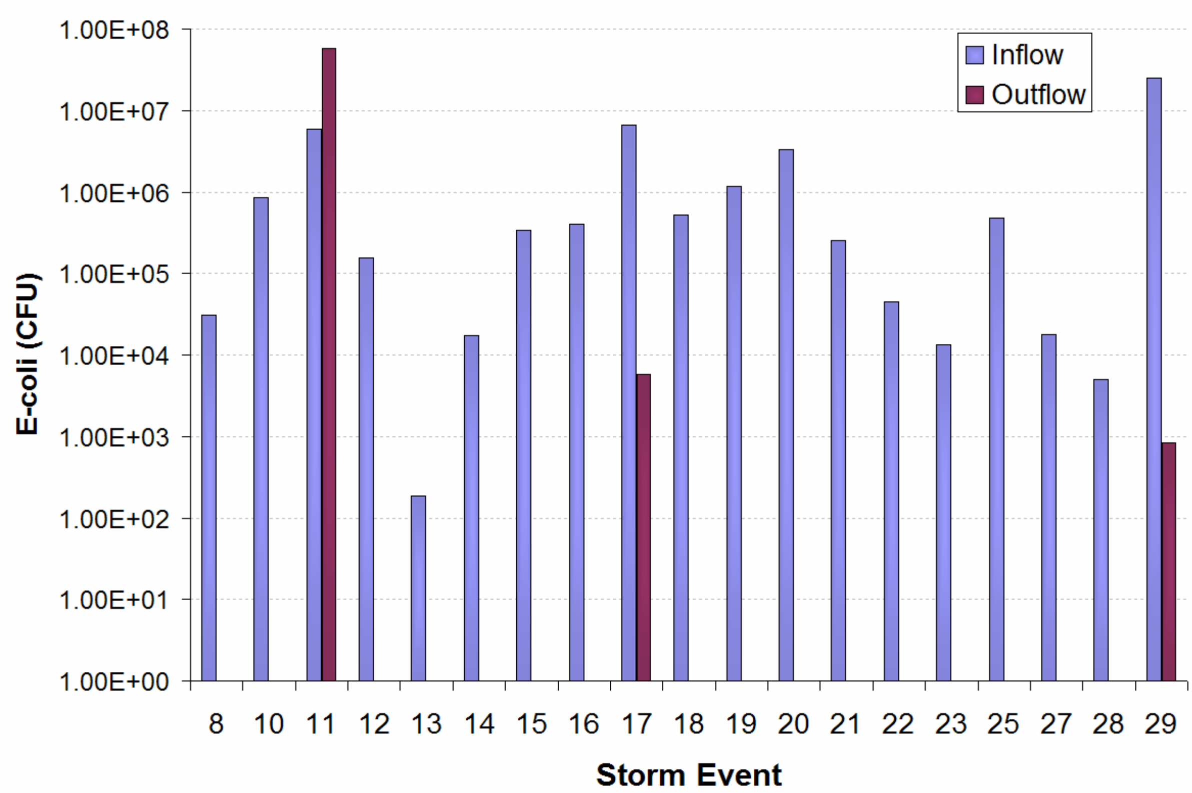


Figure 5.30. Inflow and outflow E-coli colonies for the bioretention cell. Note that the y-axis is on a logarithmic scale.

The VADCR geometric mean and single sample standards (126 CFU/100 mL and 235 CFU/100 mL), respectively, are shown in Figure 5.31 with the inflow and outflow concentrations. Only one inflow and one outflow concentration exceeded the SS standard; however, five (26.3%) of the inflow concentrations exceeded the GM standard. The majority of the E-coli inflow concentrations fell below the VADCR single sample (SS) standard discussed in section 5.2.6. Two of the three outflow concentrations collected during the study period were below both the SS standard and the GM standard.

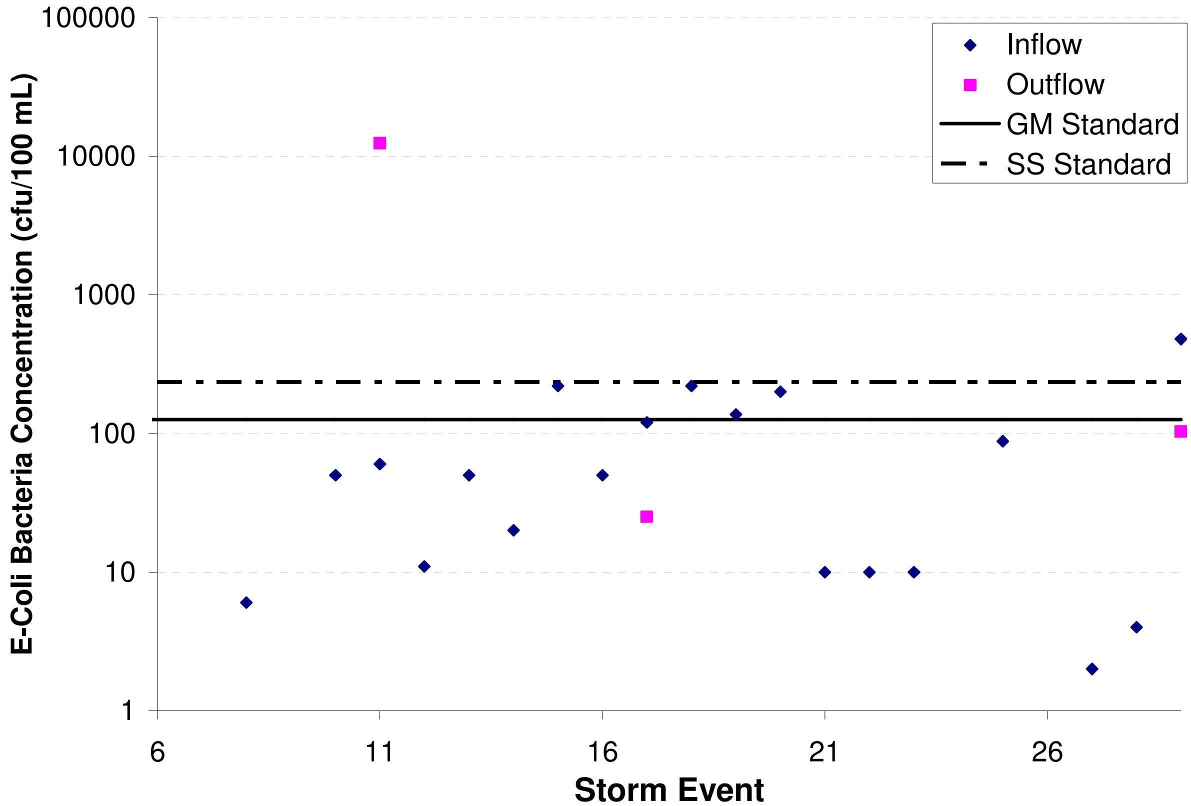


Figure 5.31. Comparison of inflow and outflow E-coli concentrations for the bioretention cell to the Virginia water quality standards. Note the y-axis is on a logarithmic scale. GM and SS refer to the geometric mean and single sample maximum standards, respectively.

When the individual removal rates for each of the monitored storm events were analyzed, the median removal rate was 100%. This removal rate became 99.9% when only the three storms that produced outflow were considered. An analysis of E-coli loads proved the number of inflow colonies was significantly greater than the number of outflow colonies ($p = 0.0006$). It is important to note that this analysis paired each storm event and performed a comparison of the inflow and outflow loads.

A total of approximately 4.52E7 colonies entered the BMP during the study period, while approximately 5.8E7 colonies exited via outflow. Consequently, the BRC had a cumulative total E-coli bacteria increase of 28% (Figure 5.32).

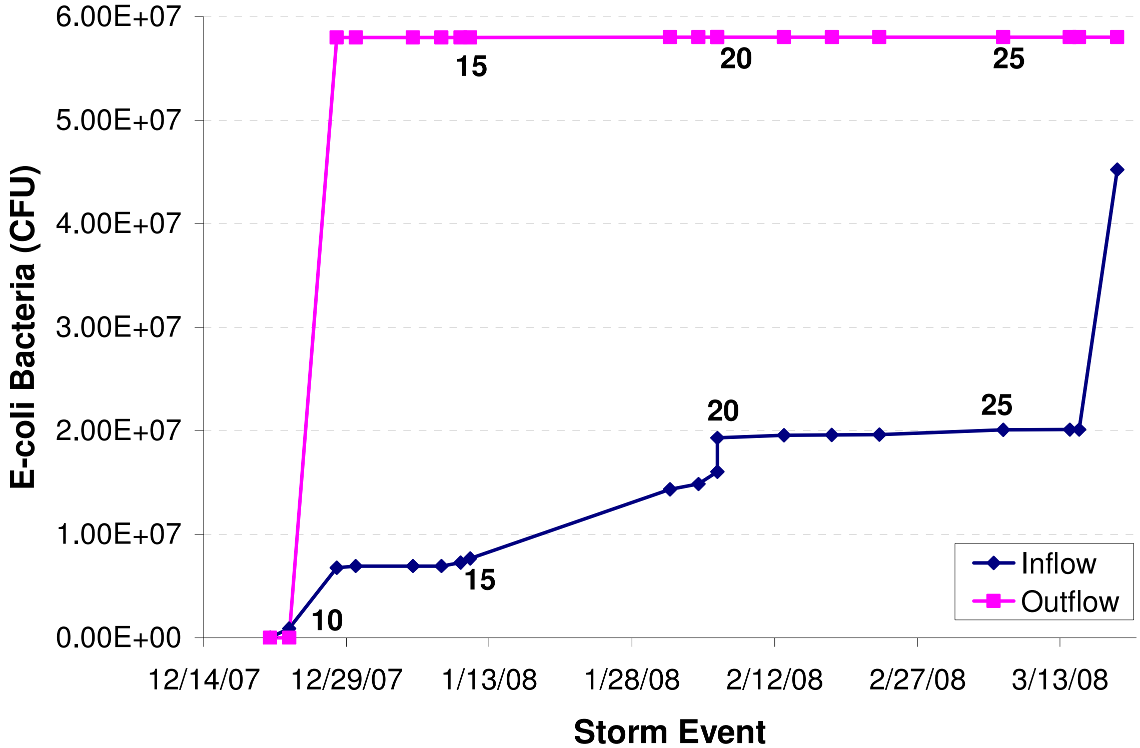


Figure 5.32. Cumulative inflow and outflow E-coli counts for the bioretention cell. Point labels indicate storm events.

The percent removal of E-coli was negatively correlated to the inflow volume (ρ = -0.681, p = 0.0013), as well as to the inflow load of EC bacteria (ρ = -0.67, p=0.0018). The correlation between the percent removal and the inflow load of EC may not be meaningful; by definition, high inflow volumes result in higher loads of bacteria and a strong correlation between the removal rate and the inflow volume will ensure a correlation between the removal rate and the inflow load. Unlike the FC bacteria, the inflow load of E-coli was positively correlated to the SSC load (ρ = 0.611, p = 0.0064), suggesting that E-coli binds to sediment particles and is transported with sediment. To the best of the author's knowledge, no other peer-reviewed studies have been conducted on the E-coli removal capabilities of bioretention BMPs.

5.3.6. ITSS: Suspended Sediment

Figure 5.33 summarizes the concentration data for the storm events that produced inflow and/or outflow for the infiltration trench. Inflow concentration values ranged from a minimum of 3.6 mg/L to a maximum of 59.5 mg/L (storms 7 and 29, respectively). Inflow concentrations were generally low due to the presence of the sediment forebay. The minimum outflow concentration was 1.4 mg/L (storm 21), while the maximum was 6.1 mg/L (storm 2). Median inflow and outflow concentrations were 18.2 mg/L and 2.4 mg/L, respectively, as shown in Figure 5.34. Statistical analysis confirmed that inflow concentrations were significantly higher than outflow concentrations ($p = 0.047$).

Figure 5.33 shows an increase in suspended sediment concentrations for storms 21, 27 and 29. Aggregate was applied to roads and parking lots during icy weather to aid in vehicle traction. This could be the source of increased SSC for storm 21. New mulch was applied to flower beds located on several parking lot islands that drain to the ITSS and BRC shortly prior to storm 27. Any mulch that would have spilled on the parking lot during application to either of these two places could be a source of increased sediment in inflow to the BMPs. Storm 29 was a typical convective thunderstorm, with very high intensity rainfall in a very short time period. Also, high flow velocities flowing through the parking lots would have picked up larger amounts of sediment than lower intensity storms, thus creating higher inflow SSC to the ITSS and BRC.

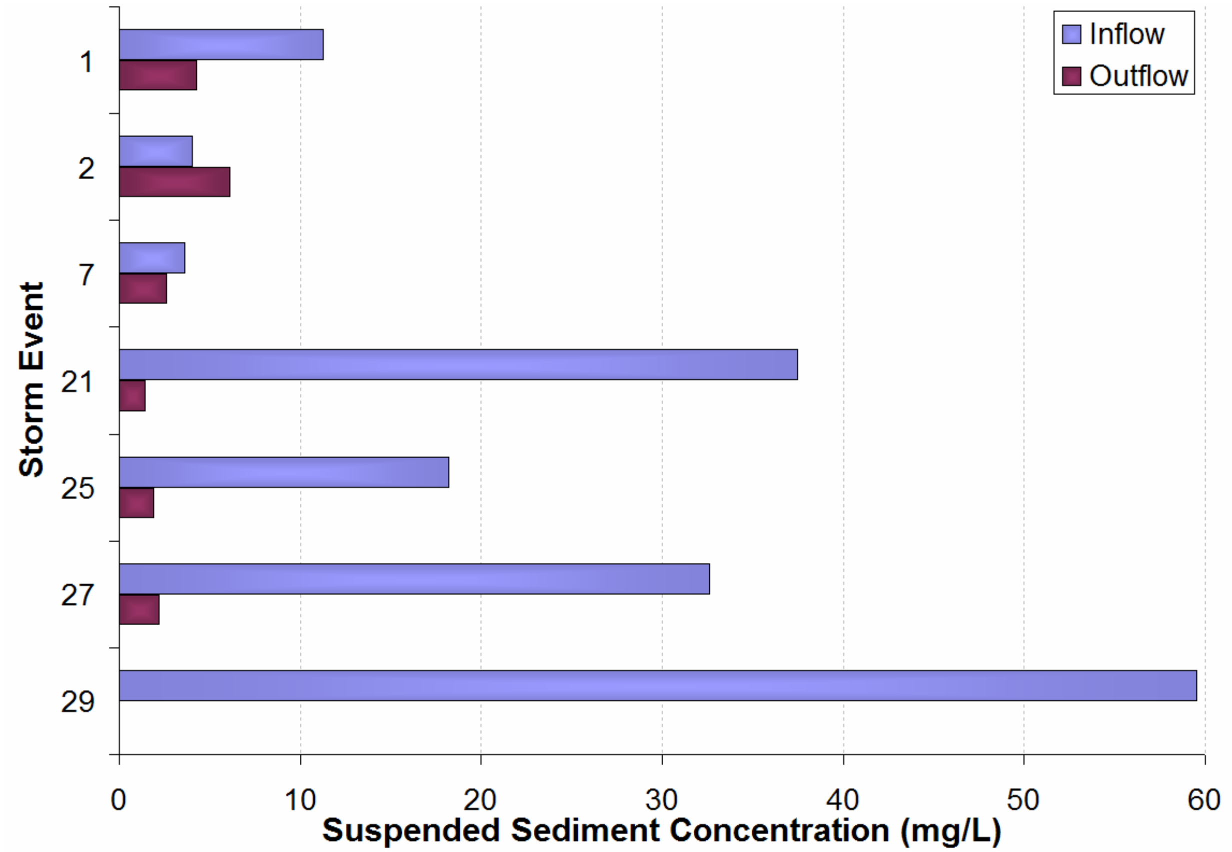


Figure 5.33. Inflow and outflow suspended sediment concentrations for the structural soil infiltration trench.

The ITSS inflow SSC concentration was negatively correlated with the average inflow rate (ρ = -0.893, p = 0.0123), indicating higher average inflow rates resulted in lower inflow concentrations of suspended sediment. This inverse relationship between SSC and inflow rate suggests the supply of sediment in the parking lot was limited, as would be expected in a largely paved watershed. Outflow suspended sediment concentrations were strongly negatively correlated with the inflow suspended sediment load (ρ = -0.857, p = 0.024): Higher concentrations of SS entering the BMP resulted in less sediment leaving the system via outflow. This result could be due to the fact that larger flows could have suspended larger particles, which led to higher mass per volume (concentration). These larger particles would be more likely to settle out or be filtered out by the BMP treatment media. There was no correlation between the inflow SSC and the amount of time since the last precipitation event.

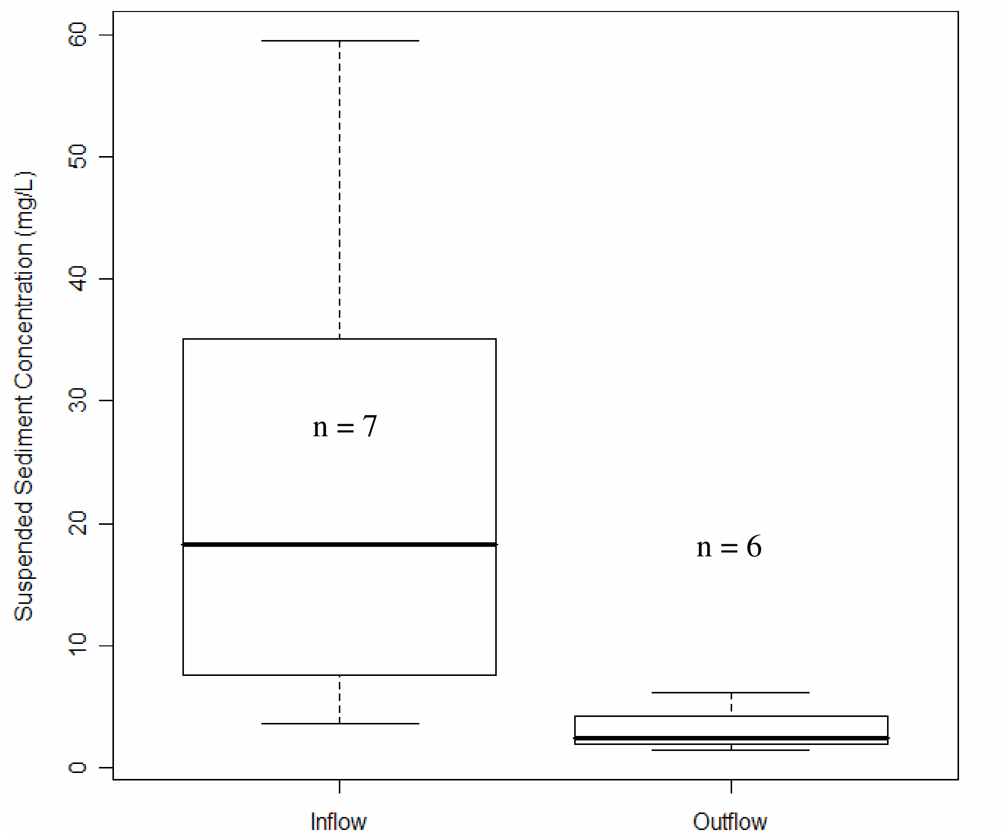


Figure 5.34. Inflow and outflow suspended sediment concentrations for the structural soil infiltration trench. Storm 29 did not produce outflow and was not included in the outflow concentration plot.

The total mass of sediment that entered and exited the ITSS for each storm event is shown in Figure 5.35. Maximum suspended sediment loads were 585 g (storm 1) and 467 g (storm 2) for inflow and outflow, respectively; minimum inflow and outflow loads were 47.8 g (storm 25) and 0 g (storm 29), respectively. Storm 29 did not produce outflow from the BMP; therefore, the total mass of sediment leaving the BMP was zero. Median loads were 116 g and 1.17 g for inflow and outflow, respectively. One outlier corresponding to storm 2 was identified in the outflow dataset.

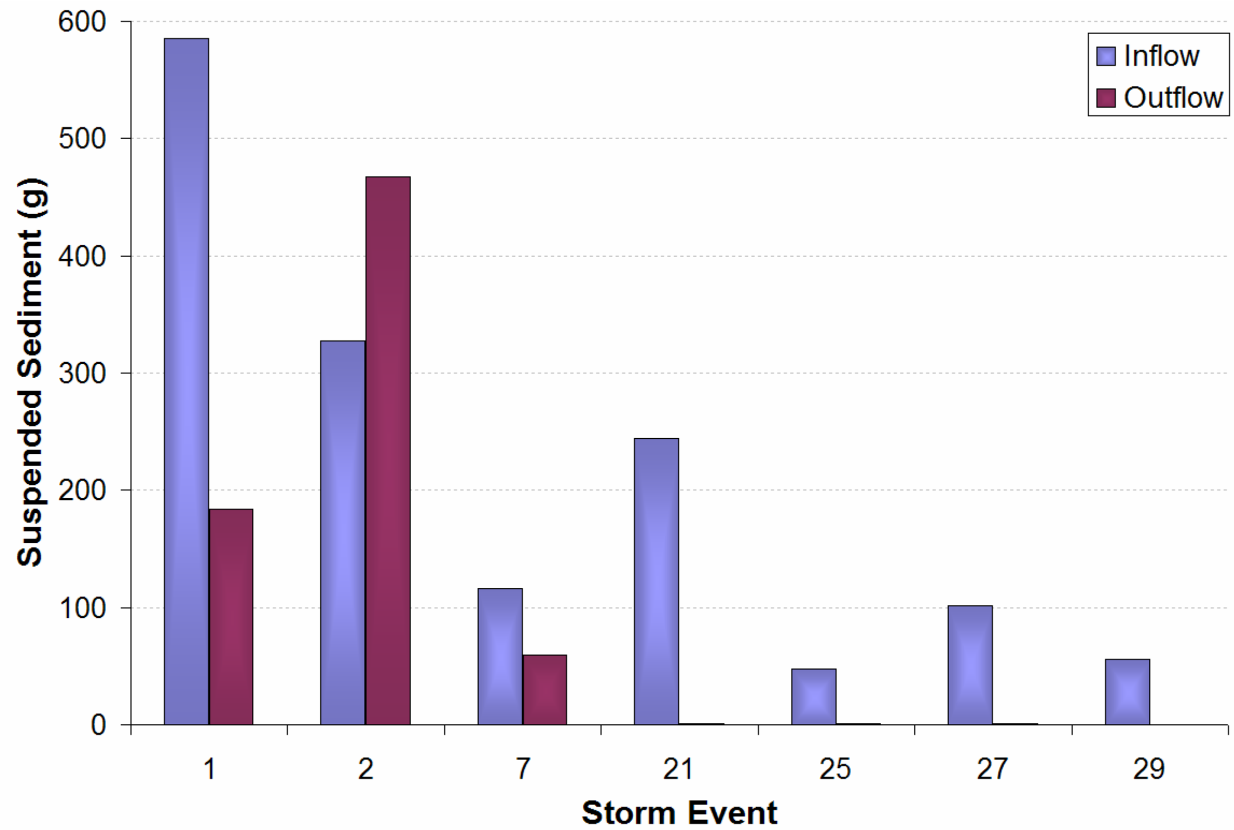


Figure 5.35. Inflow and outflow suspended sediment loads for the structural soil infiltration trench.

The unusual results for storm 2 are likely an artifact of the data analysis. On October 24, 2007, a large storm with frequent downpours created several runoff events over a three-day period. As stated in the methods, inflow events separated by six hours were considered separate runoff events. Inflow events with less than six hours between them were composited and treated as one storm. The result was two separate runoff events (storm 1 and storm 2), resulting in two individual suspended sediment removal rates of 69% and -43%, respectively. Data collected during the 'storm 1' portion of the overall storm event resulted in high inflow concentrations and low outflow concentration, thus giving a high removal rate. During the 'storm 2' portion of the event, inflow concentrations decreased towards the end of the three-day period, and while outflow concentrations varied considerably. These data resulted in a negative removal efficiency, indicating the production of suspended sediment.

The removal efficiencies reported for storm 1 and storm 2 are most likely due to a flushing effect occurring within the BMP (deposition of large amounts of sediments during storm 1 and flushing out of these sediments during storm 2). In addition, this was the first substantial rainfall treated by the ITSS since the completion of construction; therefore, the media was most likely unsettled and prone to washing. If the storm 1 and storm 2 portions of the overall event were analyzed together, the result would be an overall removal efficiency of 35% for suspended sediment, which is perhaps more indicative of the actual performance of the BMP. Figure 5.36 shows a cumulative summary of sediment load within the ITSS through the study period.

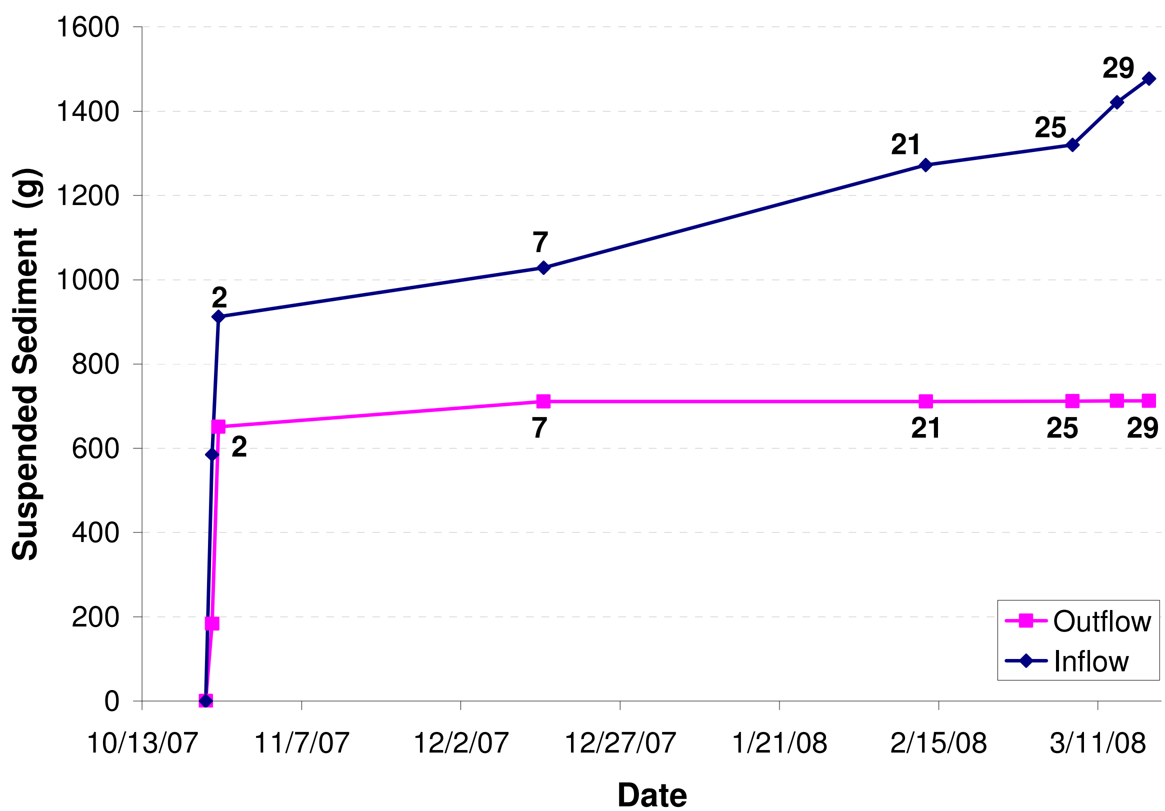


Figure 5.36. Cumulative inflow and outflow sediment for the structural soil infiltration trench. Point labels specify storm events.

Inflows delivered 1,477 g of suspended sediment to the ITSS during the study period, while 713 g left via outflow. Thus, the cumulative mass removal rate for sediment was 52%. The median mass removal rates for individual storm SSC was

98.8%. However, unlike the BRC, this decrease in SSC was not significantly different when storms were analyzed as paired data ($p = 0.078$), most likely due to the small data set.

The percent mass removal of SS was positively correlated with the inflow suspended sediment concentration ($\rho = 0.964$, $p = 0.0028$). The removal of constituents within the ITSS was unaffected by the inflow concentration; previous research has shown greater removals when inflow concentrations are higher (Davis et al., 2006). Another interesting correlation was found between the outflow concentration of suspended sediment and the peak outflow rate ($\rho = 0.964$, $p = 0.0028$). Higher peak outflow rates likely kept a greater percentage of the sediment in the BMP entrained, resulting in higher outflow SSC. A reduction in peak outflow rates through one of the means discussed in section 6.3.2 could result in lower outflow concentrations of SS and, ultimately, lower outflow loads.

The ITSS removed a sizeable amount of sediment from the stormwater that passed through it. The difference in the reduction percentages between the ITSS and the BRC are most likely due to the difference in flow reduction; however, as stated before, this is not considered a negative aspect of the design. There were several correlations between the percent mass removal of suspended sediment and various flow variables. Negative correlations existed between the percent mass removal of SS and the peak ($\rho = -0.937$, $p = 0.002$) and average ($\rho = -0.955$, $p = 0.0008$) inflow rates for the ITSS. This is what one would expect based on results from the BRC. There was also a negative correlation between percent mass removal and inflow volume ($\rho = -0.919$, $p = 0.0034$), just as there was with the BRC.

5.3.7. ITSS: Total Nitrogen

Inflow TN concentrations for the ITSS ranged from less than the detection limit (0.5 mg/l) for storms 1 and 2 to 3.3 mg/L for storm 25 (Figure 5.38). Outflow TN concentrations were generally higher, with levels that varied from 1 mg/L (storm 1) to 8 mg/L (storm 25). Mean inflow and outflow concentrations were 1.2 mg/L and 3.9 mg/L, respectively. Figure 5.36 summarizes the TN concentrations per storm event for the study period. One inflow data point, corresponding to storm 25, was identified as an outlier. Outflow TN concentrations were significantly higher than inflow concentrations ($p = 0.01$).

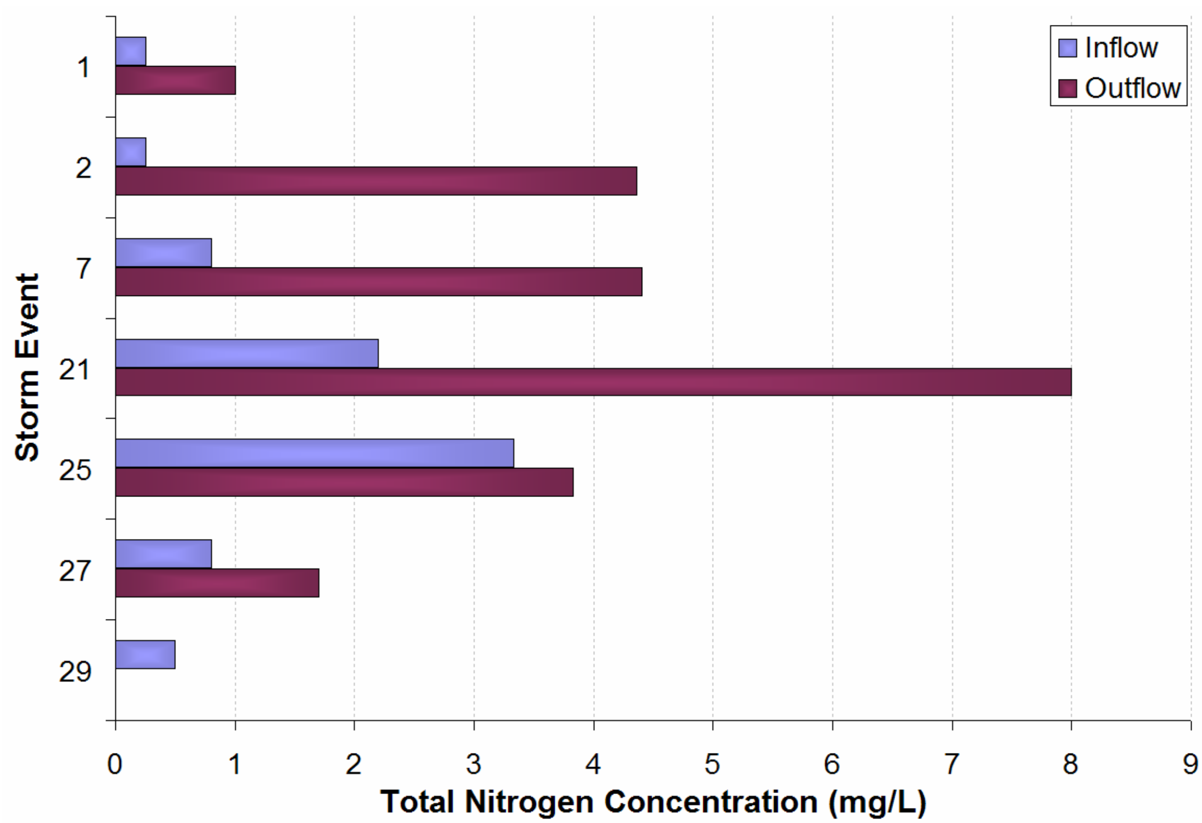


Figure 5.37. Inflow and outflow total nitrogen concentrations for the seven monitored storm events for the structural soil infiltration trench. Note storm 29 did not generate any outflow from the BMP.

Total nitrogen inflow and outflow loads for each monitored storm event for the ITSS are summarized in Figure 5.39. Minimum and maximum inflow values were 0.47 g for storm 29 and 25.7 g for storm 7. Outflow loads ranged from 0 g for storm 29 to 333 g for storm 2. Mean loads for inflow and outflow were 12.4 g and 68.8 g, respectively. Median loads were 13 g and 2.63 g for inflow and outflow, respectively. The single outflow outlier identified in the dataset corresponds to storm 2. The initially high outflow TN concentrations and loads were likely due to flushing of excess Gelscape® from the BMP. During sample analysis for SSC, ITSS outflow samples took much longer to filter than inflow samples and a clear residue was left on the filter after the sample passed through. The residue was likely the Gelscape® Hydrogel, which is 10% nitrogen by weight. The polymer is part of the treatment media and bonds the topsoil to the stones. The filter time and amount of residue on the filter paper decreased as the study period progressed. The potting media used to plant the shrubs and perennials and/or the surface mulch layer are also potential sources of nitrogen, as the high porosity of the treatment media would easily allow for the leaching of nitrogen into the underdrains.

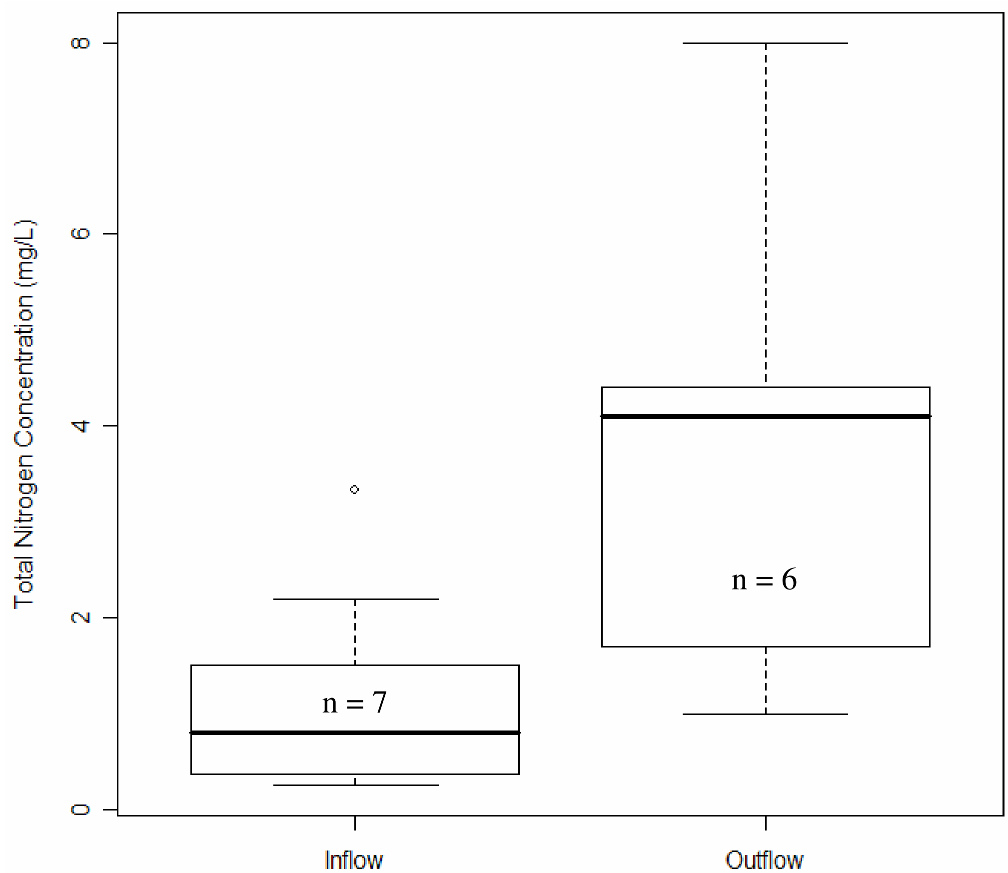


Figure 5.38. Inflow and outflow total nitrogen concentrations for the structural soil infiltration trench. Storm 29 did not produce outflow and was not included in the outflow concentration plot.

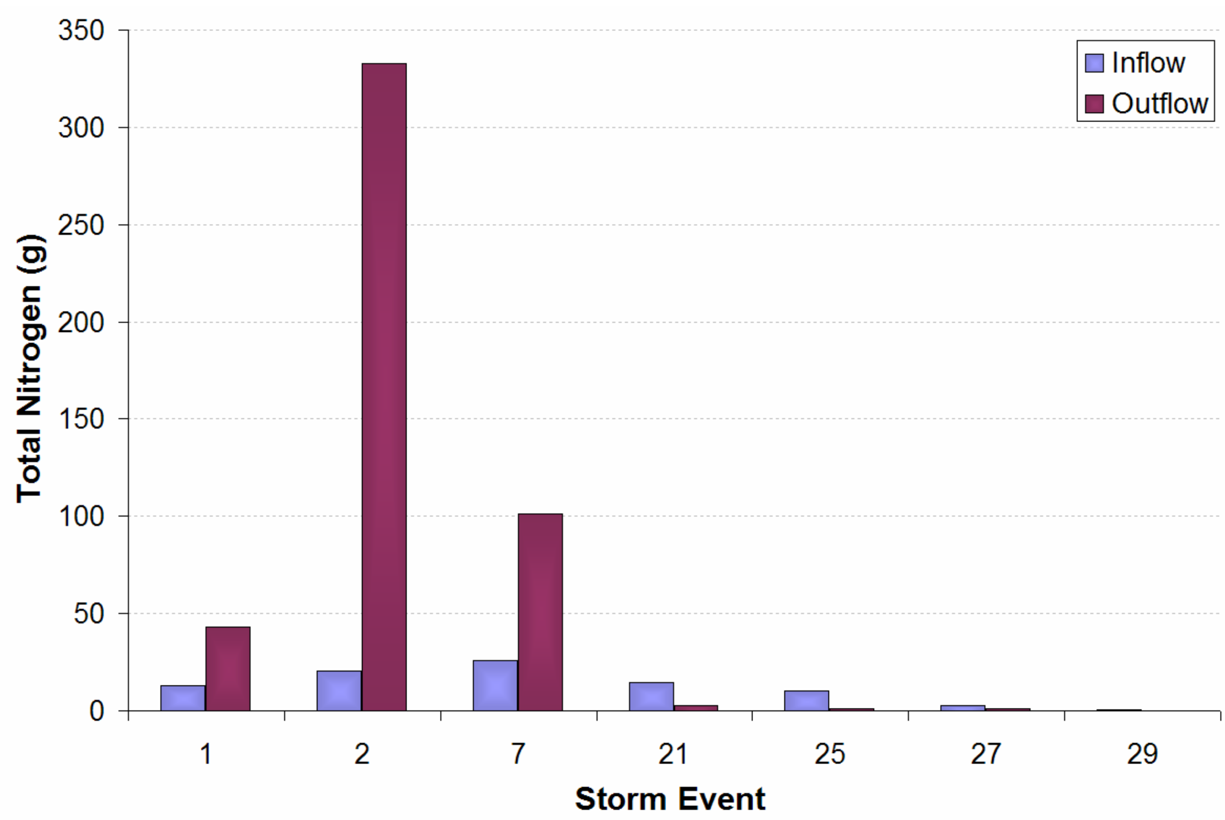


Figure 5.39. Inflow and outflow total nitrogen mass loads for the seven monitored storm events for the structural soil infiltration trench.

A TN mass balance was conducted for the ITSS. During the study period, nitrogen was assumed to only enter the BMP via inflow and to only leave the BMP via outflow. Table 5.5 summarizes the mass of nitrogen contributed by each media component; the contribution of nitrogen by living plant material was assumed negligible. Figure 5.40 shows the cumulative TN plot for the BMP.

Table 5.5. Total nitrogen concentrations for each media component in the structural soil infiltration trench and total nitrogen contributed by each component.

	Initial Mulch	**Top Soil**	**Potting Soil**	**Gelscape® Hydrogel**
Concentration (mg/kg)	4720	594	2270	100
Total Mass (kg)	29.97	26.62	0.602	6.24

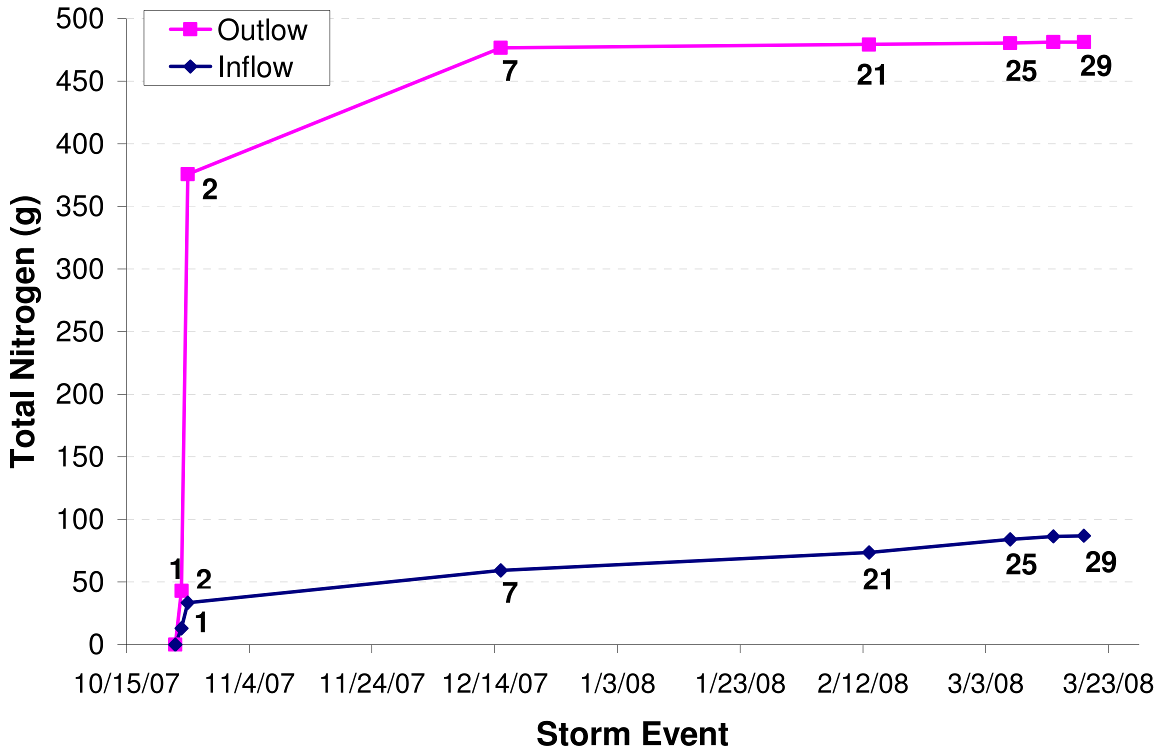


Figure 5.40. Cumulative total inflow and outflow nitrogen for the structural soil infiltration trench during study period.

The evident increase in outflow nitrogen concentrations led to the analysis of the full set of nitrogen species (ammonia, nitrite, nitrate) in the influent and effluent for several storm events to determine the nitrogen. Organic nitrogen was calculated as the difference between TN and the sum of the tested nitrogen species. The results of these analyses are summarized in Appendix E.

Figure 5.41 displays the mean percent composition of the inflow and outflow by each nitrogen species. Figure 5.42 shows the nitrogen mass balance for the ITSS. The amount of nitrogen within the system attributable to plant material and atmospheric deposition was assumed negligible. Given the observations in the laboratory during sample filtering and the sharp decrease in nitrogen export after the first three storm events, it was assumed that the Gelscape (a potassium propenoate-propenamide copolymer) was the source of the initial high nitrogen outflow loads.

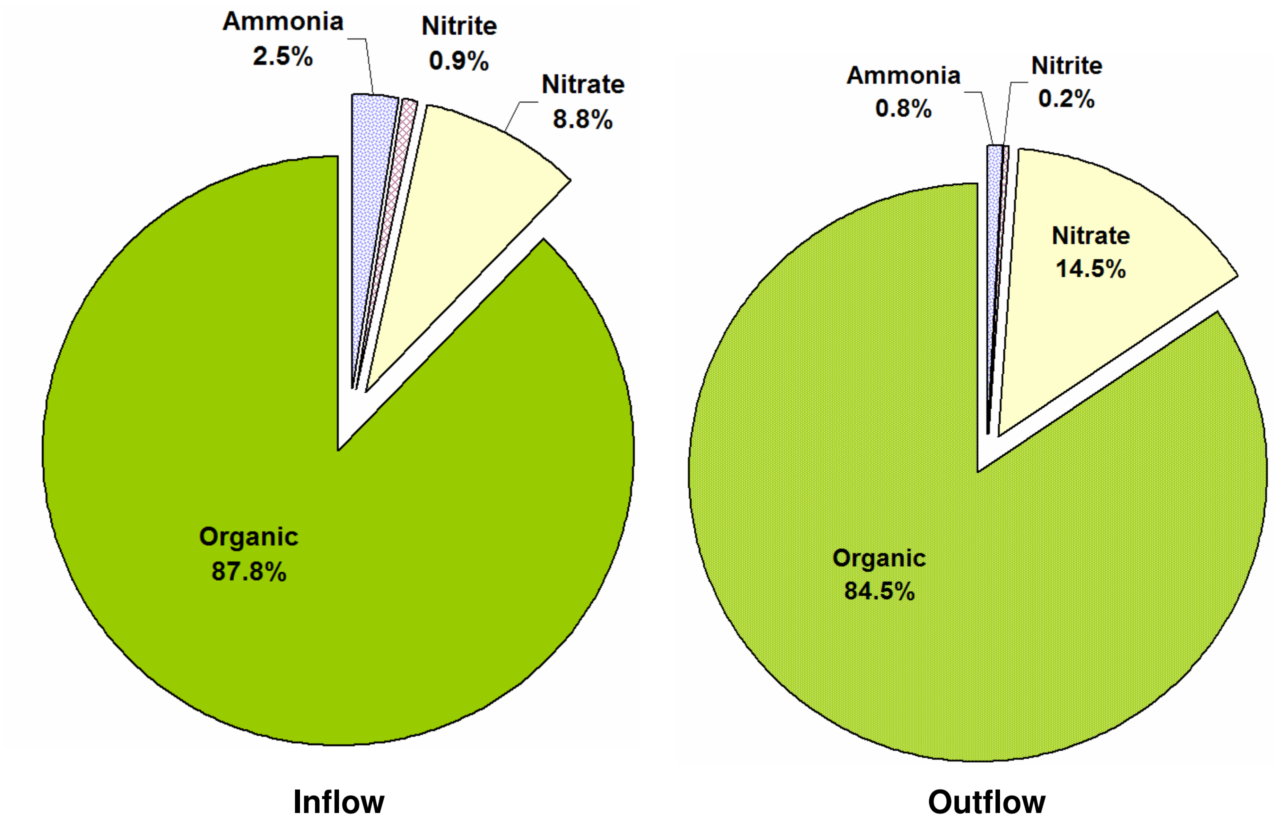


Figure 5.41. Comparison of total nitrogen composition between structural soil infiltration trench inflow and outflow.

Both the inflow and outflow for the ITSS were dominated by organic N. As discussed in section 5.3.2, this is different from the BRC, most likely due to the small grassy area with trees that drains to the BRC and is fertilized annually. However, the similarities between the composition of nitrogen in the inflow and outflow of the infiltration trench indicate few nitrogen transformations were taking place within the BMP, likely due to the short detention time within the BMP and low organic matter content of the ITSS media. Increasing the detention time within the ITSS will likely improve stormwater treatment. As discussed in section 5.2.3, the actual hydraulic conductivity for the ITSS media is higher than expected; thus, it is recommended that a flow restrictor or valve be place on the underdrains. It is also expected that treatment will improve as the plants mature and roots extend into the structural soil, providing additional surface area and carbon for bacteria growth.

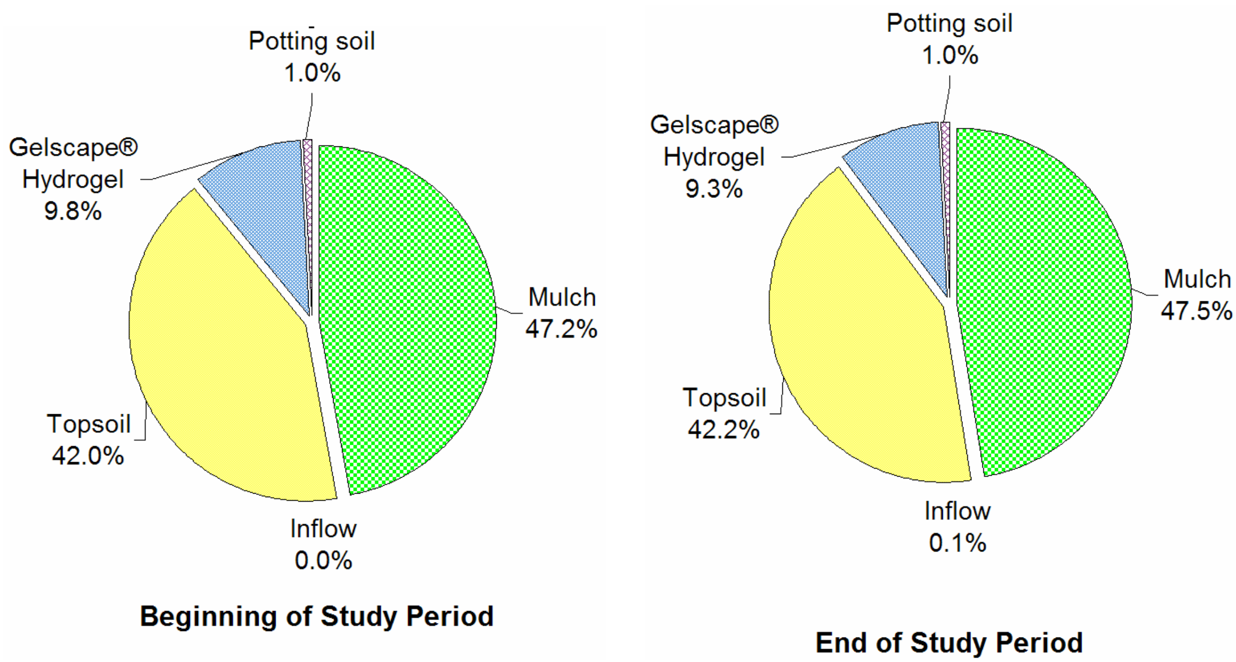


Figure 5.42. Nitrogen mass balance for the structural soil infiltration trench at the beginning and end of the study period, assuming excess nitrogen was due to the Gelscape® Hydrogel. Atmospheric deposition and plant material are considered negligible.

As shown in Figure 5.42, mulch was the largest contributor of TN in the ITSS system, representing approximately 47% of the TN within the system. Although a new mulch layer was not added during the study period, this is common practice to improve the aesthetic quality of the BMP, increase plant growth, and reduce weeds. Adding additional mulch without removing the old mulch will increase the amount of nitrogen within the system. The impact of this regular nitrogen addition to the BMP will depend on the carbon to nitrogen ratio of the mulch and the amount of labile N in the mulch.

A total of 86.9 g of nitrogen entered the ITSS via inflow during the study period; 481 g exited the system via outflow. Consequently, there was a 454% increase overall in nitrogen loading to the stormwater drainage system. On an individual storm basis, there was a median mass reduction of 64% ($p = 0.29$). While this represents a substantial decrease in TN loading from the BMP on a per-storm basis, the decrease was not statistically significant, likely due to the small data set and the large amount of export during the first three storm events.

Future monitoring will be crucial for determining the source of this exported nitrogen; a decrease in TN loss would suggest excess Hydrogel or excess potting soil as the culprit, while a steady rate of release would indicate a more fundamental issue regarding processes within the BMP.

The percent mass removal of nitrogen within the ITSS was negatively correlated with the following variables: peak inflow rate ($\rho = -0.937$, $p = 0.002$), peak outflow rate ($\rho = -0.857$, $p = 0.024$), average inflow rate ($\rho = -0.955$, $p = 0.0008$), outflow volume ($\rho = -0.964$, $p = 0.0028$), and total inflow load ($\rho = -0.847$, $p=0.0162$). These correlations support the observation that stormwater passes quickly through the ITSS with little treatment.

5.3.8. ITSS: Total Phosphorus

Total phosphorus concentrations entering and leaving the ITSS for each storm event are displayed in Figure 5.43. These values ranged from 0.046 mg/L (storm 7) to 2.84 mg/L (storm 25) for inflow, and 0.02 mg/L (storm 7) to 1.46 mg/L (storm 25) for outflow (Figure 5.43). Mean concentrations were 0.6 mg/L and 0.36 mg/L for inflow and outflow, respectively. The inflow median concentration was 0.16 mg/L, while the outflow median concentration was 0.11 mg/L. One outlier was identified for both the inflow and outflow datasets, corresponding to storm 25. Inflow concentrations of total phosphorus were significantly higher than outflow concentrations for the ITSS ($p = .02$). The TP concentration for storm 25 was much higher than other storms, but the reason for this abnormality is unknown. The cause for the high load values for storm 2 (shown in Figure 5.44) could be similar to those factors discussed in section 6.3.3: new, unsettled treatment media and/or a flushing effect of back-to-back storm events.

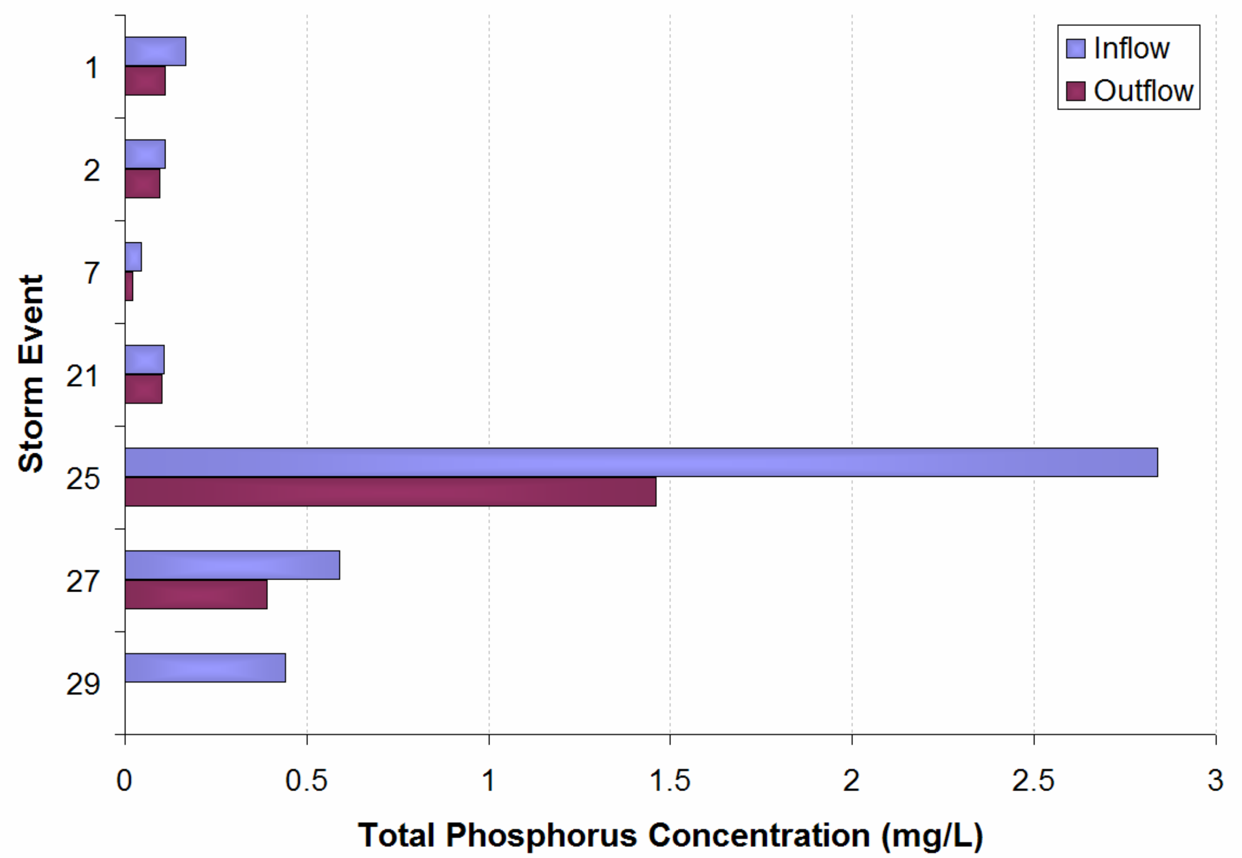


Figure 5.43. Total phosphorus concentrations for the structural soil infiltration trench.

A summary of the total mass inflow and outflow loads for each of the seven monitored storm events is shown in Figure 5.45. Inflow values ranged from 0.135 g for storm 29 and 8.98 g for storm 2; outflow loads ranged from a minimum of 0 g (storm 29) to 7.25 g (storm 2). Mean loads were 3.28 g and 1.79 g for inflow and outflow, respectively. The median inflow load value was 1.48 g, while the median outflow value was 0.14 g. One outlier was identified for both the inflow and outflow datasets, and both of these outliers corresponded with storm 2.

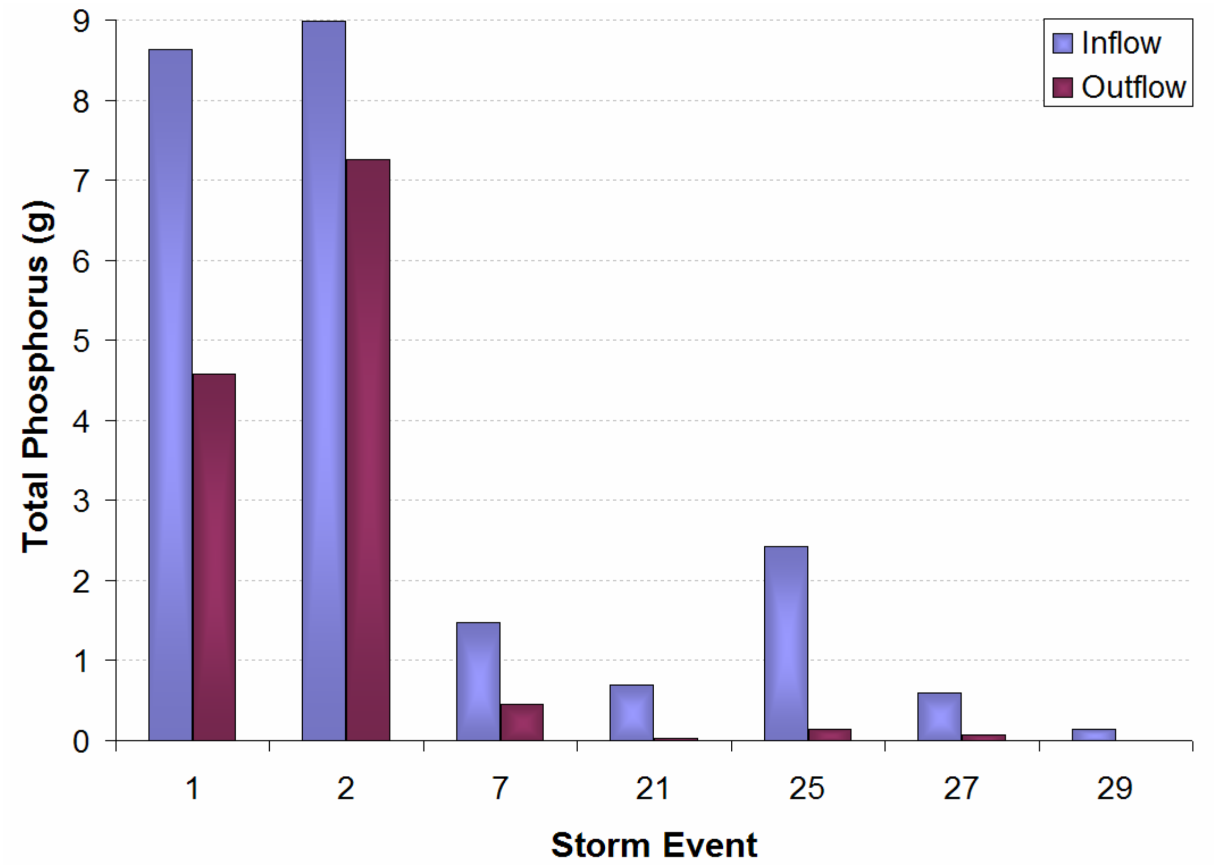


Figure 5.44. Inflow and outflow total phosphorus load for the structural soil infiltration trench.

A cumulative mass balance was performed on the ITSS. Table 5.6 summarizes the TP content in each of the media components to the BMP, in terms of both concentration and mass. The amount of phosphorus contributed to the BMP by living plant material and atmospheric deposition was considered negligible. Figure 5.45 is a cumulative plot that displays the change in TP within the BMP during the course of the study period. Phosphorus was assumed to only enter the ITSS via inflow and only leave via outflow. The relative mass contributions of phosphorus by each component of the ITSS at the beginning and end of the study period are displayed in Figure 5.46.

Table 5.6. Total phosphorus concentrations and mass for each media component in the structural soil infiltration trench at the start of the study.

	Mulch (Appl. 1)	Top Soil	Potting Soil	Gelscape® Hydrogel
Concentration (mg/kg)	200	200	400	0
Total Mass (kg)	1.27	8.96	0.106	0

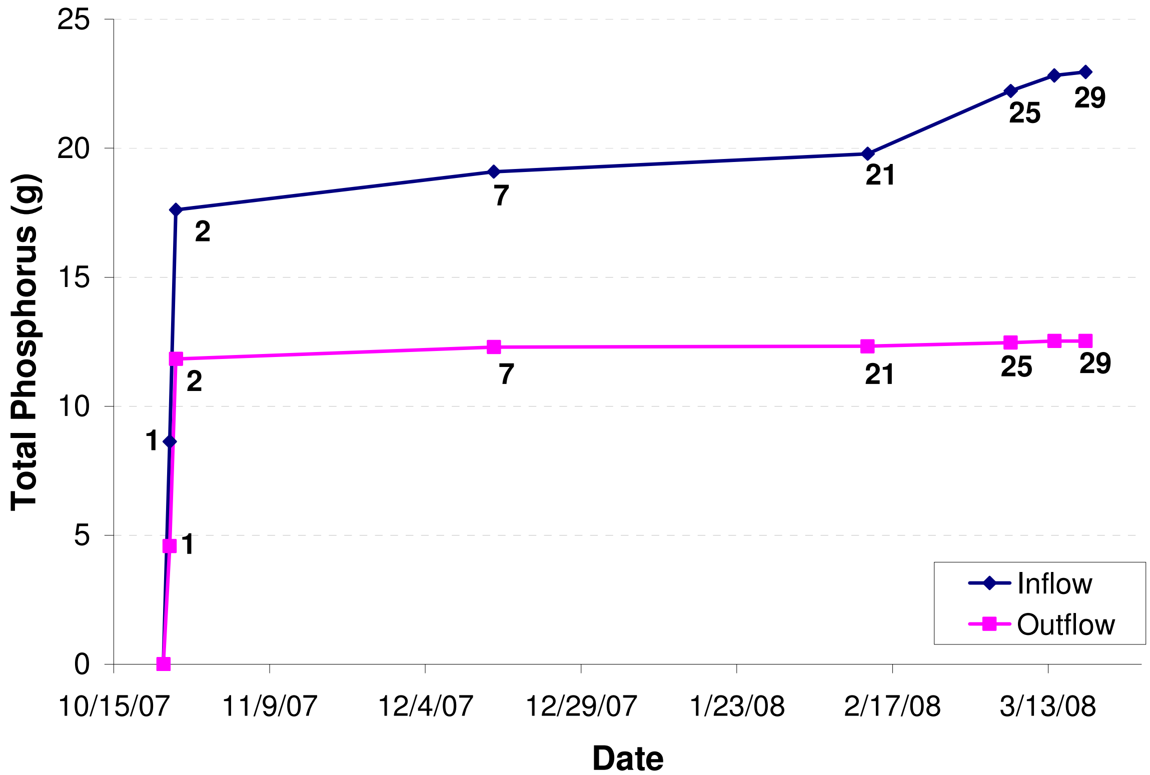


Figure 5.45. Cumulative total phosphorus inflow and outflow for the structural soil infiltration trench.

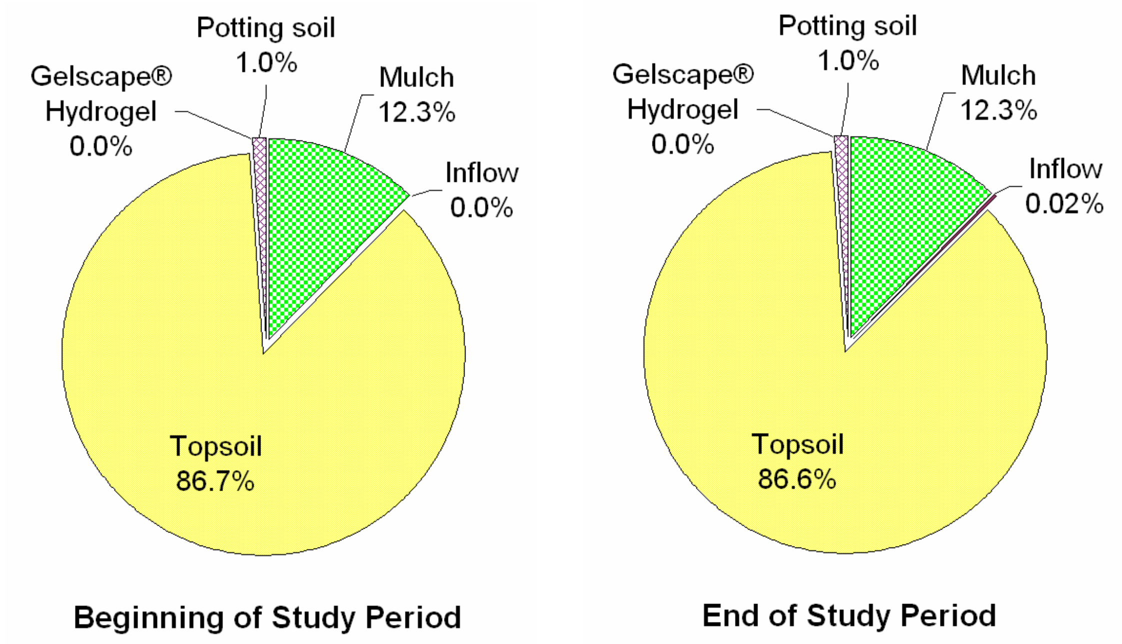


Figure 5.46. Total phosphorus mass balance for the infiltration trench (IT) at the beginning and end of the study period.

Figure 5.46 shows the relative contribution of TP by each media component within the infiltration trench. Topsoil was the major source of TP within the system, while mulch was the second largest contributor. While there was no second application of mulch as there was for the BRC, there was not a substantial amount of change in the relative contribution by any component within the ITSS. However, if a new mulch layer was applied to the BMP without removing the old layer, mulch would then account for approximately 22% of the TP mass within the system.

A Mehlich-III P analysis was conducted on each component of the treatment media, as well as the potting media surrounding the plants. A ranking of very low, low, medium, high, or very high was assigned to the media based on the amount of available phosphorus within the sample, as an indication of the quantity of readily available phosphorus within that component. The results of these analyses are summarized in Table 5.7. A mass-weighted average of the Mehlich-III results was computed and an overall ranking of ‘low’ (L) was assigned to the ITSS media.

Table 5.7. Mehlich-III ranking for each media component in the bioretention cell as well as the overall ranking for the treatment media.

Mulch	Gelscape® Hydrogel	Top Soil	Potting Soil		Overall Ranking
Medium	Very Low	Low	High		Low

As with the BRC, the treatment media for the ITSS had very low amounts of available phosphorus. Thus, based on the research conducted by Hunt et al (2006b), it is unlikely that the treatment media contributed to the outflow TP from the infiltration trench.

During the study period, 23 g of TP entered the BMP via inflow and 12.5 g exited via outflow. The cumulative TP mass reduction between inflow and outflow loads was 45%; statistical analysis confirmed that inflow mass loads were significantly greater than outflow mass loads ($p = 0.0078$). The median mass removal rate for the individual storm events was 89%.

The TP concentrations and mass loads were reduced for all storms events, substantially reducing the amount of TP introduced to the stormwater drainage system. As with TN, the TP percent mass removal was negatively correlated with the inflow volume ($\rho = -0.955$, $p = 0.0008$), peak inflow rate ($\rho = -0.901$, $p = 0.0056$) and average inflow rate ($\rho = -0.883$, $p = 0.0085$). Additionally, the percent mass removal was also negatively correlated to the total mass of phosphorus entering the BMP ($\rho = -0.955$, $p = 0.0008$). These correlations further support the finding that pollutant removal with the ITSS is highly dependent on the characteristics of the individual storm events.

5.3.9. ITSS: Fecal Coliform Bacteria

ITSS Inflow and outflow fecal coliform bacteria concentrations varied greatly throughout the study period (Figure 5.47). Inflow values ranged from 7 cfu/100 mL to 38,700 cfu/100 mL for storms 27 and 1, respectively. Outflow concentrations ranged from a minimum of 40 cfu/100 mL for storm 27 to a maximum of 2.6E5 cfu/100 mL for storm 1. The mean inflow concentration was 6,018 cfu/100 mL while the mean outflow concentration was 50,736 cfu/100 mL. The median concentrations for ITSS inflow and outflow were 343 cfu/100 mL and 400 cfu/100 mL, respectively. The identified outliers (one for each of the inflow and outflow datasets) correspond to storm 1. Fecal coliform concentrations for ITSS inflow and outflow were not significantly different.

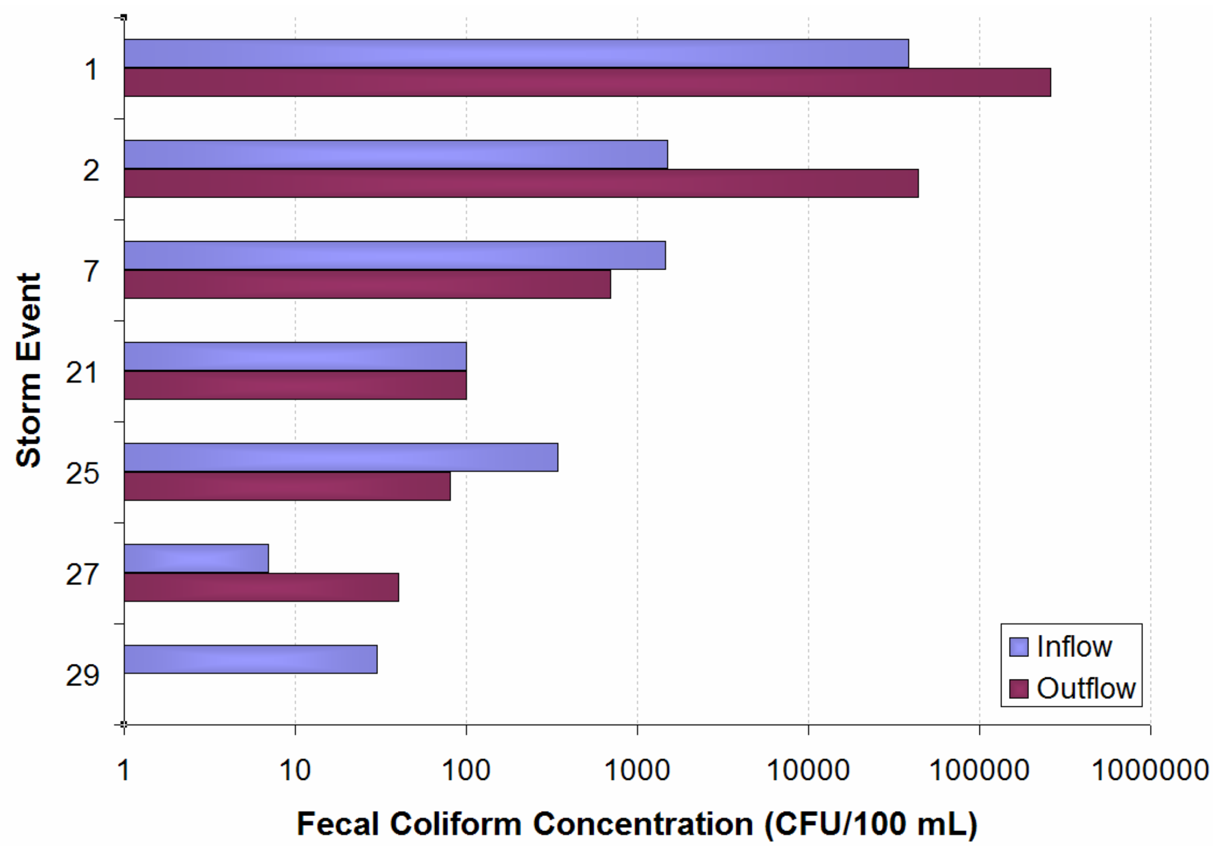


Figure 5.47. Fecal coliform concentrations for individual storm events within the study period for the structural soil infiltration trench. Note the y-axis is on a logarithmic scale.

Figure 5.48 displays the inflow and outflow concentrations of fecal coliform bacteria for the ITSS. The graph also displays the VADCR geometric mean (GM) and single sample (SS) water quality standards for streams in Virginia. As shown in the figure, 50% of the inflow concentrations and 50% of the outflow concentrations exceed the SS standard, while 67% of the inflow concentrations and 50% of the outflow concentrations exceed the GM standard.

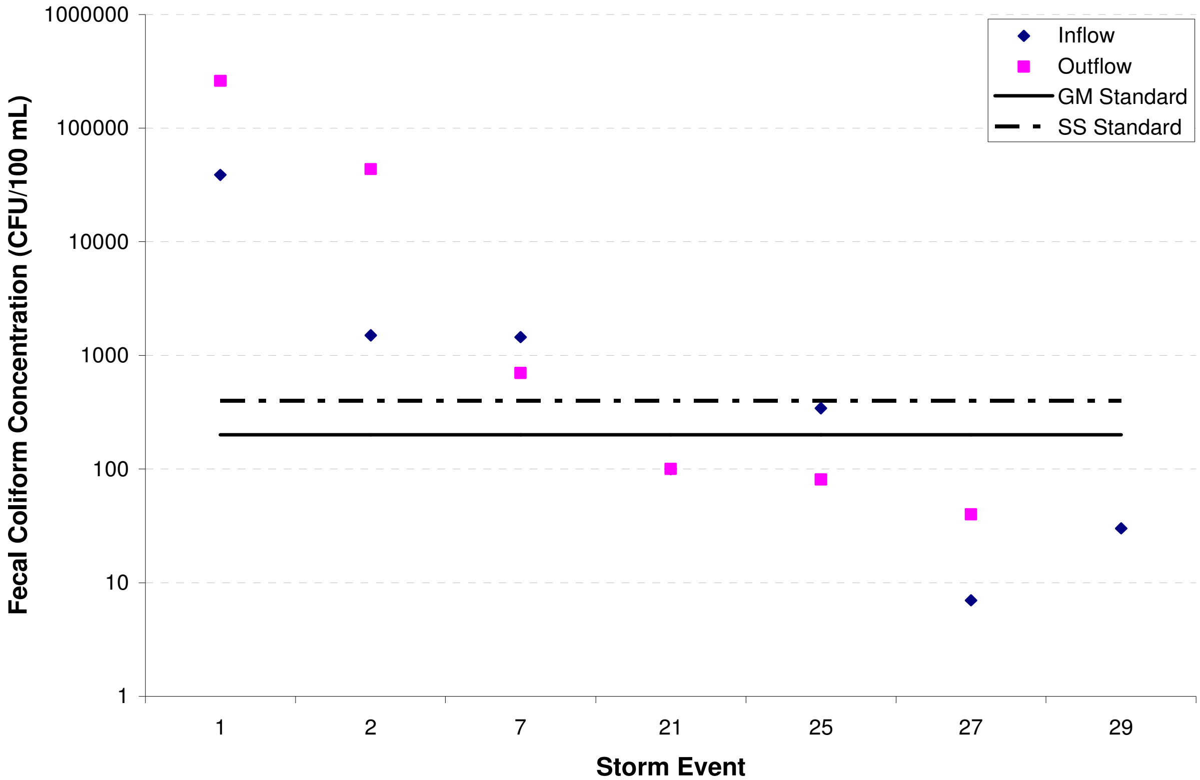


Figure 5.48. Inflow and outflow fecal coliform concentrations for the infiltration trench, as compared to the Virginia Department of Conservation and Recreation (VADCR) water quality standards. GM and SS refer to the geometric mean and single standard maximum standards, respectively, established by VADCR.

Total fecal coliform counts for the ITSS for each of the seven monitored storms are summarized in Figure 5.49. The maximum number of colonies for ITSS inflow and outflow during the study period both occurred during storm 1 (2.01E10 cfu and 1.08E11 cfu, respectively). The minimum inflow and outflow counts were 2.17E5 cfu for storm 27 and 0 cfu for storm 29, respectively. The median inflow count for the ITSS was 9.0E6 cfu, while the outflow median value was 3.28E5 cfu. One outlier was identified for each of the inflow and outflow datasets and both correspond to storm 1.

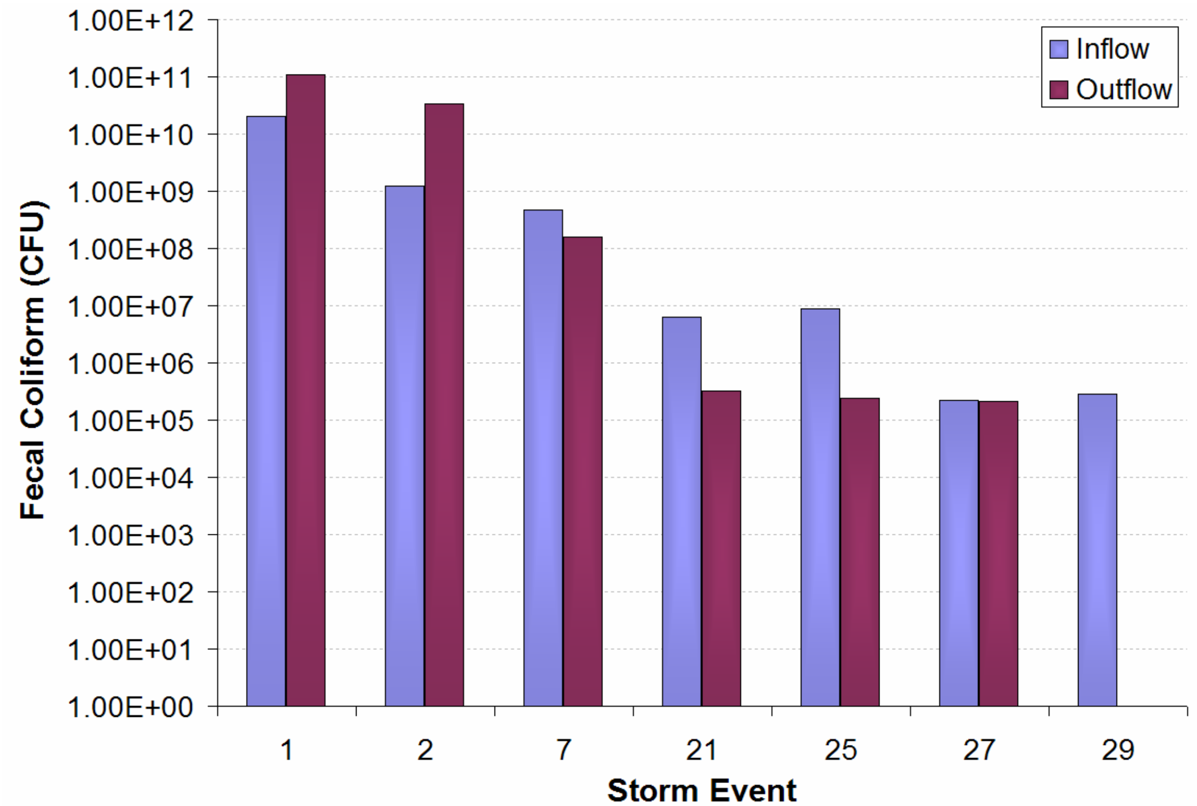


Figure 5.49. Inflow and outflow fecal coliform counts for of the structural soil infiltration trench. Note the y-axis is on a logarithmic scale.

Approximately 2.18E10 fecal coliform colonies entered the ITSS during the study period via inflow, and roughly 1.41E11 colonies exited via outflow (Figure 5.50). Thus, the ITSS had a cumulative percent increase in fecal coliform of 548%. However, the total number of inflow colonies was not statistically different from the total number of outflow colonies, most likely due to the small number of monitored storm events. Reduction percentages varied greatly between storm events; however, there was an overall median percent decrease in fecal coliforms for all monitored storm events of 66%.

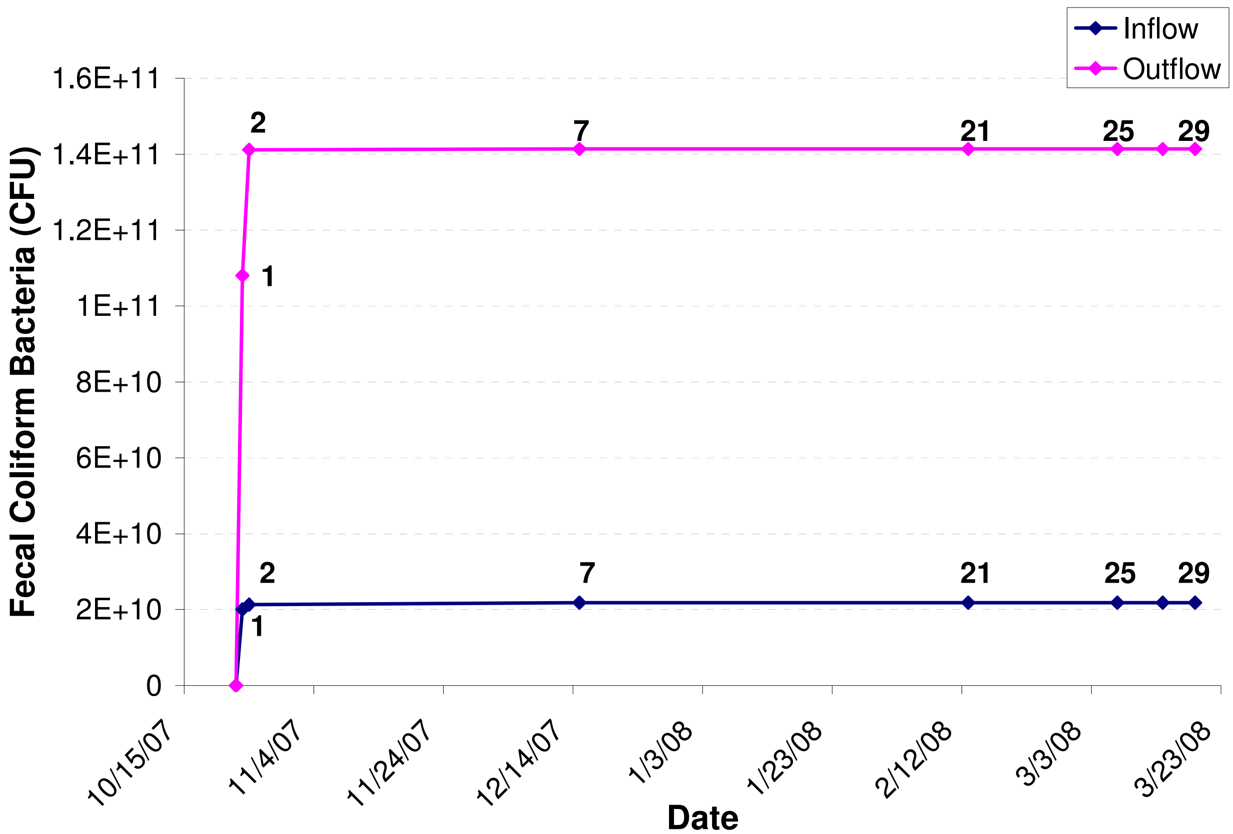


Figure 5.50. Cumulative inflow and outflow fecal coliform bacteria counts for the structural soil infiltration trench. Point labels denote storm events.

Storm 1 produced high concentrations and numbers of fecal coliform colonies. This could be due to the media being new and unconsolidated. FC bacteria could have been introduced to the media before it was mixed and put in the ITSS and fecal matter deposited in the drainage pipe while they were being stored could have been introduced to the system when the pipes were installed. Storm 1 most likely flushed the bacteria out of the system.

The changes in fecal coliform concentrations through the ITSS were highly variable and did not follow any visible trends. Inflow concentrations did, however, seem to decrease as the air temperature declined during winter months. Total inflow and outflow counts decreased slightly as the study period progressed. The reason outflow concentrations were higher than inflow concentrations is unknown; bacteria may be reproducing within the BMP treatment media or within another component of the system such as the outflow pipe, sampling equipment or underdrain pipe.

The ITSS was a major source of FC bacteria to the stormwater drainage system. As with suspended sediment, TN and TP, the percent removal was negatively correlated with the peak ($\rho = -0.823$, $p = 0.021$) and average inflow rates ($\rho = -0.775$, $p = 0.04$), as well as the inflow volume ($\rho = -0.883$, $p = 0.0085$). However, there were no correlations between the percent reduction in counts and the inflow concentration or inflow load. Interestingly, there was a positive correlation between the inflow FC bacteria load and the inflow suspended sediment load ($\rho = 0.821$, $p = 0.034$). The results for the BRC did not indicate a similar correlation for fecal coliform bacteria; however, a similar correlation existed between suspended sediment and E-coli for the BRC. These findings support the conclusions from previous studies that indicator bacteria are commonly associated with suspended sediment (Jamieson, 2004; Mahler, 2000).

As stated in Section 4.4, a 24-hr holding period was used for bacterial analysis. A 6-hr holding period is recommended by USEPA. The use of a longer holding time could have resulted in the death of bacterial colonies and slightly lower measured concentrations and loads than what was present at the time the sample was taken. This is true for fecal coliform and E-coli results.

5.3.10. ITSS: Escherichia coli (E-coli)

Inflow E-coli concentrations ranged from a minimum of 1.5 cfu/100 mL to a maximum of 2,750 cfu/100 mL for storms 2 and 1, respectively; outflow concentrations ranged from 12 cfu/100 mL (storm 27) to 6,500 cfu/100 mL (storm 1). These data are summarized in Figure 5.51. The mean inflow concentration of E-coli was 406 cfu/100 mL, while the mean outflow concentration was 1,475 cfu/100 mL. Median values for inflow and outflow data were 12 cfu/100 mL and 49.5 cfu/100 mL, respectively. The identified outliers both corresponded to storm 1. Outflow concentrations of E-coli bacteria were significantly higher than inflow concentrations ($p = 0.049$).

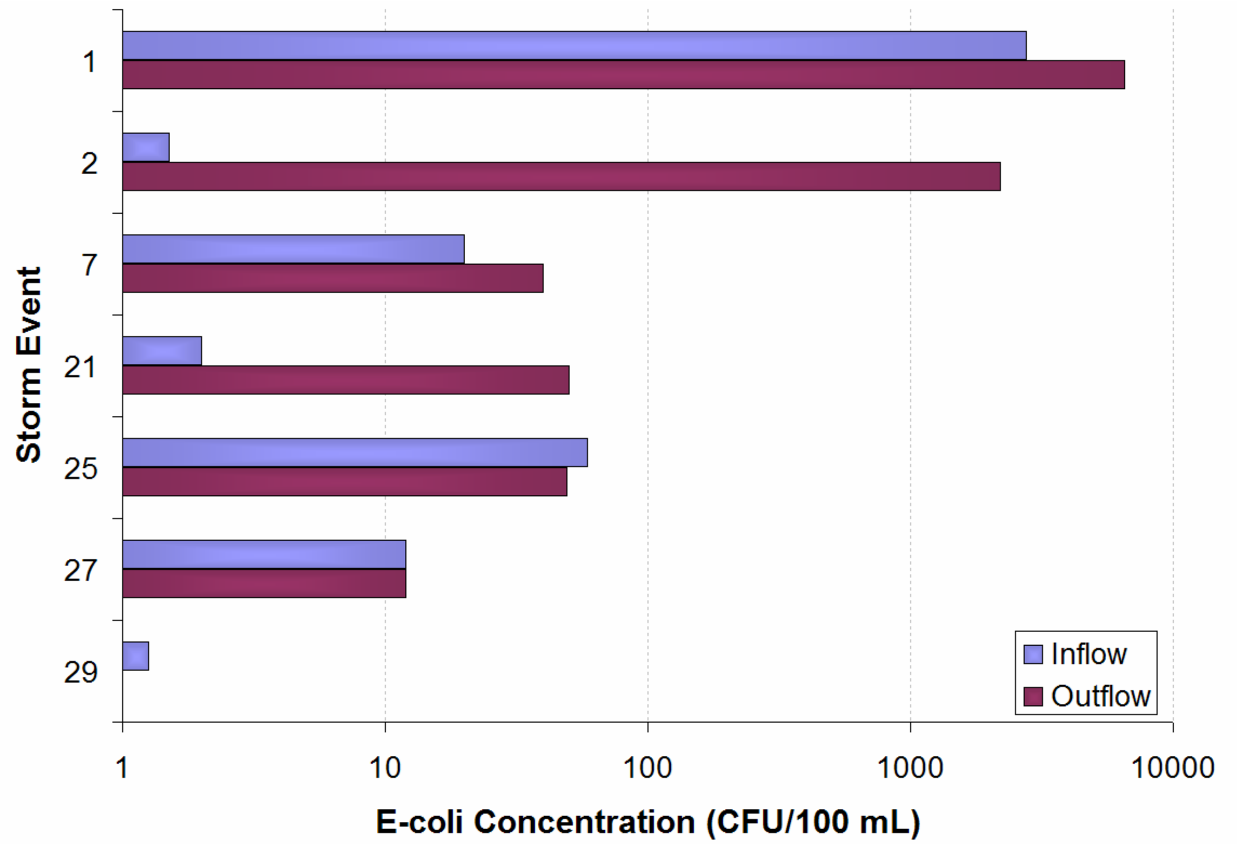


Figure 5.51. Inflow and outflow E-coli concentrations for the structural soil infiltration trench.

Inflow and outflow EC bacteria concentrations are shown in Figure 5.52. The graph also displays the Virginia water quality standards. One of six inflow events for the ITSS exceeded both the GM and the SS standards for E-coli concentrations; two of the four outflow events exceeded both standards. The two outflow concentrations that exceeded both the SS and GM standards occurred during storms 1 and 2, which were discussed in section 5.3.9. Since these were the first storm events, it is likely prior bacterial contamination was flushed from the media or the piping system. Outflow concentrations recorded after these two storm events were well below the two standards.

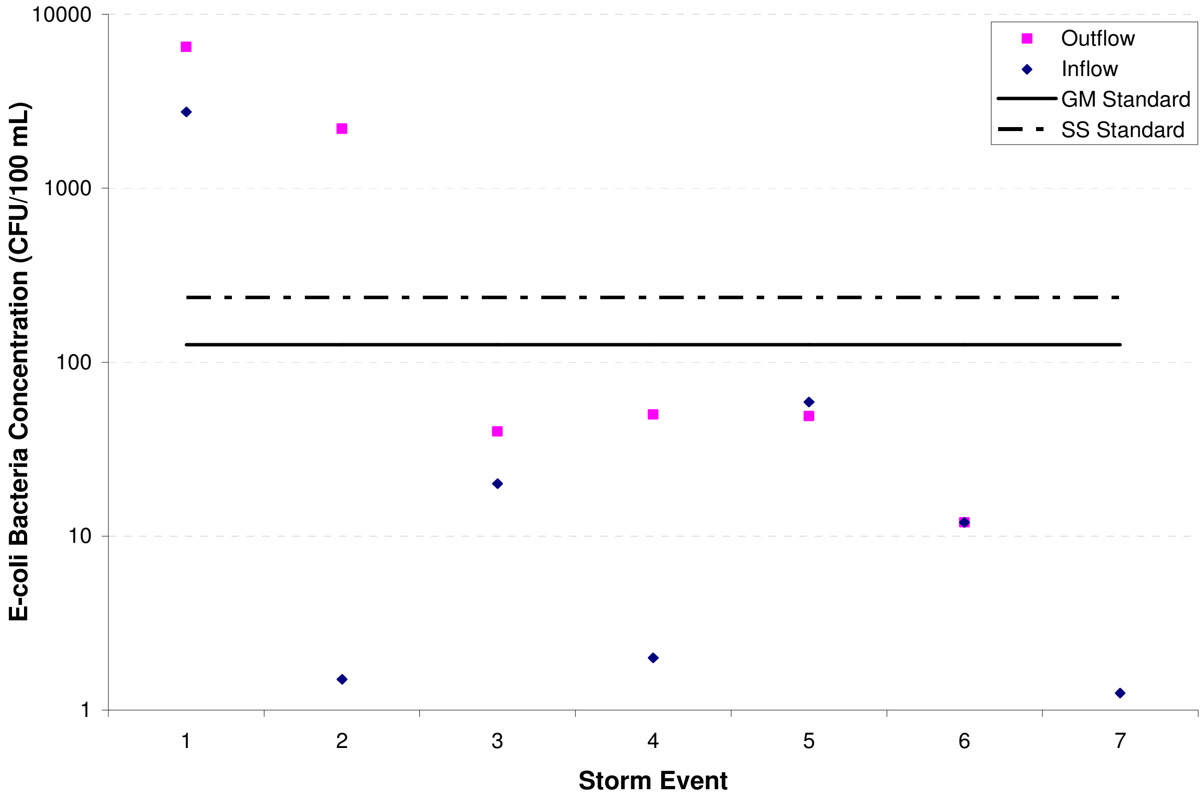


Figure 5.52. Comparison of inflow and outflow E-coli concentrations to the Virginia water quality standards. Note the y-axis is on a logarithmic scale.

Inflow and outflow loads for each monitored storm event are presented in Figure 5.54. Minimum inflow and outflow E-coli counts were 4,690 cfu (storm 29) and 0 cfu (storm 29), respectively; maximum counts were 1.43E9 cfu for inflow and 2.71E9 cfu for outflow, both corresponding to storm 1. The mean inflow number of colonies was 2.06E8 cfu, while the mean outflow number of colonies was 6.29E8 cfu. Median inflow and outflow loads were 3.81E5 cfu and 1.64E5 cfu, respectively. The outliers identified in the inflow and outflow datasets both correspond to storm 1.

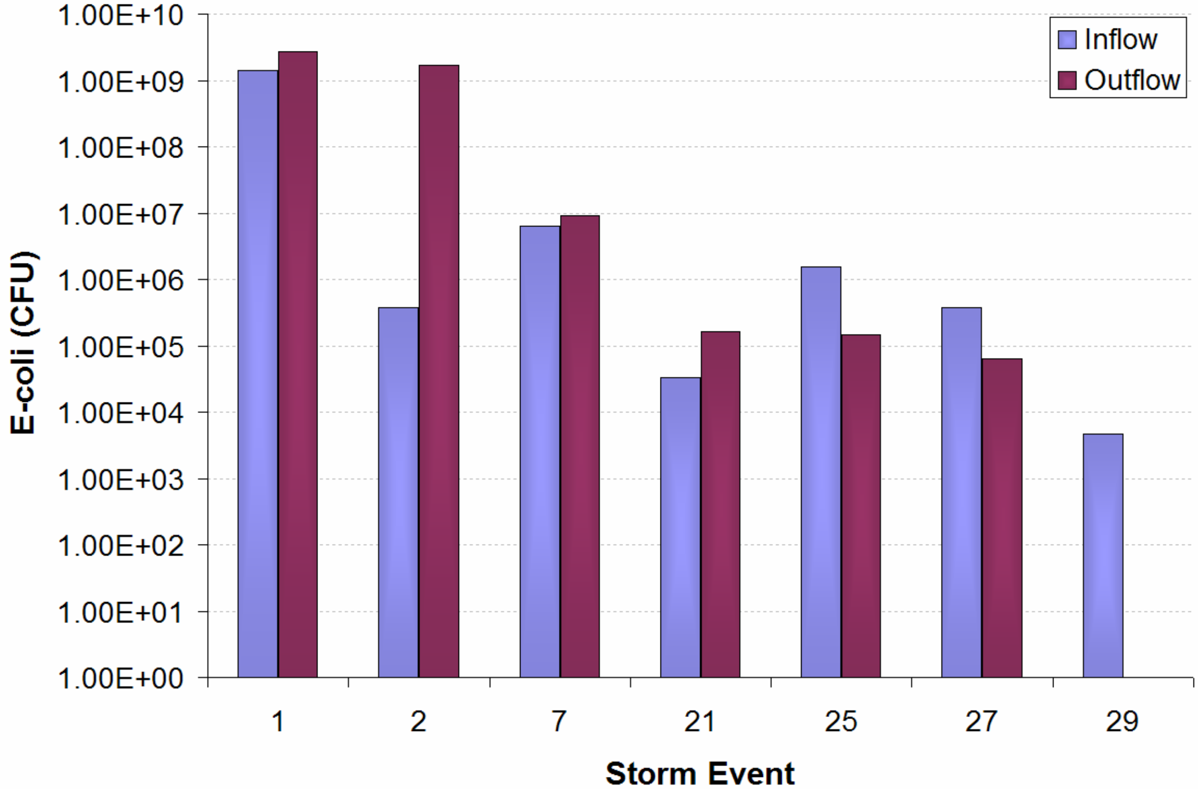


Figure 5.53. Inflow and outflow E-coli counts for the ITSS. Note the y-axis is on a logarithmic scale.

A total of approximately 1.44E9 colonies of E-coli entered the ITSS during the study period, while approximately 4.4E9 colonies exited via outflow (Figure 5.55). Consequently, the ITSS had an overall percent increase of 206% in the number of E-coli colonies. Similar to the fecal coliform results, inflow and outflow loads were not significantly different when the storms were analyzed as paired data. Removal percentages varied drastically from storm to storm. Overall, the median percent increase in load from inflow to outflow was 43%.

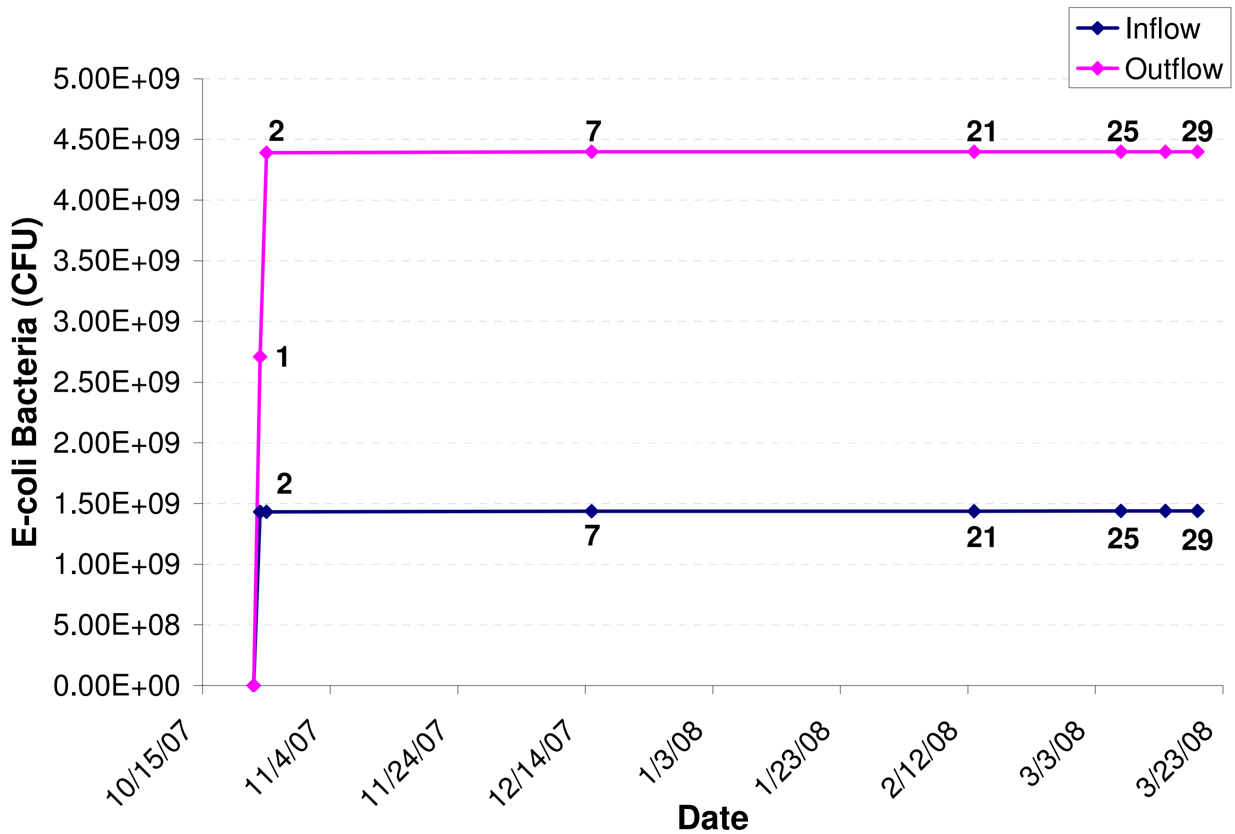


Figure 5.54. Cumulative inflow and outflow E-coli bacteria counts for the structural soil infiltration trench. Point labels represent storm events.

Unlike the BRC results, there was no correlation between EC load and SS load, but there was a negative correlation between the inflow E-coli load and inflow suspended sediment concentration (ρ = -0.821, p = 0.0341). There was also a negative correlation between the inflow volume and the percent removal of E-coli bacteria (ρ = -0.681, p = 0.0013), indicating that large inflow volumes decrease the E-coli reduction rates within the BMP.

Changes in E-coli concentrations or loads were not consistent for the ITSS. While some storms had lower outflow concentrations, the outflow concentrations overflow all were significantly higher than the inflow concentrations. The cause of this is unknown, and the possible reasons are the same as for the FC concentrations: bacteria reproduction within one or more components of the BMP system. The difference in inflow and outflow EC loads was not significant (p-value = 0.8516), but the BMP introduced a large amount of E-coli bacteria to the storm sewer.

5.3.11. BMP Water Quality Summary

The BRC significantly reduced the loads of all constituents: SSC, TN, TP, FC and EC bacteria. The high removal rates were most likely due to the high flow reduction and the few events that even produced outflow.

The mass removal rate of all constituents was negatively correlated with the inflow volume for the BRC. As the inflow volume was the primary indicator of the production of outflow, this indicates that flow volume reduction is the key to reducing pollutant loadings. Thus, the BRC is highly successful at removing pollutants for small, low intensity events. However, additional monitoring is needed to evaluate the relative important of more frequent, smaller storm events to rare, larger events in terms of overall loadings to Stroubles Creek.

The sediment forebay substantially decreased the SSC entering the ITSS when compared to the BRC inflow SSC. While the difference in the inflow and outflow SSC loads of the ITSS were not statistically significant, the test p-value (0.078) was close to the chosen alpha value of 0.05, indicating the BMP is reducing sediment concentrations.

The outflow concentrations of TN were significantly higher than the inflow concentrations for the ITSS, and the BMP served as a considerable source of nitrogen during the study period. The source of this excess nitrogen is unknown, but is likely the Gelscape. The ITSS significantly reduced TP loads.

The ITSS was unsuccessful in reducing the number of FC and EC bacteria colonies leaving the site, even though the results were not statistically significant. USEPA recommends the use of grab sampling techniques for FC and EC bacteria monitoring. This study employed automated sampling equipment; therefore, the results obtained for bacteria could possibly be biased due to the sampling methods used.

5.4 Representative Storm Events

The data presented within this section provide an example of patterns and trends in flow and pollutant concentrations that occurred within an individual monitored storm event at the study site. However, these data are not necessarily representative of all storms events that produced inflow to the BMPs, but are provided for discussion and consideration in addition to the study results.

5.4.1. BRC

Storm 6 occurred on December 28, 2007 and produced both inflow to and outflow from the BRC. The storm lasted approximately six hours and generated 1.4 cm of precipitation. Inflow to the BRC began around 3:30 pm, as shown in Figure 5.55. Flow rates varied throughout the storm, but peaked around 6:30 pm and tapered off before ending at 9:53 pm. Outflow did not begin until approximately 6:00 pm, peaked around 6:50 pm and ended at 8:30 pm. The points along the hydrograph at which samples were collected are shown in Figure 5.55. The gap in inflow sample collection between 5:15 pm and 6:15 pm was due to the occurrence of an error in the sampling program; at 6:15 the program was reset and sampling resumed. Outflow sampling occurred without error along the entire hydrograph.

Inflow suspended sediment concentrations showed a strong relationship with the incoming flow rate for the BRC (Figure 5.56). High SSC values were associated with high flow rates. When the flow rates started decreasing towards the end of the storm, the SSC values decreased dramatically. Outflow SSC values were lower than the SSC values from the first half of the storm, but not lower than those from the second half of the storm; however, they did decrease as time progressed. The high SSC values during the first half of the storm is most likely because the first flows of the storm washed the majority of the sediment on the parking lot surface into the BMP. Towards the latter part of the storm, there was very little sediment left on the parking lot surface to enter the BMP; however, the water moving through the ITSS was probably moving fast enough to pick up some of the sediment deposited within the treatment media during the first half of the storm. As the storm ended and flows through the BMP decreased, the amount of sediment in the outflow also decreased.

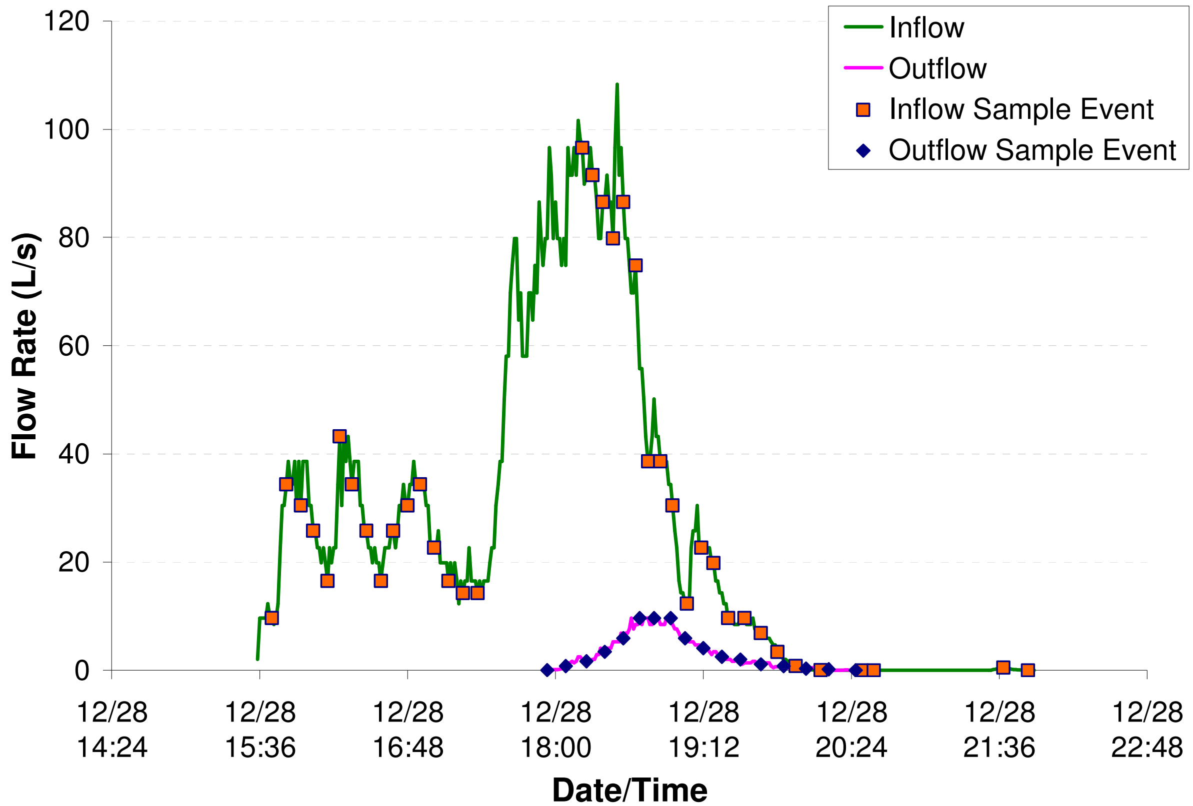


Figure 5.55. Inflow and outflow hydrograph for the bioretention cell for storm 11, which occurred on December 28, 2007.

The majority of the inflow TN concentrations for the BRC during storm 11 were under the lowest detectable concentration and, by default, were assigned a value of 0.25 mg/L (Figure 5.57). Several samples throughout the storm had higher concentrations; however, when the samples were composited to produce an overall sample for the storm event, the TN concentration was still below the detectable concentration. All outflow values were also below the detectable concentration and were set to a default value of 0.25 mg/L.

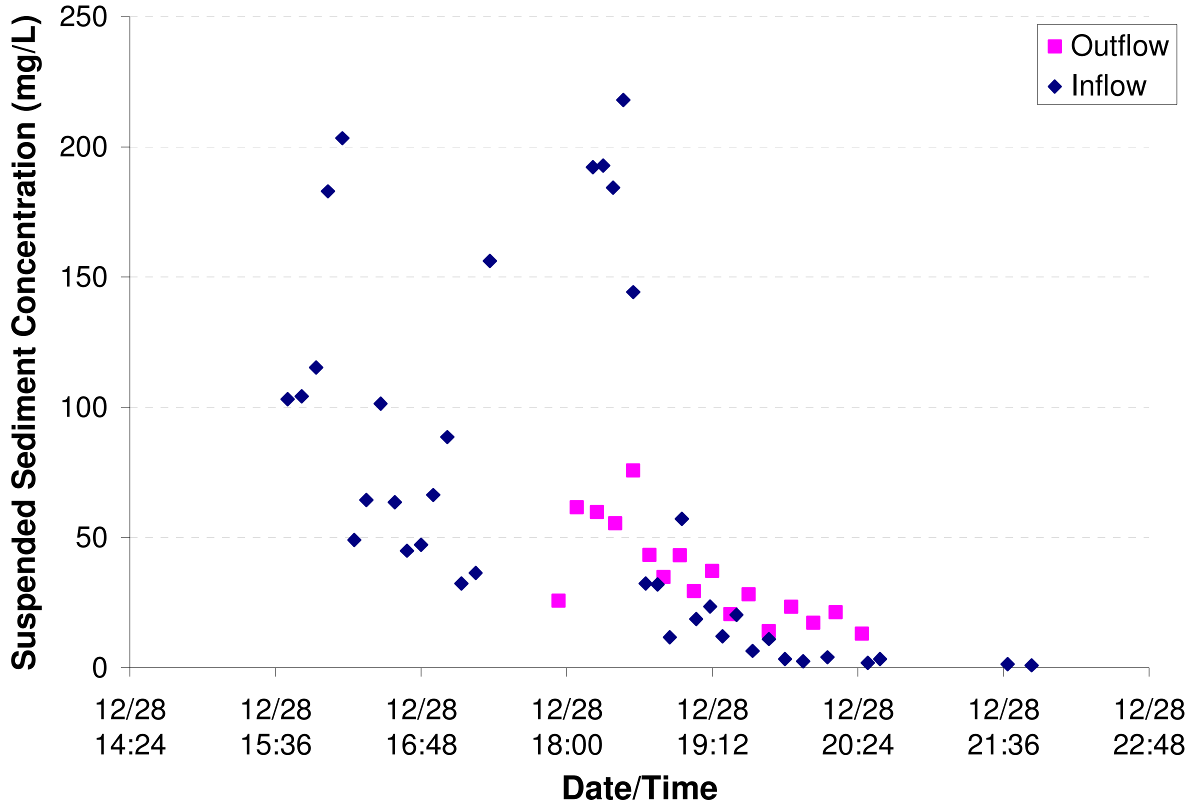


Figure 5.56. Inflow and outflow suspended sediment concentrations for storm 11 for the bioretention cell (December 28, 2007).

As shown in Figure 5.58, all inflow total phosphorus concentrations were relatively high, but below 1 mg/L, and concentrations decreased as time into the storm increased. The first outflow concentration of TP was very high (> 2 mg/L), but the remainder of the sample were below 1 mg/L and they also decreased in concentration as the storm progressed. The cause of decreasing concentration values during the length of the storm is most likely due to the same phenomenon discussed for the SSC concentrations: the majority of TP was washed off the parking lot surface during the first part of the storm. As the storm passed, less and less TP was available on the surface of the parking lot to be washed into the BMP and the inflow concentrations decreased. The very high initial outflow TP concentration is most likely due to a flushing effect within the treatment media. The decrease in outflow TP values over the course of the storm could be due to the increase in inflow concentration or the decrease in flow rates through the treatment media, which would allow for increase adsorption of TP. Although the majority of outflow concentrations are below 1 mg/L, these values are quite high, as the Virginia water quality standards for lakes are 0.04 mg/L TP or lower.

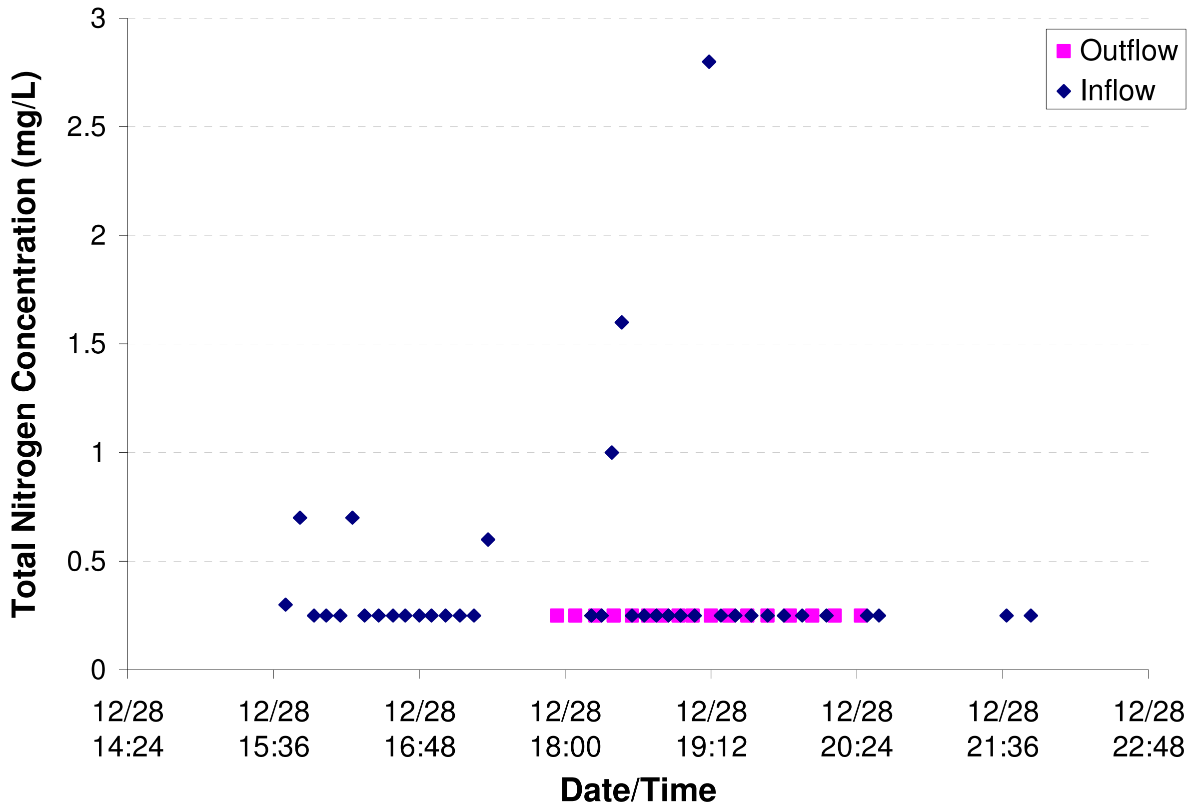


Figure 5.57. Inflow and outflow total nitrogen concentrations for the bioretention cell for storm 11 (December 28, 2007).

Inflow fecal coliform concentrations varied throughout the storm event, showing no visible trend (Figure 5.59). While there were several high outflow FC concentrations, these mainly occurred during the first half of the outflow event. This indicates that the high outflow concentrations could be due to a flushing effect.

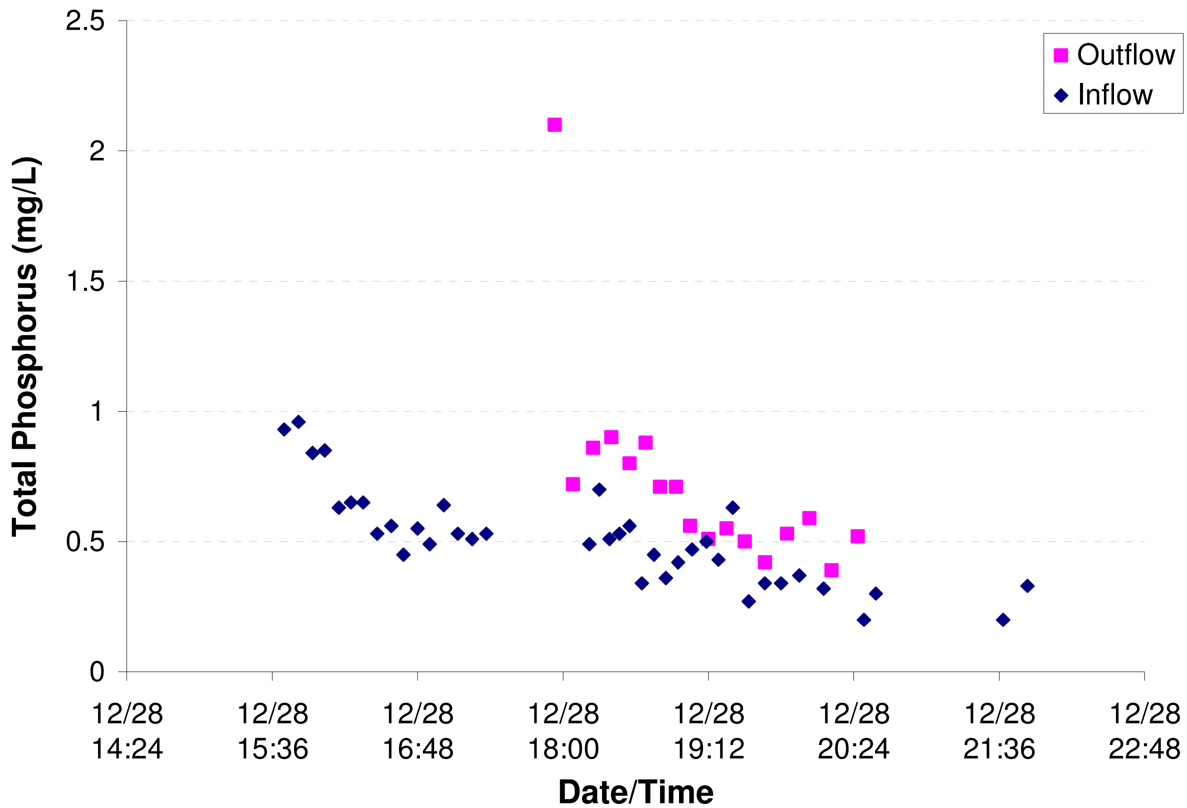


Figure 5.58. Total phosphorus concentrations for bioretention cell inflow and outflow for December 28, 2007 (storm 11).

The majority of the inflow E-coli concentrations for the BRC were low, except for two spikes in the inflow concentrations (Figure 5.60). These two spikes were associated with spikes in the inflow rate, but not with increased SSC. Trends in the outflow concentration values were similar to the FC results: the majority of the high concentrations occurred during the first half of the outflow event, suggesting they were due to a flushing effect.

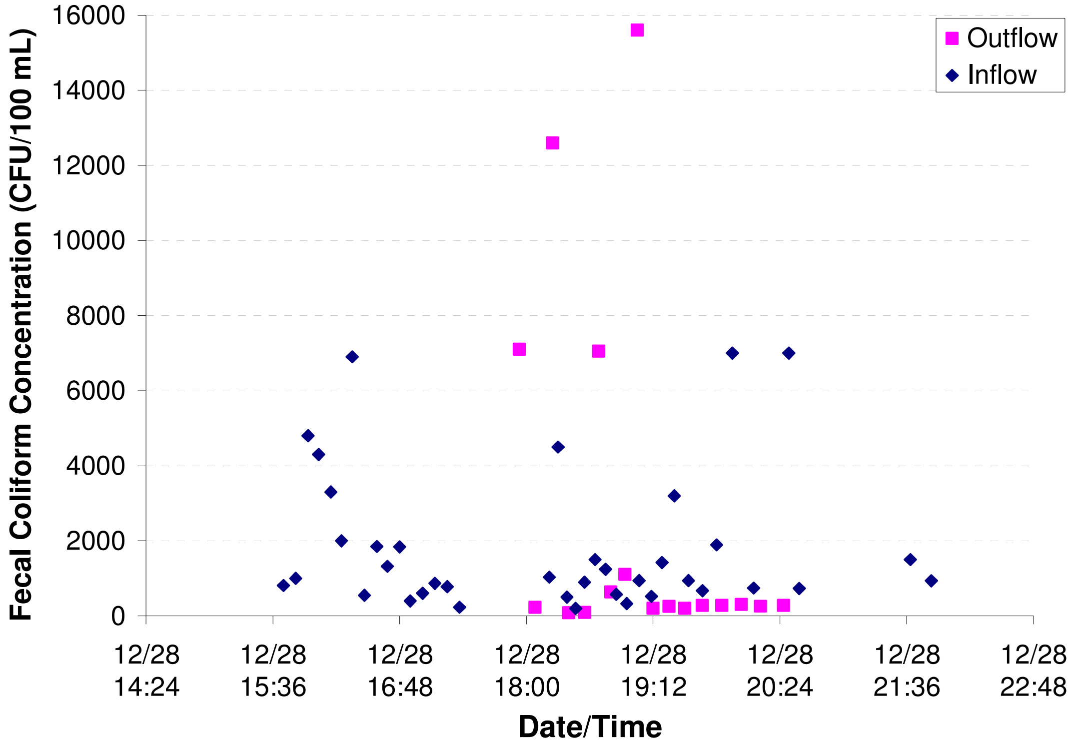


Figure 5.59. Bioretention cell inflow and outflow fecal coliform concentrations for storm 11 (December 28, 2007).

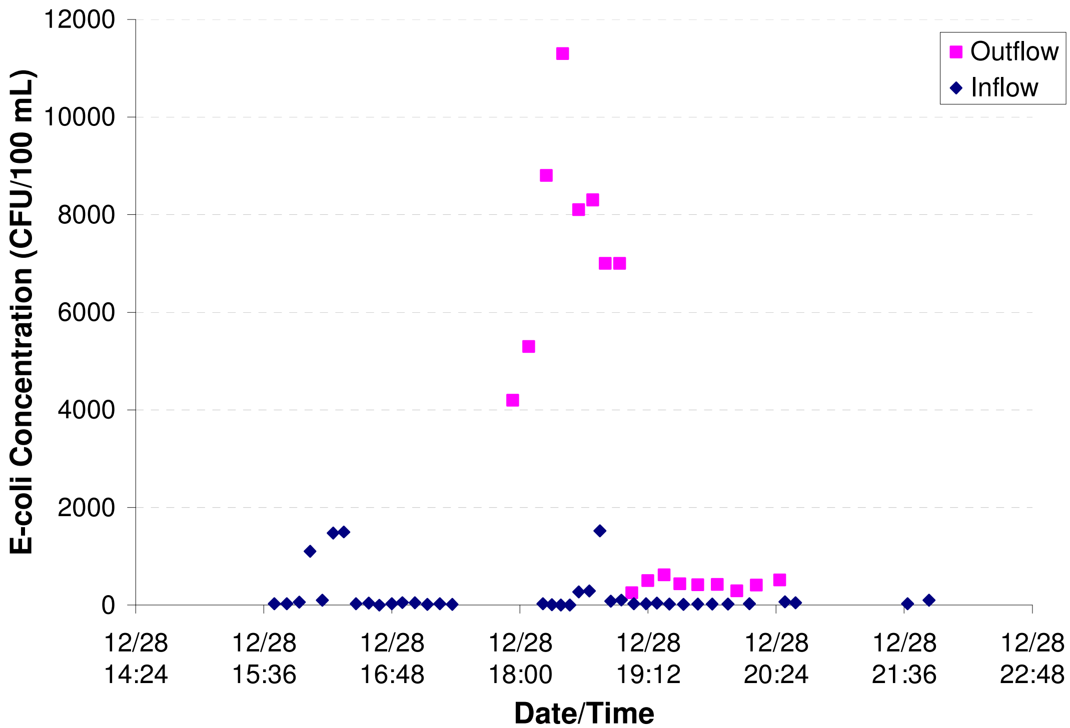


Figure 5.60. Inflow and outflow E-coli concentrations for the bioretention cell for December 28, 2007 (storm 11).

5.4.2. ITSS

Storm 25 occurred on March 7, 2008 and produced 1 cm in approximately 3 hours. Inflow began at 12:40 pm, peaked at 12:50 pm and tapered off before ending at 2:00 pm (Figure 5.61). Outflow began at approximately 1:15 pm, peaked at 1:30 pm and gradually decreased until it stopped at 3:00 pm. The inflow rates for the ITSS were much lower than for the BRC, as water must pool to a certain height in the sediment forebay before entering the infiltration trench. Points along the hydrograph at which samples were taken are indicated in Figure 5.61; inflow and outflow samples were successfully collected along the entire hydrograph.

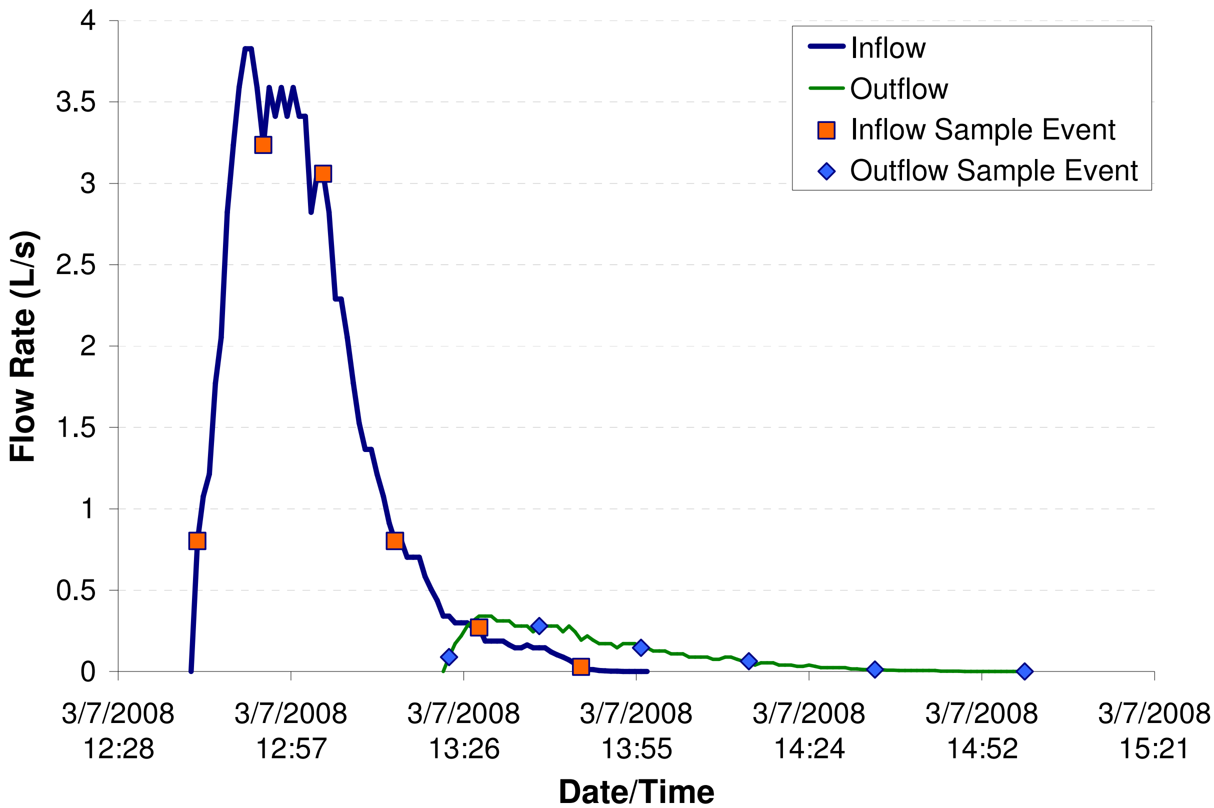


Figure 5.61. Inflow and outflow hydrographs for the structural soil infiltration trench for storm 25, which occurred on March 7, 2008.

Inflow suspended sediment concentrations, overall, were much lower than those for the BRC due to the sediment forebay (Figure 5.62). The SSC for the first sample was much higher than the remaining samples and the SSC decreased as the storm progressed, indicating a 'first flush' effect. Outflow concentrations of suspended sediment were very low (<5 mg/L) and were consistent throughout the storm event, indicating the ITSS successfully reduced the runoff SSC

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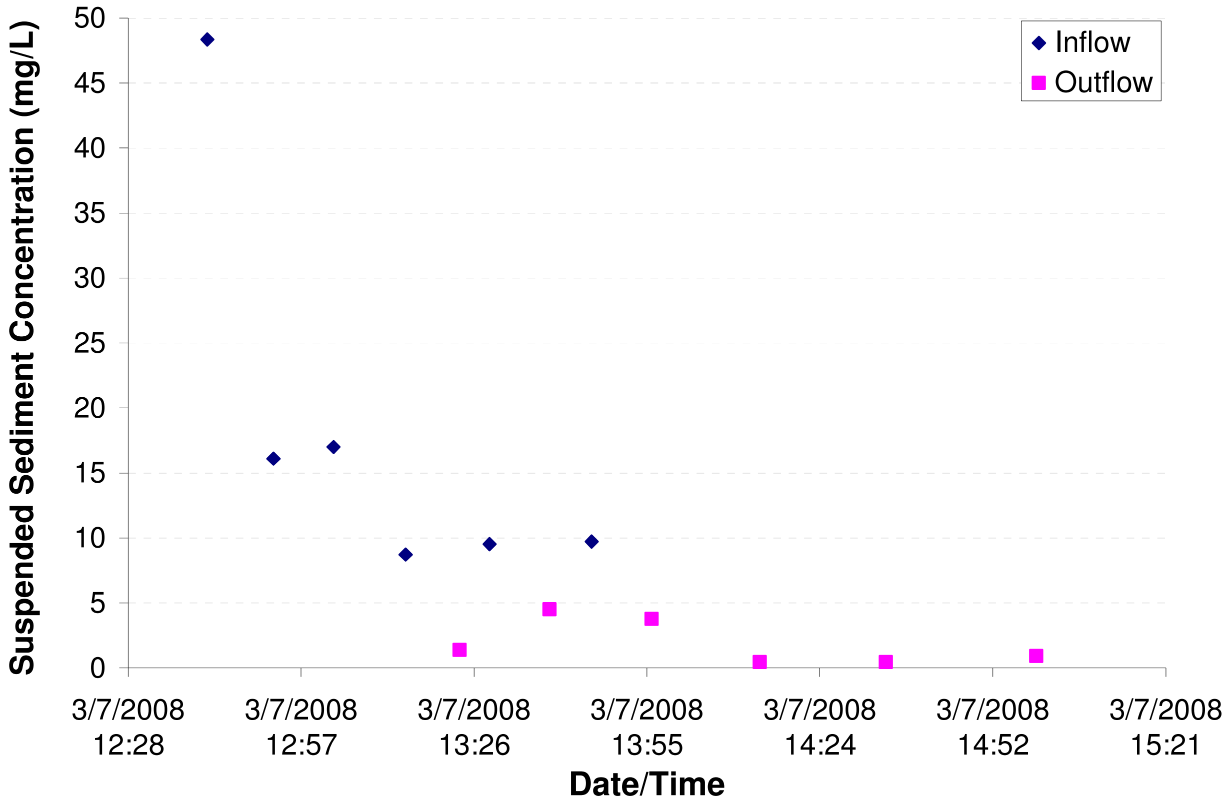

Figure 5.62. Suspended sediment concentrations for the structural soil infiltration trench for March 7, 2008 (storm 25).

There were no trends or patterns associated with the inflow TN concentrations for the ITSS (Figure 5.63). Outflow TN concentrations were initially very high, but decreased to around 3 mg/L, indicating a flushing effect. Two of the six inflow samples had TP concentrations below 1 mg/L, but two samples had very high concentrations (> 6.5 mg/L) (Figure 5.64). The cause of these inflow concentration spikes is unknown. Outflow concentrations were also high, with 4 of the 6 samples containing TP concentrations greater than 2 mg/L.

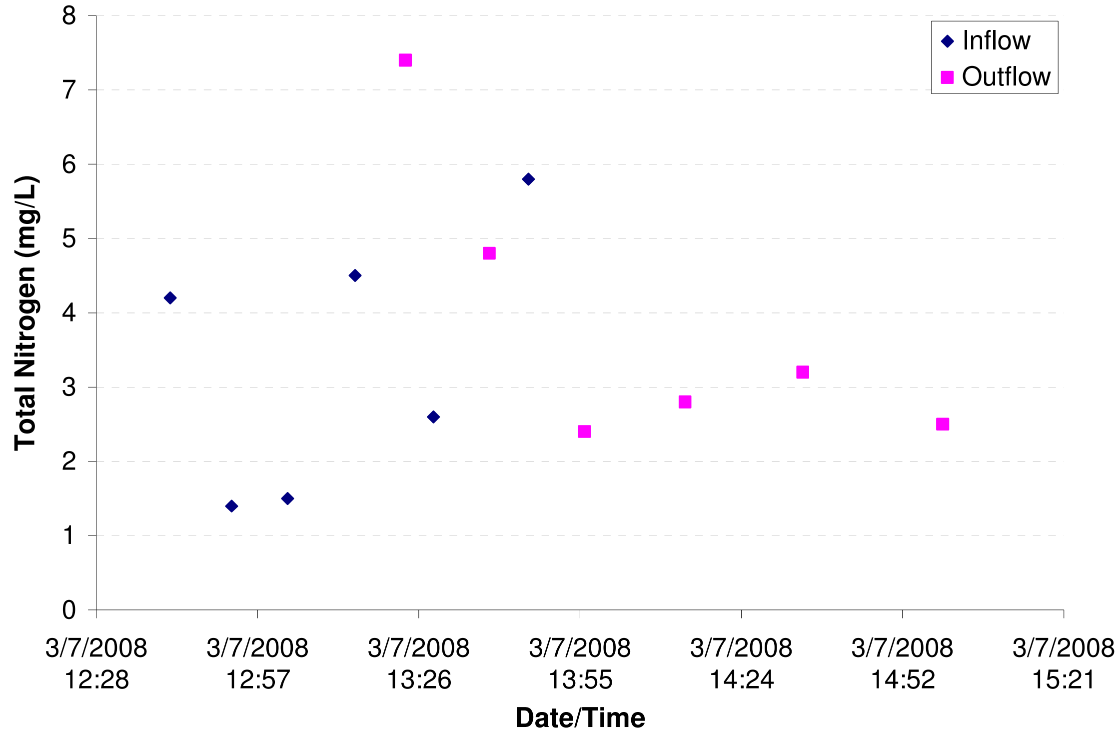

Figure 5.63. Inflow and outflow total nitrogen concentrations for the infiltration trench for storm 25 (March 7, 2008).

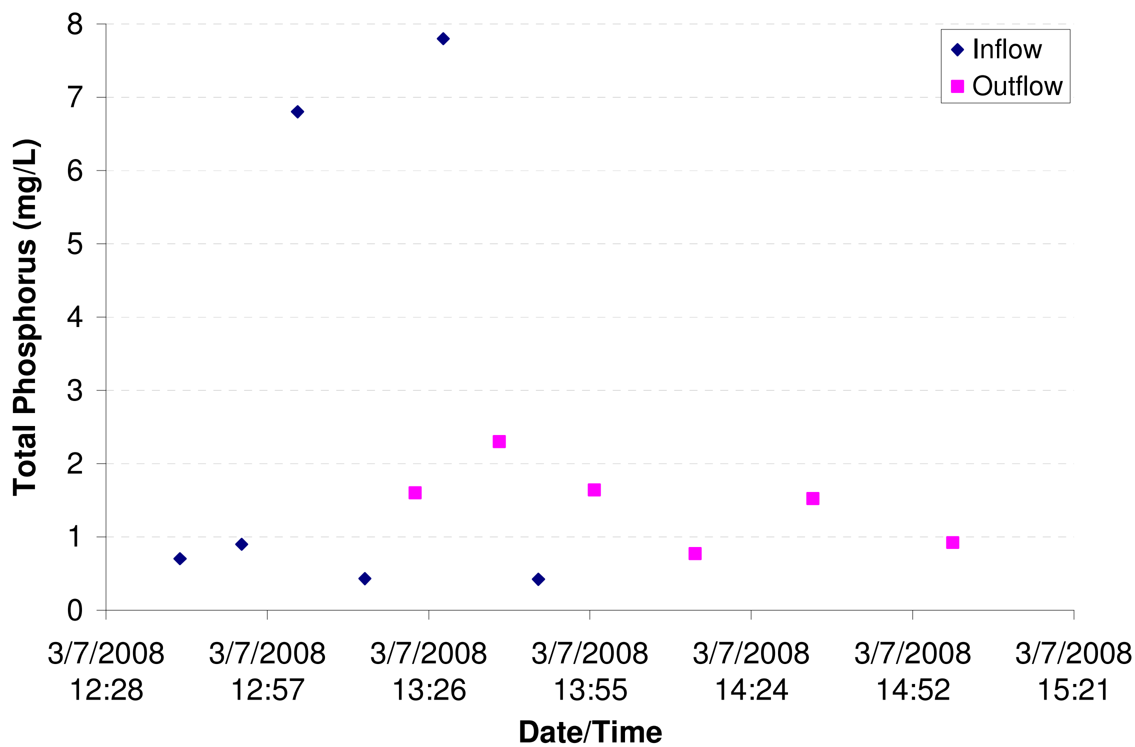

Figure 5.64. Total phosphorus concentrations (inflow and outflow) for the infiltration trench for March 7, 2008 (storm 25).

Both inflow and outflow fecal coliform concentrations increased as the storm progressed (Figure 5.65). In contrast, inflow E-coli concentrations decreased as the storm progressed while the outflow E-coli concentrations increased (Figure 5.67). The cause of increasing concentrations of bacteria could be the build-up of bacteria in stormwater pipes or in the sampling equipment (as automated sampling techniques were used for bacteria samples instead of grab sampling).

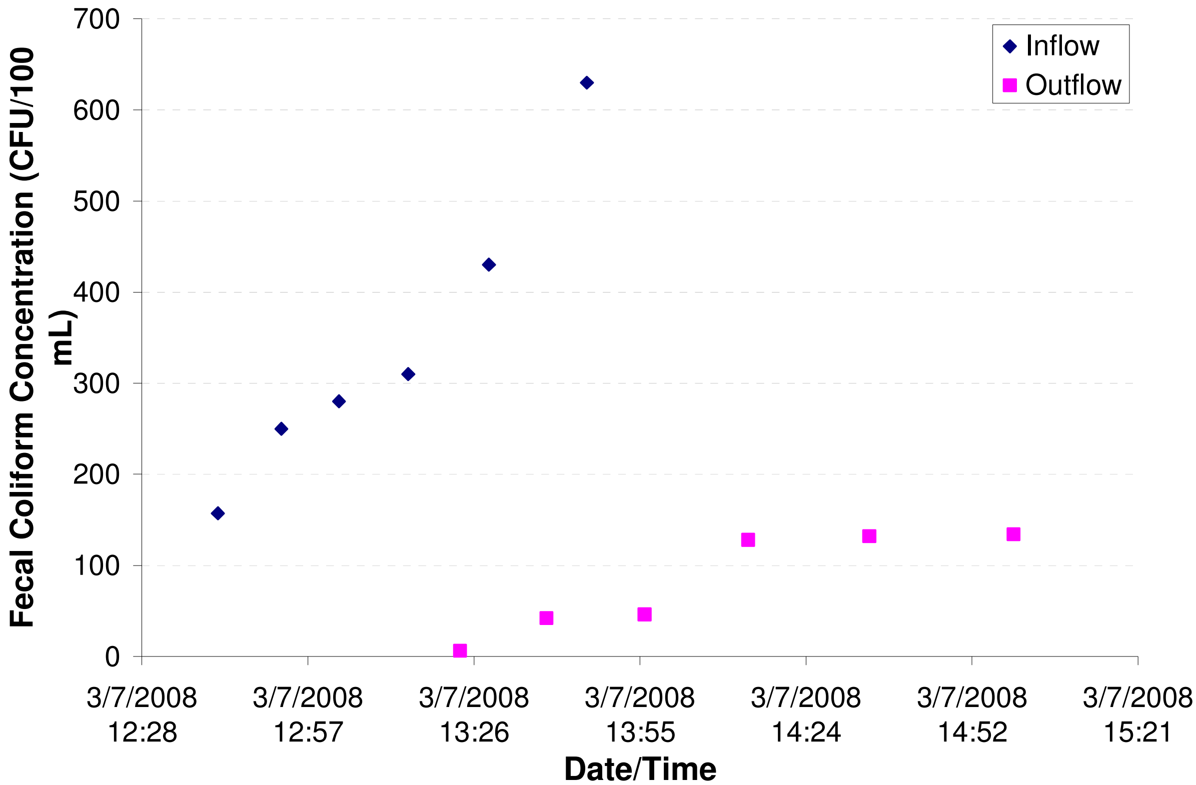

Figure 5.65. Inflow and outflow concentrations of fecal coliform bacteria for the structural soil infiltration trench for storm 25 (March 7, 2008).

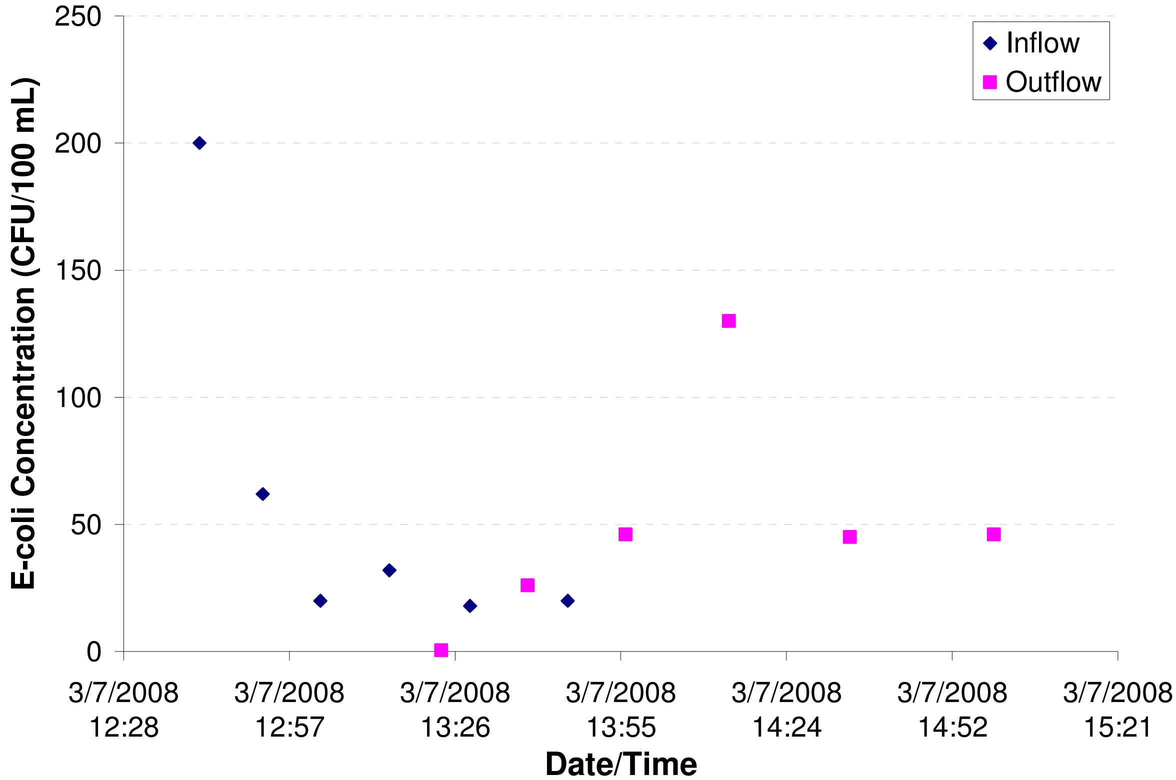

Figure 5.66. E-coli concentrations for structural soil infiltration trench inflow and outflow for March 7, 2008 (storm 25).

6. Conclusions

6.1 Bioretention Cell

Flow volumes leaving the bioretention cell were significantly less than volumes entering. The cumulative flow reduction for the BRC was greater than 99%, most likely due to water seeping out of the BMP walls through cracks in the surrounding soils. Of 23 storm events that produced inflow to the cell, only three storms produced outflow. Of these outflow events, only one produced overflow (water that bypassed the BMP). Therefore, the BRC effectively treated 99.8% of the water leaving the system.

The BRC significantly reduced peak flow rates by 99.5%. This reduction was due primarily to the large amount of flow reduction; however, when only storms that produced inflow and outflow were considered, peak flow reduction rates still averaged 96.6%.

The bioretention cell achieved a cumulative mass removal of 99.8% for suspended sediment, significantly reducing inflow suspended sediment loads. The BRC also significantly reduced inflow loads of total nitrogen and total phosphorus, achieving cumulative mass removals of 99.7% and 99.6%, respectively.

Inflow counts of fecal coliform bacteria colonies were significantly reduced by the BRC: A cumulative mass removal of 98.6% was measured. However, this high load reduction was the result of reduced flow, rather than decreased concentrations. The bioretention cell was a source of E-coli bacteria over the study period, with a cumulative increase of 28% between inflow and outflow loads; however the inflow loads were significantly greater than the outflow loads (p-value = 0.0006).

The effectiveness of the BMP at reducing stormwater volume, peak runoff rates and pollutant loadings to Stroubles Creek was strongly influenced by the magnitude of the storm event and the amount of water entering the BMP as inflow. As this study was conducted primarily during winter months, the majority of the storms monitored were low-intensity frontal events. Different results may be found during higher intensity summer storms.

Overall, the bioretention cell was successful in reducing flow volumes and peak flow rates leaving the parking lot, as well as reducing the total mass of sediment, total nitrogen, total phosphorus and fecal coliform bacteria leaving the site. The cell acted as a source of E-coli, suggesting bacteria are being harbored or generated within the BMP or the monitoring system.

Based on the results of this study, bioretention is highly recommended as a method of treating urban stormwater. The media used in this study has infiltration rates high enough to prevent standing water, but low enough to facilitate exfiltration, peak flow rate reduction and pollutant adsorption. The design could be improved by decreasing the width of the bioretention cell and increasing the length. This design modification would serve to reduce short-circuiting within the BRC, thus increasing treatment, and would lessen the probability of producing untreated overflow during high-intensity short-duration events. Although loads of bacteria were significantly reduced, the BRC produced very high concentrations of bacteria in the outflow, suggesting that the BRC may not be suitable in areas where the reduction in bacteria loads and concentrations is a primary goal of stormwater treatment.

6.2 CU-Structural Soil™ Infiltration Trench

The ITSS significantly reduced flow volumes entering the BMP during the study period. The cumulative flow reduction was approximately 60% for the seven monitored storm events. All water that entered the infiltration trench as inflow left as outflow via the underdrains; therefore, 100% of the water was treated, with 0% leaving the system as untreated overflow.

The cumulative reduction in peak flow rates for the ITSS was 68% and outflow peak flow rates were significantly less than inflow rates ($p = 0.007$). An analysis of water levels throughout the BMP indicated that the underdrain pipes were controlling the outflow rate; thus, it is recommended that pipe restrictors be used to further reduce outflow rates. In future designs, smaller underdrain pipe sizes should be used if the treatment media does not sufficiently reduce the outflow rate.

Suspended sediment loads were reduced by a cumulative 52% within the ITSS; however, the difference between the inflow and outflow loads was not significant (p-value = 0.078). A cumulative removal of 45% was achieved for total phosphorus, and outflow loads were significantly higher than inflow loads ($p = 0.007$).

The ITSS acted as a substantial source of total nitrogen throughout the study period, with a cumulative mass increase of 454%. The inflow and outflow loads were not significantly different ($p = 0.76$). The source of the exported nitrogen is unknown, although observations during the laboratory analysis suggest the Gelscape is likely the source of the additional nitrogen.

The infiltration trench also acted as a source of both fecal coliform and E-coli bacteria, the difference in inflow and outflow loads was not significant ($p = 0.47$, 0.85, respectively). Cumulative increases in the mass of fecal coliform and E-coli were 548% and 206%, respectively. These results indicate bacteria are being harbored and/or generated within the BMP. Further investigation must be conducted to determine the bacteria source.

The performance of the ITSS is strongly associated with the inflow hydrology. Larger inflow volumes led to decreases in the reduction of flow, peak flow rates and the mass of sediment, nutrients and bacteria. Increases in incoming peak flow rates and incoming average flow rates resulted in decreases in the removal efficiencies of suspended sediment, total nitrogen, total phosphorus, and fecal coliform bacteria.

Overall, the infiltration trench proved successful in reducing the flow volumes and peak flow rates of stormwater leaving the study site, as well as reducing the mass of total phosphorus leaving the site. Further monitoring and data collection are needed to determine if the BMP serves as a source of total nitrogen, fecal coliform and E-coli; however, preliminary data indicate the ITSS is not an appropriate method of addressing nitrogen and bacteria concerns in stormwater runoff.

7. Future Research

This study of bioretention and structural soil infiltration trench BMPs highlighted the need for additional research in the area of these structural stormwater BMPs as urban stormwater treatment methods. While several column and lab-scale studies exist on bioretention, very few studies have been performed on field-scale bioretention cells for sediment, nutrients and bacteria. Perhaps more importantly, to the author's knowledge, there have not been any studies to determine the performance of bioretention over a long-term period. As more bioretention cells are built in response to government LID policies and programs, there is no evidence of their long-term performance. Additionally, plants are considered an essential part of a bioretention cell. However, the lack of long term monitoring does not allow for the analysis of the specific benefits provided by the plants. Long term monitoring of flow volume reduction, pollutant sequestration and peak flow reduction due to plant uptake and root density would provide much-needed knowledge about bioretention.

Few studies have included bacteria in their data collection and analysis. While this study, as well as results reported by Hunt et al. (2006), suggested bioretention provides adequate removal of fecal coliform bacteria, the results of this study suggest that bioretention cells may not be as efficient at removing E-coli from stormwater. High outflow concentrations and loadings indicate the BMPs may harbor and/or produce bacteria. Further research must be done to characterize the behavior of bacteria (especially E-coli) within bioretention cells and to determine if this type of BMP is appropriate for reducing bacteria loads within stormwater.

No peer-reviewed studies could be found on gravel-based infiltration trenches. As this type of BMP is an acknowledged component of LID, future research on the effectiveness of the infiltration trench at removing sediment and nutrients is imperative.

Low impact development is being thought of less and less as the 'stormwater tool of the future' and is steadily becoming the popular, trendy approach to stormwater management. While research has identified many downfalls to the traditional methods of stormwater treatment, such as increased stream temperature and detrimental hydrologic effects of detention and retention ponds, there is a large knowledge gap about the consequences of implementing low impact development at the site and watershed scales.

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Appendix A: Planting Lists and Layouts

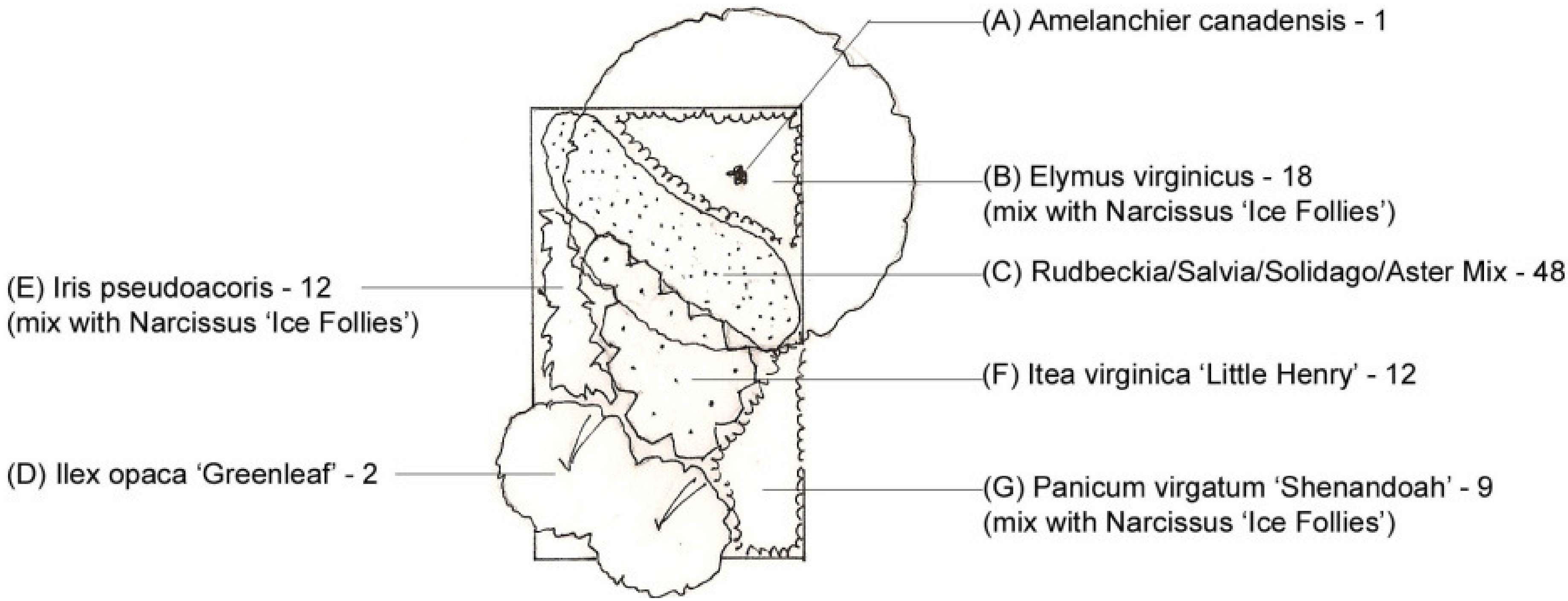


Figure A1. Planting list and layout for bioretention cell. Drawing not to scale.

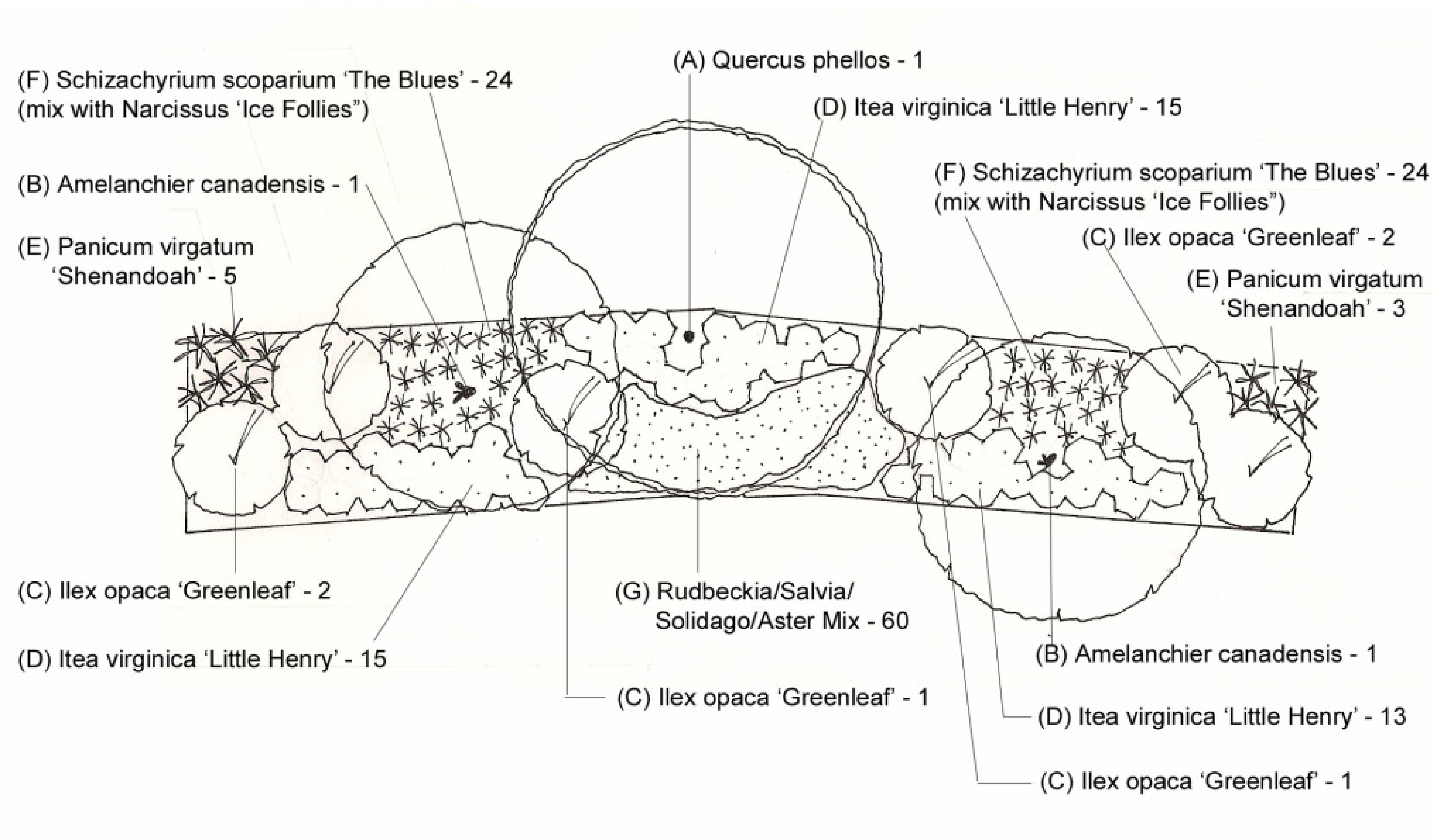
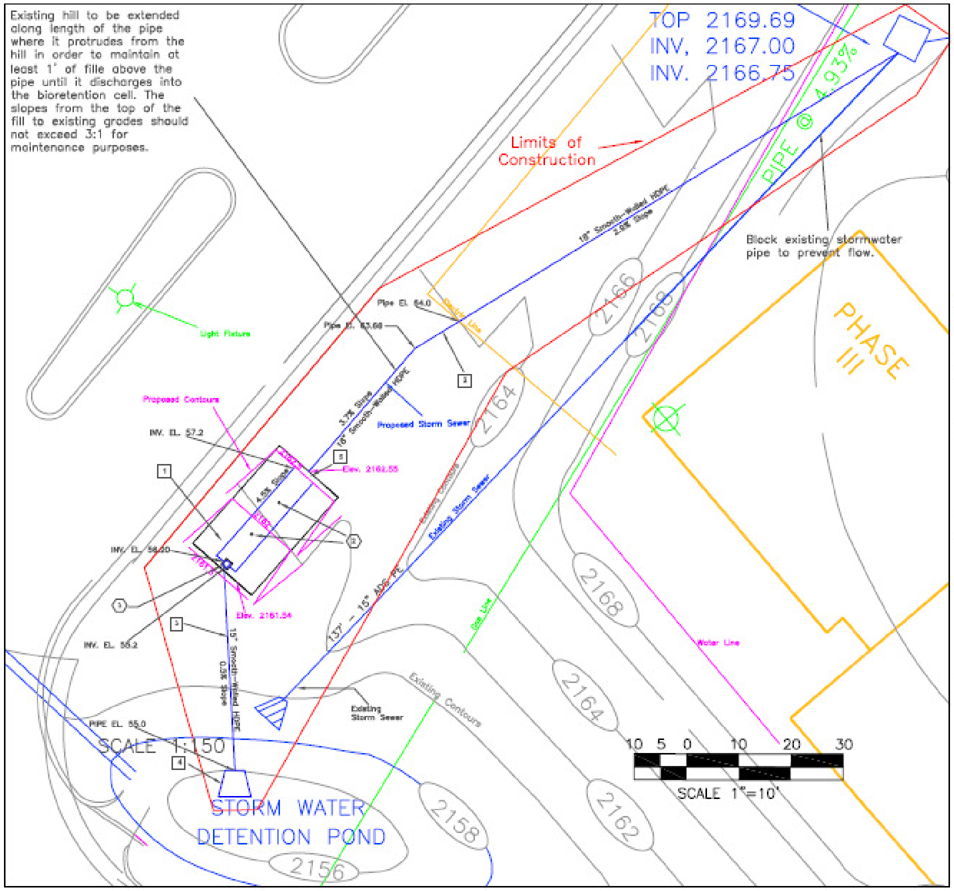
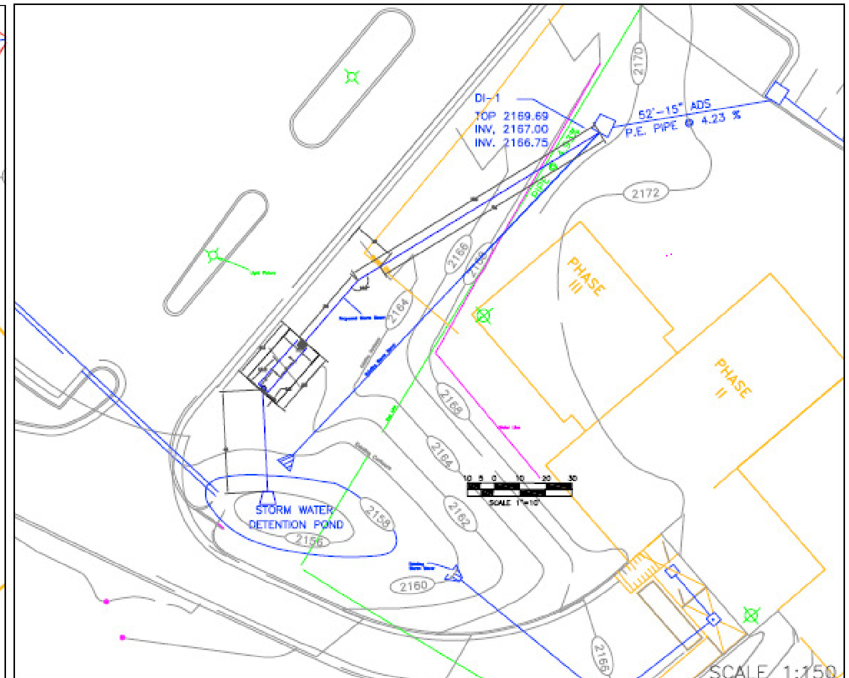


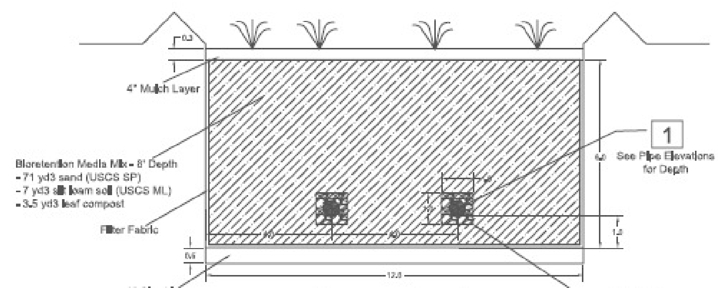
Figure A2. Planting list and layout for the structural soil infiltration trench. Drawing not to scale.

Appendix B: Construction Plans





1	6" Dia. Smooth–Walled Perforated HDPE Pipe Wrapped in Filter Fabric
2	18" Dia. Smooth–Walled HDPE Pipe
3	15" Dia. Smooth–Walled HDPE Pipe
4	Standard HDPE Flange for 15" Dia. Pipe
5	Class A1 Riprap – 3' x 3' X 1'



Cross-section A
Bioretention Cell
NOT TO SCALE

Figure B1. Construction plans for the bioretention cell. Drawings not to scale.

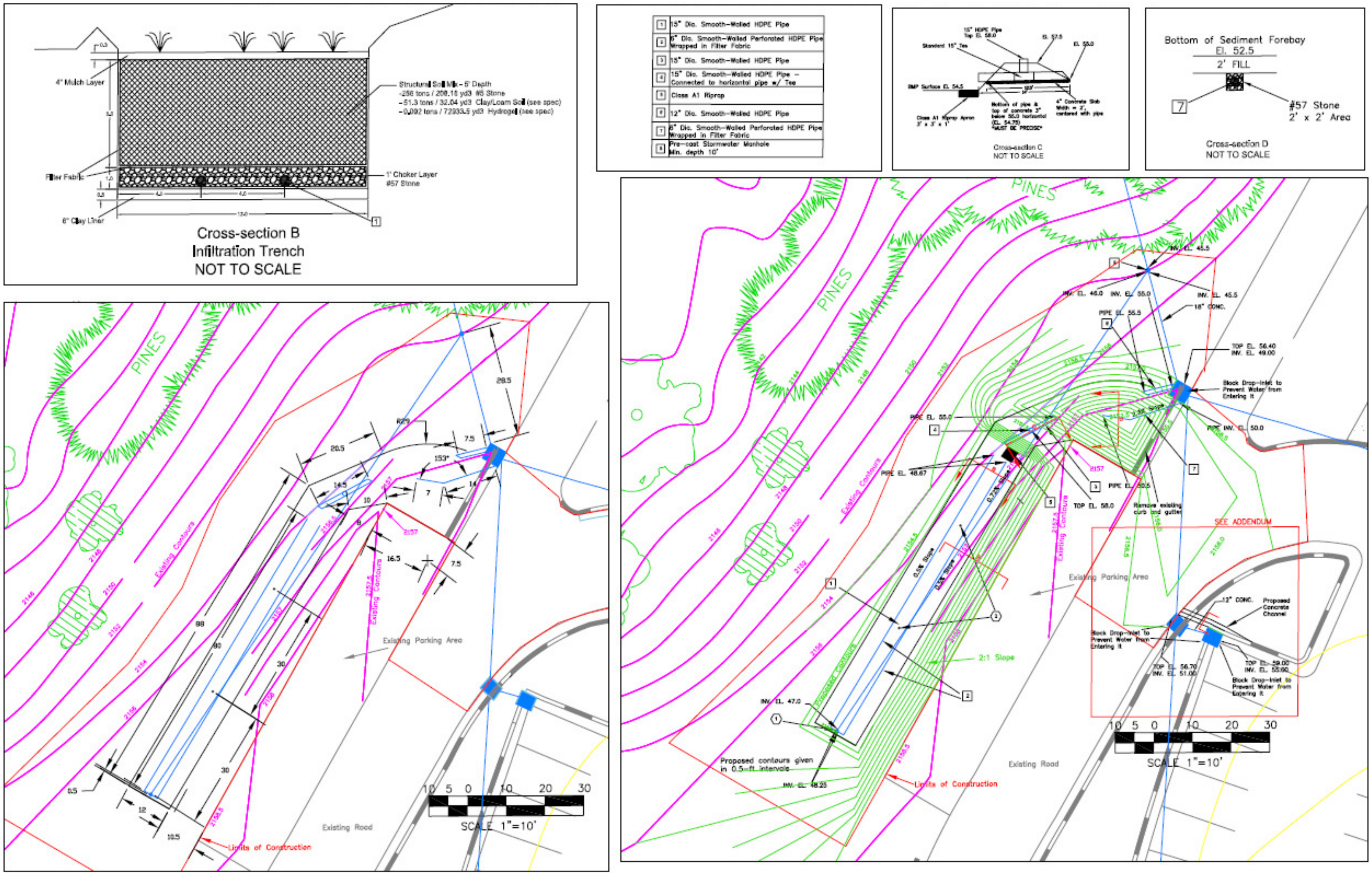


Figure B2. Construction drawings for structural soil infiltration trench. Drawings not to scale.

Appendix C: Bioretention Cell Data

Table C1. Flow and pollutant mass data for the bioretention cell.

Date	Storm	Total Nitrogen (g)		Total Phosphorus (g)		Suspended Sediment (g)		Fecal Coliform (CFU)		E-coli (CFU)		Flow Volume (L)		Peak Flow Rate (L/s)	
		In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
11/26/07	**5**	1.59	0	0.11	0	77.67	0	NA	NA	NA	NA	467.8	0	0.708	0.000
12/3/07	**6**	0.161	0	0.01	0	4.2	0	NA	NA	NA	NA	24.7	0	0.085	0.000
12/21/07	**8**	0.922	0	0.085	0	10.23	0	1.38E+07	0	3.07E+04	0	512.1	0	0.099	0.000
12/23/07	**10**	2.42	0	0.44	0	165.74	0	3.11E+06	0	8.63E+05	0	1725.8	0	1.529	0.000
12/28/07	**11**	2.45	0.12	1.34	0.086	430.9	15.2	1.17E+08	2.06E+07	5.87E+06	5.80E+07	9782.6	468	1.812	0.170
12/30/07	**12**	1.56	0	0.2	0	39.07	0	5.68E+06	0	1.56E+05	0	1420.3	0	1.699	0.000
1/5/08	**13**	0.00088	0	0.0001	0	3.34E-02	0	3.70E+03	0	1.85E+02	0	0.4	0	0.002	0.000
1/8/08	**14**	0.218	0	0.0358	0	17.02	0	1.74E+06	0	1.74E+04	0	87.2	0	0.170	0.000
1/10/08	**15**	0.215	0	0.043	0	16.26	0	6.92E+05	0	3.38E+05	0	153.7	0	0.142	0.000
1/11/08	**16**	1.28	0	0.16	0	47.2	0	1.68E+06	0	4.00E+05	0	800	0	0.623	0.000
2/1/08	**17**	39.95	0.13	2.41	0.003	1242.9	0.2	1.33E+08	1.14E+06	6.66E+06	5.70E+03	5548.5	22.8	1.161	0.008
2/4/08	**18**	0.772	0	0.207	0	68.5	0	6.08E+05	0	5.15E+05	0	233.9	0	0.340	0.000
2/6/08	**19**	5.45	0	4.258	0	186.64	0	1.29E+09	0	1.18E+06	0	858.9	0	1.161	0.000
2/6/08	**20**	5.39	0	7.78	0	875.6	0	1.80E+06	0	3.27E+06	0	1633.5	0	2.775	0.000
2/13/08	**21**	12.94	0	1.79	0	3867.4	0	3.04E+06	0	2.54E+05	0	2537	0	1.841	0.000
2/18/08	**22**	1.02	0	0.128	0	31.22	0	1.24E+05	0	4.46E+04	0	318.6	0	0.198	0.000
2/23/08	**23**	0.28	0	0.079	0	34.33	0	1.32E+05	0	1.32E+04	0	132.3	0	0.275	0.000
3/7/08	**25**	0.771	0	0.1512	0	44.8	0	2.95E+05	0	4.80E+05	0	545.5	0	0.227	0.000
3/14/08	**27**	10.73	0	1.9	0	1168.52	0	5.37E+05	0	1.79E+04	0	3577.06	0	2.435	0.000
3/15/08	**28**	1.29	0	0.335	0	122.37	0	6.97E+05	0	4.98E+03	0	995.93	0	0.538	0.000
3/19/08	**29**	3.67	0.004	1.78	0.0006	2058.5	0.71	7.86E+06	818.1	2.51E+07	834.4	5.24E+03	0.81	12.60	0.011

Table C2. Pollutant concentration data for the bioretention cell.

Storm	Date	Total Nitrogen (mg/L)		Total Phosphorus (mg/L)		Suspended Sediment (mg/L)		Fecal Coliform (CFU/100 mL)		E-coli (CFU/ 100 mL)	
		In	Out	In	Out	In	Out	In	Out	In	Out
5	**11/26/07**	3.4	NA	0.25	NA	166.0	NA	NA	NA	NA	3.4
6	**12/3/07**	3.8	NA	0.38	NA	169.5	NA	NA	NA	NA	3.8
8	**12/21/07**	1.8	NA	0.17	NA	26.1	NA	2700	NA	6	1.8
10	**12/23/07**	1.4	NA	0.25	NA	96.0	NA	180	NA	50	1.4
11	**12/28/07**	0.25	0.25	0.14	0.18	44.1	32.5	1200	4400	60	0.25
12	**12/30/07**	1.1	NA	0.14	NA	27.5	NA	400	NA	11	1.1
13	**1/5/08**	2.2	NA	0.27	NA	91.4	NA	1000	NA	50	2.2
14	**1/8/08**	2.5	NA	0.41	NA	195.2	NA	2000	NA	20	2.5
15	**1/10/08**	1.4	NA	0.28	NA	105.8	NA	450	NA	220	1.4
16	**1/11/08**	1.6	NA	0.2	NA	59.0	NA	210	NA	50	1.6
17	**2/1/08**	7.2	5.8	0.32	0.13	224	8.8	2400	5000	120	7.2
18	**2/4/08**	3.3	NA	0.88	NA	293	NA	260	NA	220	3.3
19	**2/6/08**	6.4	NA	4.96	NA	217.3	NA	150	NA	137	6.35
20	**2/6/08**	3.3	NA	4.76	NA	546	NA	110	NA	200	3.3
21	**2/13/08**	5.1	NA	0.70	NA	593	NA	120	NA	10	5.1
22	**2/18/08**	3.2	NA	0.40	NA	98	NA	30	NA	10	3.2
23	**2/23/08**	2.1	NA	0.6	NA	259.5	NA	100	NA	10	2.1
25	**3/7/08**	1.4	NA	0.97	NA	82.1	NA	54	NA	88	1.4
27	**3/14/08**	3	NA	1.63	NA	326.7	NA	15	NA	2	3
28	**3/15/08**	1.3	NA	1.03	NA	122.9	NA	70	NA	4	1.3
29	**3/19/08**	0.7	5.3	1.04	2.25	393.0	872	150	101	480	0.7

Appendix D: CU-Structural Soil™ Infiltration Trench Data

Table D1. Flow and pollutant mass data for the structural soil infiltration trench.

Date	Storm	Total Nitrogen (g)		Total Phosphorus (g)		Suspended Sediment (g)		Fecal Coliform (CFU)		E-coli (CFU)		Flow Volume (L)		Peak Flow Rate (L/s)	
		In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
10/24/07	**1**	13	43	8.63	4.58	584.96	183.6	2.01E+10	1.08E+11	1.43E+09	2.71E+09	51996.5	42999.3	11.04	5.35
10/25/07	**2**	20.4	332.62	8.98	7.25	327.3	467.3	1.22E+09	3.32E+10	3.81E+05	1.68E+09	81621.2	76288.5	19.54	9.91
12/15/07	**7**	25.73	101.1	1.48	0.46	115.8	59.73	4.66E+08	1.61E+08	6.43E+06	9.19E+06	32163.2	22974.6	13.14	4.98
2/13/08	**21**	14.35	2.63	0.7	0.033	243.9	0.47	6.25E+06	3.28E+05	3.26E+04	1.64E+05	6521.7	328.4	0.34	0.23
3/7/08	**25**	10.5	1.124	2.43	0.139	47.83	0.56	9.00E+06	2.37E+05	1.54E+06	1.44E+05	2624.0	293.1	1.81	0.17
3/14/08	**27**	2.483	0.901	0.6	0.067	101.25	1.166	2.17E+05	2.12E+05	3.73E+05	6.36E+04	3104.0	530.0	4.81	0.68
3/19/08	**29**	0.47	0	0.14	0	55.88	0	2.82E+05	0	4.69E+03	0	939.0	0.0	1.42	NA

Table D2. Pollutant concentration data for the structural soil infiltration trench.

Date	Storm	Total Nitrogen (g)		Total Phosphorus (g)		Suspended Sediment (g)		Fecal Coliform (CFU)		E-coli (CFU)	
		In	Out	In	Out	In	Out	In	Out	In	Out
10/24/07	**1**	0.25	1	0.17	0.11	11.3	4.3	38700	260000	2750	6500
10/25/07	**2**	0.25	4.4	0.11	0.10	4.0	6.1	1500	43500	1.5	2200
12/15/07	**7**	0.8	4.4	0.05	0.02	3.6	2.6	1450	700	20	40
2/13/08	**21**	2.2	8	0.11	0.10	37.5	1.4	100	100	2	50
3/7/08	**25**	3.3	3.8	2.84	1.46	18.2	1.9	343	81	59	49
3/14/08	**27**	0.8	1.7	0.59	0.39	32.6	2.2	7	40	12	12
3/19/08	**29**	0.5	NA	0.44	NA	59.5	NA	30	NA	1.25	NA

Appendix E: Total Nitrogen Series Data

Table E1. The total mass of each element in the nitrogen series for inflow and outflow for the structural soil infiltration trench.

Storm Event		Ammonia (g)	Nitrite (g)	Nitrate (g)	Organic Nitrogen (g)	Total Nitrogen (g)
21	Inflow	0.326	0.137	0.196	14.35	13.691
	Outflow	0.013	0.003	0.003	2.63	2.61
25	Inflow	0.25	0.066	1.837	8.74	6.587
	Outflow	0.017	0.004	0.542	1.12	0.557

Table E2. The concentration of each element in the nitrogen series for inflow and outflow for the structural soil infiltration trench.

Table E2. The concentration of each element in the nitrogen series for inflow and outflow for the structural soil infiltration trench. **Storm Event**		Ammonia (mg/L)	Nitrite (mg/L)	Nitrate (mg/L)	Organic Nitrogen (mg/L)	Total Nitrogen (mg/L)
21	Inflow	0.05	0.02	0.03	2.1	2.2
	Outflow	0.04	0.01	0.01	7.9	8.0
25	Inflow	0.09	0.03	0.7	2.5	3.3
	Outflow	0.06	0.01	1.9	1.9	3.8

Table E3. The mass of each element in the nitrogen series for inflow and outflow for the bioretention cell.

Storm Event	Ammonia (g)	Nitrite (g)	Nitrate (g)	Organic Nitrogen (g)	Total Nitrogen (g)
21	1.93	0.39	2.03	8.593	12.94
22	0.166	0.032	0.478	0.344	1.02
23	0.091	0.028	0.159	0.0003	0.278
25	0.093	0.0104*	0.341*	0.325	0.769

* Tests were performed on filtered sample due to high turbidity.

Table E4. The concentration of each element in the nitrogen series for inflow and outflow for the bioretention cell.

Storm Event	Ammonia (g)	Nitrite (g)	Nitrate (g)	Organic Nitrogen (g)	Total Nitrogen (g)
21	0.76	0.15	0.8	3.4	5.1
22	0.52	0.1	1.5	1.1	3.2
23	0.69	0.21	1.2	.01	2.1
25	0.17	0.02	0.63	.58	1.4

* Tests were performed on filtered sample due to high turbidity.

Appendix F: Water Level Data

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/28/2007 0:00	0.19	0.24
12/28/2007 0:05	0.4	0.24
12/28/2007 0:10	0.3	0.12
12/28/2007 0:15	0.19	0.24
12/28/2007 0:20	0.19	0.24
12/28/2007 0:25	0.3	0.12
12/28/2007 0:30	0.3	0.34
12/28/2007 0:35	0.3	0.45
12/28/2007 0:40	0.4	0.34
12/28/2007 0:45	-1.06	-0.91
12/28/2007 0:50	-1.06	-0.91
12/28/2007 0:55	-0.86	-0.69
12/28/2007 1:00	-0.96	-0.81
12/28/2007 1:05	-0.76	-0.69
12/28/2007 1:10	-0.86	-0.69
12/28/2007 1:15	-0.86	-0.58
12/28/2007 1:20	-0.76	-0.69
12/28/2007 1:25	-0.67	-0.48
12/28/2007 1:30	-0.56	-0.58
12/28/2007 1:35	-0.86	-0.58
12/28/2007 1:40	-0.76	-0.69
12/28/2007 1:45	-0.67	-0.58
12/28/2007 1:50	-0.67	-0.58
12/28/2007 1:55	-0.46	-0.26
12/28/2007 2:00	-0.36	-0.15
12/28/2007 2:05	-0.67	-0.37
12/28/2007 2:10	-0.46	-0.15
12/28/2007 2:15	-0.26	-0.15
12/28/2007 2:20	-0.46	-0.15

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/24/2007 0:00	0.55	0.51
10/24/2007 0:05	0.01	0.31
10/24/2007 0:10	0.01	0.41
10/24/2007 0:15	0.26	0.41
10/24/2007 0:20	-0.26	0.12
10/24/2007 0:25	0.01	0.31
10/24/2007 0:30	-0.26	0.12
10/24/2007 0:35	0.01	0.21
10/24/2007 0:40	0.01	0.31
10/24/2007 0:45	0.26	0.31
10/24/2007 0:50	0.26	0.31
10/24/2007 0:55	-0.26	0.12
10/24/2007 1:00	0.26	0.12
10/24/2007 1:05	-0.54	0.12
10/24/2007 1:10	0.01	0.12
10/24/2007 1:15	-0.26	0.12
10/24/2007 1:20	0.01	0.01
10/24/2007 1:25	0.01	0.12
10/24/2007 1:30	-0.26	0.12
10/24/2007 1:35	-0.26	0.12
10/24/2007 1:40	-0.26	0.21
10/24/2007 1:45	0.01	0.21
10/24/2007 1:50	0.26	0.01
10/24/2007 1:55	0.26	0.12
10/24/2007 2:00	0.82	0.41
10/24/2007 2:05	0.82	0.31
10/24/2007 2:10	-0.26	0.12
10/24/2007 2:15	-0.54	-0.09
10/24/2007 2:20	2.91	0.96

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/28/2007 2:25	-0.46	-0.48
12/28/2007 2:30	-0.67	-0.37
12/28/2007 2:35	-0.56	-0.37
12/28/2007 2:40	-0.56	-0.26
12/28/2007 2:45	-0.67	-0.37
12/28/2007 2:50	-0.56	-0.37
12/28/2007 2:55	-0.76	-0.37
12/28/2007 3:00	-0.56	-0.15
12/28/2007 3:05	-0.36	-0.37
12/28/2007 3:10	-0.36	-0.26
12/28/2007 3:15	-0.46	-0.26
12/28/2007 3:20	-0.36	-0.15
12/28/2007 3:25	-0.36	-0.26
12/28/2007 3:30	-0.46	-0.04
12/28/2007 3:35	-0.36	0.06
12/28/2007 3:40	-0.15	-0.15
12/28/2007 3:45	-0.26	-0.15
12/28/2007 3:50	-0.36	-0.26
12/28/2007 3:55	-0.15	-0.26
12/28/2007 4:00	-0.46	-0.26
12/28/2007 4:05	-0.56	-0.37
12/28/2007 4:10	-0.56	-0.15
12/28/2007 4:15	-0.46	-0.15
12/28/2007 4:20	-0.36	-0.04
12/28/2007 4:25	-0.46	-0.26
12/28/2007 4:30	-0.46	-0.37
12/28/2007 4:35	-0.56	-0.26
12/28/2007 4:40	-0.46	-0.26
12/28/2007 4:45	-0.46	-0.37

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/24/2007 2:25	2.39	1.07
10/24/2007 2:30	2.14	0.96
10/24/2007 2:35	1.86	0.96
10/24/2007 2:40	1.59	1.07
10/24/2007 2:45	1.59	0.96
10/24/2007 2:50	1.86	0.87
10/24/2007 2:55	1.59	0.96
10/24/2007 3:00	2.14	1.07
10/24/2007 3:05	-1.59	-0.19
10/24/2007 3:10	2.14	1.17
10/24/2007 3:15	-1.06	-0.19
10/24/2007 3:20	-0.79	-0.09
10/24/2007 3:25	-0.79	-0.29
10/24/2007 3:30	-1.06	-0.19
10/24/2007 3:35	-0.54	-0.19
10/24/2007 3:40	-0.79	-0.19
10/24/2007 3:45	-0.54	0.01
10/24/2007 3:50	0.01	0.01
10/24/2007 3:55	0.01	-0.09
10/24/2007 4:00	-0.54	-0.19
10/24/2007 4:05	-0.26	-0.09
10/24/2007 4:10	0.01	0.01
10/24/2007 4:15	-0.26	0.01
10/24/2007 4:20	-0.26	0.01
10/24/2007 4:25	-0.26	0.12
10/24/2007 4:30	0.82	0.12
10/24/2007 4:35	0.82	0.21
10/24/2007 4:40	0.26	0.31
10/24/2007 4:45	0.82	0.21

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/28/2007 4:50	-0.46	-0.26
12/28/2007 4:55	-0.46	-0.37
12/28/2007 5:00	-0.67	-0.37
12/28/2007 5:05	-0.36	-0.26
12/28/2007 5:10	-0.46	-0.26
12/28/2007 5:15	-0.56	-0.26
12/28/2007 5:20	-0.56	-0.04
12/28/2007 5:25	-0.46	-0.37
12/28/2007 5:30	-0.56	-0.26
12/28/2007 5:35	-0.67	-0.48
12/28/2007 5:40	-0.67	-0.26
12/28/2007 5:45	-0.46	-0.37
12/28/2007 5:50	-0.56	-0.26
12/28/2007 5:55	-0.46	-0.26
12/28/2007 6:00	-0.36	-0.26
12/28/2007 6:05	-0.56	-0.37
12/28/2007 6:10	-0.46	-0.15
12/28/2007 6:15	-0.46	-0.26
12/28/2007 6:20	-0.56	-0.26
12/28/2007 6:25	-0.56	-0.26
12/28/2007 6:30	-0.46	-0.15
12/28/2007 6:35	-0.47	-0.15
12/28/2007 6:40	-0.46	-0.15
12/28/2007 6:45	-0.37	-0.15
12/28/2007 6:50	-0.06	0.06
12/28/2007 6:55	-0.15	0.06
12/28/2007 7:00	-0.17	0.17
12/28/2007 7:05	-0.17	0.17
12/28/2007 7:10	-0.17	0.17

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/24/2007 4:50	0.55	0.31
10/24/2007 4:55	0.26	0.41
10/24/2007 5:00	0.55	0.31
10/24/2007 5:05	0.55	0.21
10/24/2007 5:10	0.26	0.31
10/24/2007 5:15	0.82	0.31
10/24/2007 5:20	0.26	0.12
10/24/2007 5:25	0.55	0.31
10/24/2007 5:30	0.82	0.51
10/24/2007 5:35	0.82	0.51
10/24/2007 5:40	1.07	0.51
10/24/2007 5:45	1.62	0.72
10/24/2007 5:50	2.14	0.92
10/24/2007 5:55	2.14	1.01
10/24/2007 6:00	-1.58	-0.35
10/24/2007 6:05	2.39	0.92
10/24/2007 6:10	-1.32	-0.35
10/24/2007 6:15	-1.32	-0.24
10/24/2007 6:20	-1.07	-0.35
10/24/2007 6:25	-1.07	-0.24
10/24/2007 6:30	-1.32	-0.14
10/24/2007 6:35	-0.78	-0.14
10/24/2007 6:40	-0.78	-0.04
10/24/2007 6:45	-0.51	-0.14
10/24/2007 6:50	-0.78	0.06
10/24/2007 6:55	-0.78	-0.14
10/24/2007 7:00	-1.32	-0.24
10/24/2007 7:05	-0.78	-0.24
10/24/2007 7:10	-1.07	-0.35

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/28/2007 7:15	-0.27	-0.04
12/28/2007 7:20	-0.17	-0.04
12/28/2007 7:25	-0.27	-0.15
12/28/2007 7:30	-0.27	-0.04
12/28/2007 7:35	-0.47	-0.37
12/28/2007 7:40	-0.56	-0.26
12/28/2007 7:45	-0.56	-0.58
12/28/2007 7:50	-0.67	-0.58
12/28/2007 7:55	-0.37	-0.26
12/28/2007 8:00	-0.56	-0.48
12/28/2007 8:05	-0.67	-0.37
12/28/2007 8:10	-0.67	-0.37
12/28/2007 8:15	-0.37	-0.26
12/28/2007 8:20	-0.17	-0.04
12/28/2007 8:25	-0.17	-0.04
12/28/2007 8:30	-0.17	-0.04
12/28/2007 8:35	-0.17	0.06
12/28/2007 8:40	0.13	0.17
12/28/2007 8:45	0.03	0.17
12/28/2007 8:50	-0.17	-0.15
12/28/2007 8:55	-0.06	-0.15
12/28/2007 9:00	-0.06	-0.04
12/28/2007 9:05	-0.17	-0.04
12/28/2007 9:10	0.03	0.06
12/28/2007 9:15	0.03	-0.04
12/28/2007 9:20	-0.06	0.06
12/28/2007 9:25	0.03	0.28
12/28/2007 9:30	0.13	0.28
12/28/2007 9:35	0.03	0.06

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/24/2007 7:15	-0.51	0.06
10/24/2007 7:20	-0.51	0.16
10/24/2007 7:25	-0.51	0.06
10/24/2007 7:30	-0.26	0.16
10/24/2007 7:35	-0.51	-0.04
10/24/2007 7:40	-0.78	0.06
10/24/2007 7:45	-0.26	-0.04
10/24/2007 7:50	0.29	0.06
10/24/2007 7:55	-0.26	-0.04
10/24/2007 8:00	0.29	0.26
10/24/2007 8:05	-0.26	0.26
10/24/2007 8:10	-0.51	-0.14
10/24/2007 8:15	-0.26	0.16
10/24/2007 8:20	0.02	0.06
10/24/2007 8:25	0.29	0.37
10/24/2007 8:30	0.81	0.46
10/24/2007 8:35	0.81	0.37
10/24/2007 8:40	0.81	0.87
10/24/2007 8:45	1.10	0.66
10/24/2007 8:50	1.35	0.66
10/24/2007 8:55	1.90	0.76
10/24/2007 9:00	1.61	0.76
10/24/2007 9:05	2.15	0.97
10/24/2007 9:10	-1.55	-0.49
10/24/2007 9:15	1.90	0.97
10/24/2007 9:20	-1.55	-0.49
10/24/2007 9:25	-1.30	-0.39
10/24/2007 9:30	-1.55	-0.49
10/24/2007 9:35	-1.55	-0.49

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/28/2007 9:40	0.13	0.06
12/28/2007 9:45	0.13	0.28
12/28/2007 9:50	0.03	0.28
12/28/2007 9:55	0.13	0.39
12/28/2007 10:00	0.34	0.49
12/28/2007 10:05	-0.92	-0.65
12/28/2007 10:10	-0.73	-0.65
12/28/2007 10:15	-1.02	-0.76
12/28/2007 10:20	-0.82	-0.65
12/28/2007 10:25	-0.73	-0.44
12/28/2007 10:30	-0.63	-0.32
12/28/2007 10:35	0.54	0.6
12/28/2007 10:40	0.13	0.49
12/28/2007 10:45	0.23	0.39
12/28/2007 10:50	-1.02	-0.76
12/28/2007 10:55	-1.13	-0.97
12/28/2007 11:00	0.44	0.49
12/28/2007 11:05	0.44	0.6
12/28/2007 11:10	0.23	0.49
12/28/2007 11:15	0.23	0.49
12/28/2007 11:20	0.13	0.28
12/28/2007 11:25	0.13	0.06
12/28/2007 11:30	-0.06	0.06
12/28/2007 11:35	-0.17	-0.04
12/28/2007 11:40	-0.17	-0.04
12/28/2007 11:45	-0.47	-0.48
12/28/2007 11:50	-0.47	-0.58
12/28/2007 11:55	-0.67	-0.58
12/28/2007 12:00	-0.67	-0.69

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/24/2007 9:40	-1.55	-0.39
10/24/2007 9:45	-1.30	-0.60
10/24/2007 9:50	1.61	0.87
10/24/2007 9:55	1.61	0.66
10/24/2007 10:00	1.90	0.76
10/24/2007 10:05	1.61	0.76
10/24/2007 10:10	-1.55	-0.60
10/24/2007 10:15	-1.55	-0.49
10/24/2007 10:20	2.15	0.76
10/24/2007 10:25	2.15	0.76
10/24/2007 10:30	2.15	0.87
10/24/2007 10:35	1.61	0.76
10/24/2007 10:40	-1.55	-0.80
10/24/2007 10:45	1.90	0.76
10/24/2007 10:50	2.67	1.07
10/24/2007 10:55	2.95	1.17
10/24/2007 11:00	-1.30	-0.80
10/24/2007 11:05	1.90	0.46
10/24/2007 11:10	2.42	0.66
10/24/2007 11:15	1.90	0.56
10/24/2007 11:20	1.35	0.46
10/24/2007 11:25	1.61	0.26
10/24/2007 11:30	2.15	0.26
10/24/2007 11:35	1.61	0.46
10/24/2007 11:40	1.35	0.37
10/24/2007 11:45	1.90	0.37
10/24/2007 11:50	1.61	0.46
10/24/2007 11:55	1.61	0.46
10/24/2007 12:00	1.61	0.46

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/28/2007 12:05	-0.77	-0.58
12/28/2007 12:10	0.69	0.67
12/28/2007 12:15	0.39	0.55
12/28/2007 12:20	0.39	0.34
12/28/2007 12:25	0.19	0.34
12/28/2007 12:30	0.19	0.34
12/28/2007 12:35	-0.01	0.24
12/28/2007 12:40	0.19	0.34
12/28/2007 12:45	-0.11	0.12
12/28/2007 12:50	0.09	0.12
12/28/2007 12:55	0.19	0.24
12/28/2007 13:00	0.09	0.12
12/28/2007 13:05	-0.01	0.12
12/28/2007 13:10	0.45	0.73
12/28/2007 13:15	0.25	0.19
12/28/2007 13:20	-0.71	-0.53
12/28/2007 13:25	-0.81	-0.31
12/28/2007 13:30	-0.61	-0.42
12/28/2007 13:35	-0.51	-0.3
12/28/2007 13:40	-0.61	-0.42
12/28/2007 13:45	-0.41	-0.31
12/28/2007 13:50	-0.71	-0.53
12/28/2007 13:55	-0.61	-0.42
12/28/2007 14:00	-0.61	-0.63
12/28/2007 14:05	-0.41	-0.31
12/28/2007 14:10	0.55	0.84
12/28/2007 14:15	0.35	0.63
12/28/2007 14:20	0.45	0.63
12/28/2007 14:25	0.15	0.4

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/24/2007 12:05	1.61	0.37
10/24/2007 12:10	1.35	0.37
10/24/2007 12:15	1.10	0.26
10/24/2007 12:20	0.81	0.16
10/24/2007 12:25	1.35	0.37
10/24/2007 12:30	1.35	0.56
10/24/2007 12:35	1.35	0.37
10/24/2007 12:40	1.90	0.46
10/24/2007 12:45	1.90	0.56
10/24/2007 12:50	1.90	0.56
10/24/2007 12:55	2.15	0.66
10/24/2007 13:00	2.15	0.66
10/24/2007 13:05	1.61	0.46
10/24/2007 13:10	1.10	0.16
10/24/2007 13:15	14.67	1.77
10/24/2007 13:20	25.56	1.47
10/24/2007 13:25	20.51	1.26
10/24/2007 13:30	12.54	-0.14
10/24/2007 13:35	3.74	-0.24
10/24/2007 13:40	0.29	0.06
10/24/2007 13:45	-0.51	-0.24
10/24/2007 13:50	2.39	1.01
10/24/2007 13:55	-1.32	-1.05
10/24/2007 14:00	-1.07	-1.15
10/24/2007 14:05	-0.26	-0.54
10/24/2007 14:10	-0.51	-1.24
10/24/2007 14:15	23.70	1.77
10/24/2007 14:20	38.60	1.67
10/24/2007 14:25	29.81	0.56

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/28/2007 14:30	-0.04	0.19
12/28/2007 14:35	0.05	0.19
12/28/2007 14:40	0.15	0.29
12/28/2007 14:45	0.64	0.62
12/28/2007 14:50	0.05	0.3
12/28/2007 14:55	-0.15	0.3
12/28/2007 15:00	0.15	0.29
12/28/2007 15:05	0.25	0.62
12/28/2007 15:10	0.55	0.83
12/28/2007 15:15	0.35	0.83
12/28/2007 15:20	0.25	0.4
12/28/2007 15:25	0.05	0.51
12/28/2007 15:30	-0.15	0.62
12/28/2007 15:35	-0.15	0.4
12/28/2007 15:40	1.14	0.4
12/28/2007 15:45	10.27	0.4
12/28/2007 15:50	15.59	0.29
12/28/2007 15:55	19.21	0.19
12/28/2007 16:00	22.33	-0.14
12/28/2007 16:05	25.34	0.08
12/28/2007 16:10	27.56	0.08
12/28/2007 16:15	28.87	-0.03
12/28/2007 16:20	30.68	4.09
12/28/2007 16:25	31.69	9.27
12/28/2007 16:30	32.29	12.62
12/28/2007 16:35	32.99	15.87
12/28/2007 16:40	33.2	17.93
12/28/2007 16:45	33.91	20.41
12/28/2007 16:50	33.92	21.61

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/24/2007 14:30	21.81	-1.35
10/24/2007 14:35	16.47	-1.35
10/24/2007 14:40	20.44	-0.19
10/24/2007 14:45	11.13	-1.15
10/24/2007 14:50	1.33	-1.55
10/24/2007 14:55	2.10	-0.19
10/24/2007 15:00	1.85	0.62
10/24/2007 15:05	1.85	-0.14
10/24/2007 15:10	11.70	-0.44
10/24/2007 15:15	7.96	0.92
10/24/2007 15:20	1.58	0.82
10/24/2007 15:25	2.39	0.92
10/24/2007 15:30	2.14	1.01
10/24/2007 15:35	2.39	1.01
10/24/2007 15:40	1.33	0.82
10/24/2007 15:45	2.14	0.82
10/24/2007 15:50	-1.58	-0.44
10/24/2007 15:55	2.14	0.92
10/24/2007 16:00	2.14	0.82
10/24/2007 16:05	1.62	0.72
10/24/2007 16:10	1.33	0.82
10/24/2007 16:15	1.33	0.62
10/24/2007 16:20	1.33	0.62
10/24/2007 16:25	1.33	0.72
10/24/2007 16:30	1.33	0.82
10/24/2007 16:35	1.07	0.72
10/24/2007 16:40	-1.58	-0.44
10/24/2007 16:45	-1.07	-0.24
10/24/2007 16:50	-1.07	-0.35

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/28/2007 16:55	34.62	23.22
12/28/2007 17:00	35.13	24.85
12/28/2007 17:05	36.14	26.91
12/28/2007 17:10	36.64	28.74
12/28/2007 17:15	37.25	30.36
12/28/2007 17:20	37.55	32.1
12/28/2007 17:25	37.75	33.73
12/28/2007 17:30	37.96	35.24
12/28/2007 17:35	38.07	36.74
12/28/2007 17:40	38.07	38.05
12/28/2007 17:45	38.27	39.23
12/28/2007 17:50	37.88	39.77
12/28/2007 17:55	37.88	39.99
12/28/2007 18:00	37.78	40.31
12/28/2007 18:05	37.59	39.99
12/28/2007 18:10	37.39	39.77
12/28/2007 18:15	36.99	39.54
12/28/2007 18:20	36.4	38.89
12/28/2007 18:25	36	38.46
12/28/2007 18:30	35.5	38.14
12/28/2007 18:35	36.16	39.05
12/28/2007 18:40	34.69	37.26
12/28/2007 18:45	34.5	37.26
12/28/2007 18:50	34.31	37.04
12/28/2007 18:55	34.2	36.93
12/28/2007 19:00	33.81	36.81
12/28/2007 19:05	33.31	36.38
12/28/2007 19:10	34.17	37.31
12/28/2007 19:15	32.21	35.63

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/24/2007 16:55	-0.51	-0.14
10/24/2007 17:00	-0.78	-0.14
10/24/2007 17:05	-1.07	-0.35
10/24/2007 17:10	-0.78	-0.24
10/24/2007 17:15	-0.78	-0.04
10/24/2007 17:20	-0.78	-0.04
10/24/2007 17:25	0.02	0.26
10/24/2007 17:30	-0.26	-0.04
10/24/2007 17:35	-0.26	0.06
10/24/2007 17:40	-0.51	-0.14
10/24/2007 17:45	-0.51	-0.04
10/24/2007 17:50	-0.51	-0.04
10/24/2007 17:55	0.29	0.06
10/24/2007 18:00	1.10	0.56
10/24/2007 18:05	1.61	0.76
10/24/2007 18:10	-0.79	-0.39
10/24/2007 18:15	-0.23	-0.29
10/24/2007 18:20	-0.79	-0.49
10/24/2007 18:25	-0.79	-0.39
10/24/2007 18:30	-1.04	-0.39
10/24/2007 18:35	-0.50	-0.39
10/24/2007 18:40	-0.50	-0.29
10/24/2007 18:45	29.30	1.52
10/24/2007 18:50	42.07	1.42
10/24/2007 18:55	32.52	0.51
10/24/2007 19:00	18.18	-1.30
10/24/2007 19:05	6.73	-0.99
10/24/2007 19:10	-0.16	-0.49
10/24/2007 19:15	-0.16	-0.29

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/28/2007 19:20	32.76	36.65
12/28/2007 19:25	32.16	35.78
12/28/2007 19:30	31.36	35.02
12/28/2007 19:35	30.65	34.27
12/28/2007 19:40	30.35	33.73
12/28/2007 19:45	29.85	33.18
12/28/2007 19:50	29.26	32.53
12/28/2007 19:55	28.36	31.77
12/28/2007 20:00	27.95	31.23
12/28/2007 20:05	27.46	30.79
12/28/2007 20:10	26.86	29.93
12/28/2007 20:15	26.45	29.38
12/28/2007 20:20	25.86	28.95
12/28/2007 20:25	25.45	28.08
12/28/2007 20:30	24.76	27.64
12/28/2007 20:35	24.26	26.56
12/28/2007 20:40	23.74	25.92
12/28/2007 20:45	23.15	25.26
12/28/2007 20:50	22.65	24.72
12/28/2007 20:55	22.25	24.51
12/28/2007 21:00	21.75	23.74
12/28/2007 21:05	21.04	23.2
12/28/2007 21:10	20.24	22.66
12/28/2007 21:15	20.7	23.38
12/28/2007 21:20	20.3	22.93
12/28/2007 21:25	19.7	22.28
12/28/2007 21:30	19.19	21.86
12/28/2007 21:35	18.4	21.21
12/28/2007 21:40	17.9	20.67

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/24/2007 19:20	-0.66	-0.39
10/24/2007 19:25	7.37	0.31
10/24/2007 19:30	28.75	1.93
10/24/2007 19:35	25.09	1.53
10/24/2007 19:40	13.93	0.32
10/24/2007 19:45	0.37	-1.74
10/24/2007 19:50	-1.76	-0.44
10/24/2007 19:55	-0.67	-0.23
10/24/2007 20:00	-0.67	-1.04
10/24/2007 20:05	-1.19	-1.23
10/24/2007 20:10	15.60	1.09
10/24/2007 20:15	32.96	1.48
10/24/2007 20:20	27.40	1.09
10/24/2007 20:25	22.37	0.47
10/24/2007 20:30	23.46	1.53
10/24/2007 20:35	13.89	-0.22
10/24/2007 20:40	5.12	-1.03
10/24/2007 20:45	-1.26	-1.13
10/24/2007 20:50	-1.53	-0.82
10/24/2007 20:55	-1.53	-1.03
10/24/2007 21:00	-0.72	0.07
10/24/2007 21:05	0.08	0.17
10/24/2007 21:10	0.08	-0.33
10/24/2007 21:15	0.60	-0.33
10/24/2007 21:20	0.89	0.39
10/24/2007 21:25	0.89	0.29
10/24/2007 21:30	5.14	0.48
10/24/2007 21:35	19.80	1.59
10/24/2007 21:40	23.26	2.00

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/28/2007 21:45	17.38	20.23
12/28/2007 21:50	16.79	19.69
12/28/2007 21:55	16.18	19.37
12/28/2007 22:00	15.99	18.94
12/28/2007 22:05	15.58	18.4
12/28/2007 22:10	15.08	17.96
12/28/2007 22:15	14.49	17.86
12/28/2007 22:20	14.09	17.43
12/28/2007 22:25	13.39	16.68
12/28/2007 22:30	13.07	16.35
12/28/2007 22:35	12.67	16.02
12/28/2007 22:40	13.43	16.84
12/28/2007 22:45	11.78	15.37
12/28/2007 22:50	12.84	16.09
12/28/2007 22:55	11.27	14.62
12/28/2007 23:00	11.08	14.5
12/28/2007 23:05	10.67	14.19
12/28/2007 23:10	11.73	15.1
12/28/2007 23:15	11.33	14.68
12/28/2007 23:20	11.13	14.58
12/28/2007 23:25	10.83	14.24
12/28/2007 23:30	10.43	13.81
12/28/2007 23:35	10.13	13.6
12/28/2007 23:40	9.93	13.37
12/28/2007 23:45	9.62	13.16
12/28/2007 23:50	9.43	12.94
12/28/2007 23:55	9.22	12.51
12/29/2007 0:00	8.72	12.19
12/29/2007 0:05	8.41	12.19

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/24/2007 21:45	19.03	1.60
10/24/2007 21:50	12.10	1.30
10/24/2007 21:55	3.87	0.39
10/24/2007 22:00	-0.11	-0.52
10/24/2007 22:05	-0.11	-0.72
10/24/2007 22:10	-0.40	-0.31
10/24/2007 22:15	-0.40	-0.42
10/24/2007 22:20	-0.67	-0.01
10/24/2007 22:25	-0.67	0.19
10/24/2007 22:30	0.14	-0.31
10/24/2007 22:35	-0.40	-0.42
10/24/2007 22:40	0.14	-0.61
10/24/2007 22:45	-0.11	-0.71
10/24/2007 22:50	-0.11	-0.51
10/24/2007 22:55	-0.15	-0.61
10/24/2007 23:00	-0.15	-0.21
10/24/2007 23:05	-0.95	-0.21
10/24/2007 23:10	-0.15	-0.01
10/24/2007 23:15	0.92	0.40
10/24/2007 23:20	0.92	0.49
10/24/2007 23:25	0.89	0.40
10/24/2007 23:30	1.15	0.30
10/24/2007 23:35	1.40	0.30
10/24/2007 23:40	1.15	0.40
10/24/2007 23:45	1.15	0.40
10/24/2007 23:50	1.67	0.50
10/24/2007 23:55	1.64	0.30
10/25/2007 0:00	0.58	0.19
10/25/2007 0:05	0.58	0.19

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/29/2007 0:10	8.22	11.64
12/29/2007 0:15	8.02	11.43
12/29/2007 0:20	7.82	11
12/29/2007 0:25	7.32	10.88
12/29/2007 0:30	7.11	10.79
12/29/2007 0:35	7.11	10.56
12/29/2007 0:40	7.01	10.34
12/29/2007 0:45	6.71	10.13
12/29/2007 0:50	6.51	10.13
12/29/2007 0:55	6.11	9.91
12/29/2007 1:00	5.9	9.58
12/29/2007 1:05	5.51	9.04
12/29/2007 1:10	5.01	8.82
12/29/2007 1:15	5.01	8.71
12/29/2007 1:20	4.81	8.5
12/29/2007 1:25	4.6	8.5
12/29/2007 1:30	4.29	8.28
12/29/2007 1:35	5.46	9.32
12/29/2007 1:40	4.1	7.73
12/29/2007 1:45	5.06	8.98
12/29/2007 1:50	5.06	8.76
12/29/2007 1:55	4.86	8.76
12/29/2007 2:00	4.56	8.55
12/29/2007 2:05	4.45	8.34
12/29/2007 2:10	2.99	6.98
12/29/2007 2:15	2.89	6.98
12/29/2007 2:20	3.95	7.79
12/29/2007 2:25	3.45	7.46
12/29/2007 2:30	3.35	7.13

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/25/2007 0:10	0.83	0.30
10/25/2007 0:15	0.83	0.19
10/25/2007 0:20	0.83	0.10
10/25/2007 0:25	0.81	0.19
10/25/2007 0:30	1.10	0.10
10/25/2007 0:35	1.10	0.10
10/25/2007 0:40	1.10	0.00
10/25/2007 0:45	1.10	0.10
10/25/2007 0:50	22.14	1.80
10/25/2007 0:55	23.74	2.01
10/25/2007 1:00	18.17	2.22
10/25/2007 1:05	9.39	1.31
10/25/2007 1:10	1.72	0.60
10/25/2007 1:15	0.37	0.00
10/25/2007 1:20	1.17	-0.90
10/25/2007 1:25	25.99	1.21
10/25/2007 1:30	35.08	2.11
10/25/2007 1:35	34.35	1.80
10/25/2007 1:40	27.98	1.41
10/25/2007 1:45	17.89	0.60
10/25/2007 1:50	8.05	-0.40
10/25/2007 1:55	0.35	0.00
10/25/2007 2:00	0.89	0.10
10/25/2007 2:05	0.35	0.10
10/25/2007 2:10	0.92	0.00
10/25/2007 2:15	0.64	-0.40
10/25/2007 2:20	0.12	-0.30
10/25/2007 2:25	0.92	-0.29
10/25/2007 2:30	0.64	-0.49

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/29/2007 2:35	3.25	7.25
12/29/2007 2:40	2.19	6.22
12/29/2007 2:45	3.25	7.46
12/29/2007 2:50	1.89	6
12/29/2007 2:55	1.89	5.77
12/29/2007 3:00	2	5.99
12/29/2007 3:05	1.69	5.77
12/29/2007 3:10	1.38	5.66
12/29/2007 3:15	2.74	6.81
12/29/2007 3:20	1.48	5.34
12/29/2007 3:25	1.28	5.34
12/29/2007 3:30	2.74	6.7
12/29/2007 3:35	2.55	6.37
12/29/2007 3:40	2.34	6.49
12/29/2007 3:45	2.05	5.83
12/29/2007 3:50	1.74	5.83
12/29/2007 3:55	1.93	5.93
12/29/2007 4:00	2.03	5.72
12/29/2007 4:05	0.67	4.47
12/29/2007 4:10	0.78	4.57
12/29/2007 4:15	0.67	4.36
12/29/2007 4:20	0.47	4.14
12/29/2007 4:25	0.47	4.14
12/29/2007 4:30	0.37	4.03
12/29/2007 4:35	0.17	3.82
12/29/2007 4:40	0.37	3.92
12/29/2007 4:45	0.47	4.03
12/29/2007 4:50	0.28	3.71
12/29/2007 4:55	0.28	3.49

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/25/2007 2:35	0.92	-0.60
10/25/2007 2:40	1.17	0.41
10/25/2007 2:45	0.92	0.10
10/25/2007 2:50	1.17	0.21
10/25/2007 2:55	0.37	0.21
10/25/2007 3:00	1.40	0.31
10/25/2007 3:05	1.40	0.21
10/25/2007 3:10	1.67	0.22
10/25/2007 3:15	1.67	0.51
10/25/2007 3:20	-1.50	-0.64
10/25/2007 3:25	-1.01	-0.64
10/25/2007 3:30	-1.01	-0.44
10/25/2007 3:35	-1.01	-0.54
10/25/2007 3:40	-0.21	-0.64
10/25/2007 3:45	-0.75	-0.64
10/25/2007 3:50	-1.01	-0.64
10/25/2007 3:55	-0.78	-0.64
10/25/2007 4:00	-0.51	-0.34
10/25/2007 4:05	-0.51	-0.44
10/25/2007 4:10	-0.23	-0.34
10/25/2007 4:15	-0.23	-0.34
10/25/2007 4:20	-0.80	-0.24
10/25/2007 4:25	-0.80	-0.24
10/25/2007 4:30	-0.55	-0.24
10/25/2007 4:35	0.52	-0.13
10/25/2007 4:40	0.25	-0.24
10/25/2007 4:45	0.00	-0.13
10/25/2007 4:50	0.24	-0.13
10/25/2007 4:55	0.24	-0.13

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/29/2007 5:00	0.28	3.38
12/29/2007 5:05	0.17	3.16
12/29/2007 5:10	0.37	3.59
12/29/2007 5:15	0.47	3.49
12/29/2007 5:20	0.56	3.49
12/29/2007 5:25	0.47	3.48
12/29/2007 5:30	0.47	3.27
12/29/2007 5:35	0.37	2.84
12/29/2007 5:40	0.47	2.84
12/29/2007 5:45	0.67	3.05
12/29/2007 5:50	0.77	3.05
12/29/2007 5:55	0.97	3.16
12/29/2007 6:00	0.67	2.94
12/29/2007 6:05	0.87	2.94
12/29/2007 6:10	0.97	2.73
12/29/2007 6:15	0.97	2.73
12/29/2007 6:20	0.87	2.73
12/29/2007 6:25	0.87	2.51
12/29/2007 6:30	0.67	2.4
12/29/2007 6:35	0.87	2.51
12/29/2007 6:40	0.66	2.51
12/29/2007 6:45	0.76	2.4
12/29/2007 6:50	0.76	2.3
12/29/2007 6:55	0.76	2.3
12/29/2007 7:00	0.96	2.3
12/29/2007 7:05	0.86	2.3
12/29/2007 7:10	0.96	2.19
12/29/2007 7:15	0.76	2.08
12/29/2007 7:20	0.86	2.08

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/25/2007 5:00	-0.03	-0.24
10/25/2007 5:05	0.49	-0.24
10/25/2007 5:10	0.49	-0.13
10/25/2007 5:15	0.24	-0.03
10/25/2007 5:20	1.04	-0.13
10/25/2007 5:25	0.72	-0.13
10/25/2007 5:30	0.72	-0.03
10/25/2007 5:35	0.47	-0.13
10/25/2007 5:40	0.47	-0.03
10/25/2007 5:45	0.20	-0.03
10/25/2007 5:50	0.72	0.26
10/25/2007 5:55	1.27	0.17
10/25/2007 6:00	1.79	0.47
10/25/2007 6:05	1.77	0.47
10/25/2007 6:10	1.77	0.57
10/25/2007 6:15	1.25	0.26
10/25/2007 6:20	1.50	0.57
10/25/2007 6:25	-2.20	-0.89
10/25/2007 6:30	-1.41	-0.79
10/25/2007 6:35	-1.68	-0.79
10/25/2007 6:40	-1.15	-0.69
10/25/2007 6:45	-0.90	-0.69
10/25/2007 6:50	-0.38	-0.58
10/25/2007 6:55	-0.65	-0.58
10/25/2007 7:00	-0.91	-0.58
10/25/2007 7:05	-0.65	-0.38
10/25/2007 7:10	-0.38	-0.38
10/25/2007 7:15	0.14	-0.08
10/25/2007 7:20	0.69	-0.08

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/29/2007 7:25	0.86	1.86
12/29/2007 7:30	0.86	1.97
12/29/2007 7:35	1.07	1.97
12/29/2007 7:40	-0.19	0.72
12/29/2007 7:45	-0.19	0.61
12/29/2007 7:50	-0.29	0.61
12/29/2007 7:55	-0.1	0.72
12/29/2007 8:00	-0.1	0.6
12/29/2007 8:05	-0.4	0.29
12/29/2007 8:10	-0.19	0.39
12/29/2007 8:15	-0.1	0.17
12/29/2007 8:20	0	0.5
12/29/2007 8:25	0.09	0.29
12/29/2007 8:30	-0.2	0.39
12/29/2007 8:35	0.95	1.42
12/29/2007 8:40	-0.1	0.06
12/29/2007 8:45	-0.01	0.29
12/29/2007 8:50	-0.01	0.29
12/29/2007 8:55	0.09	0.17
12/29/2007 9:00	0.09	0.06
12/29/2007 9:05	0.09	0.06
12/29/2007 9:10	-0.01	0.06
12/29/2007 9:15	0.09	-0.15
12/29/2007 9:20	0.09	-0.15
12/29/2007 9:25	0.3	-0.04
12/29/2007 9:30	0.19	-0.04
12/29/2007 9:35	0.5	0.06
12/29/2007 9:40	0.5	0.29
12/29/2007 9:45	0.3	-0.04

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/25/2007 7:25	0.69	-0.08
10/25/2007 7:30	0.69	0.01
10/25/2007 7:35	1.21	0.12
10/25/2007 7:40	-2.24	-1.04
10/25/2007 7:45	1.46	0.12
10/25/2007 7:50	1.19	0.22
10/25/2007 7:55	1.44	0.12
10/25/2007 8:00	1.19	0.01
10/25/2007 8:05	0.93	0.01
10/25/2007 8:10	0.66	-0.19
10/25/2007 8:15	0.39	-0.19
10/25/2007 8:20	0.66	-0.29
10/25/2007 8:25	0.66	-0.08
10/25/2007 8:30	0.93	0.01
10/25/2007 8:35	1.19	0.22
10/25/2007 8:40	1.44	0.22
10/25/2007 8:45	1.19	0.12
10/25/2007 8:50	-2.01	-1.14
10/25/2007 8:55	-0.67	-0.64
10/25/2007 9:00	0.08	-0.23
10/25/2007 9:05	0.08	-0.33
10/25/2007 9:10	0.37	-0.13
10/25/2007 9:15	0.88	-0.23
10/25/2007 9:20	1.17	-0.04
10/25/2007 9:25	2.24	0.17
10/25/2007 9:30	1.44	-0.04
10/25/2007 9:35	2.49	0.27
10/25/2007 9:40	1.96	0.07
10/25/2007 9:45	0.63	0.07

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/29/2007 9:50	0.4	-0.04
12/29/2007 9:55	0.3	0.06
12/29/2007 10:00	0.59	0.06
12/29/2007 10:05	0.59	0.17
12/29/2007 10:10	0.69	0.5
12/29/2007 10:15	0.8	0.39
12/29/2007 10:20	0.69	0.29
12/29/2007 10:25	0.9	0.17
12/29/2007 10:30	0.9	0.29
12/29/2007 10:35	0.9	0.29
12/29/2007 10:40	0.69	-0.04
12/29/2007 10:45	0.78	0.29
12/29/2007 10:50	0.89	0.29
12/29/2007 10:55	0.78	0.29
12/29/2007 11:00	0.99	0.29
12/29/2007 11:05	0.89	0.39
12/29/2007 11:10	0.89	0.39
12/29/2007 11:15	0.69	0.29
12/29/2007 11:20	0.49	0.06
12/29/2007 11:25	0.39	-0.15
12/29/2007 11:30	0.59	-0.26
12/29/2007 11:35	0.49	-0.04
12/29/2007 11:40	0.39	-0.26
12/29/2007 11:45	0.19	-0.58
12/29/2007 11:50	0.19	-0.48
12/29/2007 11:55	0.19	-0.48
12/29/2007 12:00	-0.01	-0.69
12/29/2007 12:05	0.09	-0.37
12/29/2007 12:10	0.19	-0.48

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/25/2007 9:50	1.17	0.17
10/25/2007 9:55	1.44	0.27
10/25/2007 10:00	21.92	0.27
10/25/2007 10:05	54.46	2.18
10/25/2007 10:10	46.51	1.88
10/25/2007 10:15	31.68	-1.09
10/25/2007 10:20	23.19	0.37
10/25/2007 10:25	12.30	0.27
10/25/2007 10:30	2.99	-0.33
10/25/2007 10:35	1.72	-0.63
10/25/2007 10:40	-1.96	-1.49
10/25/2007 10:45	-1.39	-1.98
10/25/2007 10:50	23.94	1.00
10/25/2007 10:55	35.75	0.94
10/25/2007 11:00	33.43	0.85
10/25/2007 11:05	30.03	1.70
10/25/2007 11:10	16.22	-0.56
10/25/2007 11:15	7.18	-1.26
10/25/2007 11:20	2.92	0.39
10/25/2007 11:25	-1.57	-0.86
10/25/2007 11:30	-2.36	-0.97
10/25/2007 11:35	-0.73	-0.56
10/25/2007 11:40	-1.53	-1.06
10/25/2007 11:45	-1.53	-0.96
10/25/2007 11:50	-0.98	-0.66
10/25/2007 11:55	-1.53	-0.86
10/25/2007 12:00	-1.25	-0.65
10/25/2007 12:05	-0.98	-0.65
10/25/2007 12:10	-0.46	-0.76

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/29/2007 12:15	-0.31	-0.69
12/29/2007 12:20	-0.31	-1.02
12/29/2007 12:25	1.05	0.56
12/29/2007 12:30	1.05	0.45
12/29/2007 12:35	1.05	0.45
12/29/2007 12:40	1.05	0.56
12/29/2007 12:45	0.95	0.34
12/29/2007 12:50	0.85	0.24
12/29/2007 12:55	0.85	0.24
12/29/2007 13:00	0.85	0.34
12/29/2007 13:05	0.95	0.34
12/29/2007 13:10	0.95	0.24
12/29/2007 13:15	0.95	0.34
12/29/2007 13:20	0.75	0.13
12/29/2007 13:25	0.75	0.02
12/29/2007 13:30	0.65	0.02
12/29/2007 13:35	0.95	0.13
12/29/2007 13:40	0.85	-0.09
12/29/2007 13:45	0.65	0.02
12/29/2007 13:50	0.65	-0.09
12/29/2007 13:55	0.65	0.02
12/29/2007 14:00	0.65	0.02
12/29/2007 14:05	0.44	-0.3
12/29/2007 14:10	0.35	-0.09
12/29/2007 14:15	0.35	-0.3
12/29/2007 14:20	0.55	-0.3
12/29/2007 14:25	0.24	-0.19
12/29/2007 14:30	0.34	-0.3
12/29/2007 14:35	0.14	-0.52

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/25/2007 12:15	-0.73	-0.76
10/25/2007 12:20	-0.18	-0.86
10/25/2007 12:25	-0.46	-0.65
10/25/2007 12:30	0.07	-0.96
10/25/2007 12:35	-0.46	-1.06
10/25/2007 12:40	-0.75	-0.96
10/25/2007 12:45	-1.02	-0.96
10/25/2007 12:50	-0.75	-1.05
10/25/2007 12:55	-0.75	-0.95
10/25/2007 13:00	2.17	0.41
10/25/2007 13:05	1.88	0.41
10/25/2007 13:10	-1.57	-0.95
10/25/2007 13:15	-1.57	-0.76
10/25/2007 13:20	-1.32	-0.85
10/25/2007 13:25	-0.53	-0.65
10/25/2007 13:30	-0.28	-0.55
10/25/2007 13:35	-0.28	-0.65
10/25/2007 13:40	-1.09	-0.76
10/25/2007 13:45	-0.85	-0.65
10/25/2007 13:50	-0.30	-0.55
10/25/2007 13:55	-0.05	-0.24
10/25/2007 14:00	-0.30	-0.55
10/25/2007 14:05	-0.87	-0.65
10/25/2007 14:10	-0.87	-0.85
10/25/2007 14:15	-1.39	-0.85
10/25/2007 14:20	-0.87	-0.65
10/25/2007 14:25	-0.34	-0.65
10/25/2007 14:30	-0.64	-0.65
10/25/2007 14:35	-0.64	-0.65

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/29/2007 14:40	0.04	-0.62
12/29/2007 14:45	1.2	0.73
12/29/2007 14:50	0.99	0.52
12/29/2007 14:55	0.99	0.52
12/29/2007 15:00	1.1	0.4
12/29/2007 15:05	1.2	0.52
12/29/2007 15:10	1.3	0.63
12/29/2007 15:15	-0.06	-0.52
12/29/2007 15:20	0.14	-0.62
12/29/2007 15:25	-0.06	-0.52
12/29/2007 15:30	-0.06	-0.41
12/29/2007 15:35	0.24	-0.52
12/29/2007 15:40	0.14	-0.19
12/29/2007 15:45	0.14	-0.41
12/29/2007 15:50	0.34	-0.19
12/29/2007 15:55	0.24	-0.3
12/29/2007 16:00	0.34	-0.19
12/29/2007 16:05	0.44	-0.19
12/29/2007 16:10	0.34	-0.19
12/29/2007 16:15	0.44	-0.19
12/29/2007 16:20	0.55	-0.19
12/29/2007 16:25	0.64	0.02
12/29/2007 16:30	0.74	0.13
12/29/2007 16:35	0.84	0.24
12/29/2007 16:40	0.94	0.45
12/29/2007 16:45	0.94	0.45
12/29/2007 16:50	1.05	0.68
12/29/2007 16:55	-0.02	-0.58
12/29/2007 17:00	0.08	-0.68

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/25/2007 14:40	-0.64	-0.55
10/25/2007 14:45	-1.16	-0.76
10/25/2007 14:50	-0.35	-0.76
10/25/2007 14:55	-0.68	-0.85
10/25/2007 15:00	-0.93	-0.95
10/25/2007 15:05	-1.19	-0.76
10/25/2007 15:10	-0.68	-0.45
10/25/2007 15:15	0.40	-0.45
10/25/2007 15:20	0.91	-0.04
10/25/2007 15:25	0.91	-0.14
10/25/2007 15:30	0.36	-0.45
10/25/2007 15:35	-0.44	-0.55
10/25/2007 15:40	-0.69	-0.55
10/25/2007 15:45	0.34	-0.65
10/25/2007 15:50	0.07	-0.24
10/25/2007 15:55	0.59	-0.34
10/25/2007 16:00	0.59	-0.34
10/25/2007 16:05	0.88	-0.24
10/25/2007 16:10	0.88	-0.14
10/25/2007 16:15	0.59	-0.24
10/25/2007 16:20	1.15	-0.04
10/25/2007 16:25	0.88	-0.24
10/25/2007 16:30	0.59	-0.34
10/25/2007 16:35	0.34	-0.24
10/25/2007 16:40	-0.46	-0.55
10/25/2007 16:45	-0.46	-0.65
10/25/2007 16:50	-0.98	-0.85
10/25/2007 16:55	-1.27	-0.65
10/25/2007 17:00	-0.46	-0.45

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/29/2007 17:05	-0.02	-0.37
12/29/2007 17:10	0.28	-0.25
12/29/2007 17:15	0.28	-0.25
12/29/2007 17:20	0.38	-0.14
12/29/2007 17:25	0.48	-0.04
12/29/2007 17:30	0.58	0.18
12/29/2007 17:35	0.78	0.18
12/29/2007 17:40	0.87	0.18
12/29/2007 17:45	0.78	0.18
12/29/2007 17:50	0.78	0.18
12/29/2007 17:55	0.69	0.18
12/29/2007 18:00	0.78	0.18
12/29/2007 18:05	0.58	0.29
12/29/2007 18:10	0.69	0.18
12/29/2007 18:15	0.78	0.4
12/29/2007 18:20	0.58	0.4
12/29/2007 18:25	0.69	0.29
12/29/2007 18:30	0.58	0.4
12/29/2007 18:35	0.69	0.4
12/29/2007 18:40	0.78	0.29
12/29/2007 18:45	0.78	0.4
12/29/2007 18:50	0.78	0.5
12/29/2007 18:55	0.87	0.5
12/29/2007 19:00	0.98	0.5
12/29/2007 19:05	0.98	0.5
12/29/2007 19:10	0.87	0.5
12/29/2007 19:15	0.87	0.5
12/29/2007 19:20	0.87	0.61
12/29/2007 19:25	0.98	0.61

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/25/2007 17:05	0.34	-0.24
10/25/2007 17:10	0.34	0.46
10/25/2007 17:15	0.82	0.46
10/25/2007 17:20	-2.08	-0.59
10/25/2007 17:25	-1.27	-0.30
10/25/2007 17:30	1.63	1.16
10/25/2007 17:35	-1.56	-0.40
10/25/2007 17:40	-1.83	-0.40
10/25/2007 17:45	2.18	1.16
10/25/2007 17:50	0.82	0.86
10/25/2007 17:55	0.81	0.77
10/25/2007 18:00	1.09	0.66
10/25/2007 18:05	-2.36	-0.59
10/25/2007 18:10	-1.31	-0.30
10/25/2007 18:15	-1.04	-0.30
10/25/2007 18:20	-0.79	0.01
10/25/2007 18:25	-0.24	-0.09
10/25/2007 18:30	-0.79	-0.20
10/25/2007 18:35	-0.52	0.01
10/25/2007 18:40	-0.56	0.01
10/25/2007 18:45	0.00	0.11
10/25/2007 18:50	0.25	0.11
10/25/2007 18:55	0.00	-0.30
10/25/2007 19:00	-0.56	-0.20
10/25/2007 19:05	-0.56	-0.20
10/25/2007 19:10	-0.81	0.11
10/25/2007 19:15	0.25	0.21
10/25/2007 19:20	0.75	0.41
10/25/2007 19:25	0.75	0.30

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/29/2007 19:30	0.98	0.5
12/29/2007 19:35	0.87	0.5
12/29/2007 19:40	0.98	0.5
12/29/2007 19:45	-0.48	-0.64
12/29/2007 19:50	1.07	0.72
12/29/2007 19:55	0.98	0.5
12/29/2007 20:00	0.98	0.72
12/29/2007 20:05	-0.29	-0.42
12/29/2007 20:10	-0.38	-0.53
12/29/2007 20:15	-0.48	-0.64
12/29/2007 20:20	-0.29	-0.64
12/29/2007 20:25	-0.29	-0.53
12/29/2007 20:30	-0.29	-0.53
12/29/2007 20:35	-0.29	-0.64
12/29/2007 20:40	-0.19	-0.53
12/29/2007 20:45	-0.19	-0.75
12/29/2007 20:50	-0.29	-0.53
12/29/2007 20:55	-0.38	-0.53
12/29/2007 21:00	-0.19	-0.42
12/29/2007 21:05	0.01	-0.42
12/29/2007 21:10	-0.19	-0.31
12/29/2007 21:15	-0.19	-0.31
12/29/2007 21:20	-0.08	-0.31
12/29/2007 21:25	-0.08	-0.31
12/29/2007 21:30	0.12	-0.19
12/29/2007 21:35	0.12	-0.1
12/29/2007 21:40	-0.08	-0.1
12/29/2007 21:45	0.12	-0.1
12/29/2007 21:50	0.21	-0.1

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/25/2007 19:30	1.03	0.51
10/25/2007 19:35	0.48	0.30
10/25/2007 19:40	1.28	0.51
10/25/2007 19:45	1.84	0.71
10/25/2007 19:50	1.84	0.61
10/25/2007 19:55	1.55	0.61
10/25/2007 20:00	32.43	0.91
10/25/2007 20:05	60.91	2.92
10/25/2007 20:10	54.34	2.22
10/25/2007 20:15	64.05	2.93
10/25/2007 20:20	75.64	7.70
10/25/2007 20:25	57.61	4.81
10/25/2007 20:30	42.96	0.39
10/25/2007 20:35	30.77	0.39
10/25/2007 20:40	20.41	0.20
10/25/2007 20:45	13.51	0.01
10/25/2007 20:50	3.20	-1.15
10/25/2007 20:55	-1.31	-1.75
10/25/2007 21:00	-0.98	-0.95
10/25/2007 21:05	49.40	1.37
10/25/2007 21:10	49.44	1.06
10/25/2007 21:15	38.54	-1.25
10/25/2007 21:20	25.53	-0.85
10/25/2007 21:25	14.67	-0.75
10/25/2007 21:30	5.10	-0.75
10/25/2007 21:35	-0.74	-0.55
10/25/2007 21:40	-1.26	-0.45
10/25/2007 21:45	-0.46	-1.15
10/25/2007 21:50	-0.74	-0.45

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/29/2007 21:55	0.01	-0.19
12/29/2007 22:00	-0.08	-0.19
12/29/2007 22:05	0.01	-0.19
12/29/2007 22:10	0.01	-0.19
12/29/2007 22:15	-0.08	-0.19
12/29/2007 22:20	-0.08	-0.31
12/29/2007 22:25	0.12	-0.19
12/29/2007 22:30	0.12	-0.42
12/29/2007 22:35	-0.19	-0.19
12/29/2007 22:40	0.01	-0.31
12/29/2007 22:45	-0.08	-0.31
12/29/2007 22:50	0.01	-0.19
12/29/2007 22:55	0.01	-0.1
12/29/2007 23:00	0.01	-0.31
12/29/2007 23:05	0.01	-0.31
12/29/2007 23:10	-0.08	-0.42
12/29/2007 23:15	-0.19	-0.52
12/29/2007 23:20	-0.1	-0.52
12/29/2007 23:25	0.01	-0.42
12/29/2007 23:30	0.01	-0.42
12/29/2007 23:35	0.01	-0.31
12/29/2007 23:40	0.01	-0.31
12/29/2007 23:45	0.01	-0.31
12/29/2007 23:50	0.01	-0.19
12/29/2007 23:55	-0.29	-0.64
12/30/2007 0:00	-0.1	-0.42
12/30/2007 0:05	-0.29	-0.85
12/30/2007 0:10	-0.19	-0.74
12/30/2007 0:15	-0.29	-0.85

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/25/2007 21:55	-0.74	-0.14
10/25/2007 22:00	-0.42	-0.14
10/25/2007 22:05	-0.98	-0.85
10/25/2007 22:10	-0.98	-0.95
10/25/2007 22:15	0.10	-0.05
10/25/2007 22:20	-0.42	-0.15
10/25/2007 22:25	-0.42	-0.45
10/25/2007 22:30	-0.74	-0.25
10/25/2007 22:35	-0.46	-0.25
10/25/2007 22:40	-0.46	-0.15
10/25/2007 22:45	0.06	-0.25
10/25/2007 22:50	0.06	-0.06
10/25/2007 22:55	-0.46	-0.36
10/25/2007 23:00	-0.46	-0.15
10/25/2007 23:05	-0.76	-0.25
10/25/2007 23:10	-0.76	-0.56
10/25/2007 23:15	-0.51	-0.56
10/25/2007 23:20	-0.23	-0.56
10/25/2007 23:25	-0.76	-0.36
10/25/2007 23:30	-0.53	-0.47
10/25/2007 23:35	-0.53	-0.36
10/25/2007 23:40	-0.24	-0.36
10/25/2007 23:45	0.27	-0.16
10/25/2007 23:50	-0.01	-0.26
10/25/2007 23:55	-0.01	-0.26
10/26/2007 0:00	0.24	-0.16
10/26/2007 0:05	0.24	-0.16
10/26/2007 0:10	1.04	-0.36
10/26/2007 0:15	0.74	-0.36

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/30/2007 0:20	0.97	0.62
12/30/2007 0:25	-0.39	-0.64
12/30/2007 0:30	-0.19	-0.74
12/30/2007 0:35	-0.39	-0.64
12/30/2007 0:40	-0.39	-0.74
12/30/2007 0:45	-0.39	-0.85
12/30/2007 0:50	1.07	0.51
12/30/2007 0:55	0.87	0.51
12/30/2007 1:00	0.97	0.62
12/30/2007 1:05	0.87	0.62
12/30/2007 1:10	0.87	0.51
12/30/2007 1:15	0.76	0.72
12/30/2007 1:20	0.76	0.51
12/30/2007 1:25	0.97	0.62
12/30/2007 1:30	0.87	0.51
12/30/2007 1:35	0.97	0.84
12/30/2007 1:40	0.87	0.52
12/30/2007 1:45	-0.39	-0.74
12/30/2007 1:50	0.87	0.62
12/30/2007 1:55	-0.39	-0.64
12/30/2007 2:00	1.07	0.62
12/30/2007 2:05	0.97	0.52
12/30/2007 2:10	-0.19	-0.62
12/30/2007 2:15	-0.29	-0.74
12/30/2007 2:20	-0.39	-0.62
12/30/2007 2:25	-0.29	-0.52
12/30/2007 2:30	-0.29	-0.52
12/30/2007 2:35	-0.39	-0.41
12/30/2007 2:40	-0.39	-0.62

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/26/2007 0:20	1.02	-0.26
10/26/2007 0:25	1.54	-0.36
10/26/2007 0:30	0.47	-0.26
10/26/2007 0:35	1.02	-0.36
10/26/2007 0:40	1.51	-0.36
10/26/2007 0:45	1.51	-0.36
10/26/2007 0:50	1.26	-0.36
10/26/2007 0:55	0.97	-0.47
10/26/2007 1:00	1.20	-0.36
10/26/2007 1:05	0.94	-0.47
10/26/2007 1:10	1.20	-0.38
10/26/2007 1:15	0.94	-0.57
10/26/2007 1:20	0.69	-0.57
10/26/2007 1:25	0.67	-0.57
10/26/2007 1:30	0.67	-0.67
10/26/2007 1:35	0.92	-0.47
10/26/2007 1:40	0.67	-0.47
10/26/2007 1:45	0.11	-0.57
10/26/2007 1:50	0.67	-0.57
10/26/2007 1:55	0.90	-0.47
10/26/2007 2:00	0.10	-0.47
10/26/2007 2:05	0.63	-0.47
10/26/2007 2:10	0.35	-0.47
10/26/2007 2:15	0.35	-0.27
10/26/2007 2:20	0.86	-0.58
10/26/2007 2:25	1.13	-0.38
10/26/2007 2:30	1.38	-0.27
10/26/2007 2:35	1.38	-0.47
10/26/2007 2:40	2.45	0.33

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/30/2007 2:45	-0.49	-0.62
12/30/2007 2:50	0.87	0.74
12/30/2007 2:55	0.87	0.74
12/30/2007 3:00	0.76	0.52
12/30/2007 3:05	0.76	0.62
12/30/2007 3:10	0.87	0.62
12/30/2007 3:15	0.97	0.74
12/30/2007 3:20	0.87	0.52
12/30/2007 3:25	0.57	0.41
12/30/2007 3:30	0.57	0.29
12/30/2007 3:35	0.66	0.2
12/30/2007 3:40	0.97	0.29
12/30/2007 3:45	0.66	0.41
12/30/2007 3:50	0.47	0.2
12/30/2007 3:55	0.66	0.08
12/30/2007 4:00	0.57	0.2
12/30/2007 4:05	0.57	-0.02
12/30/2007 4:10	0.26	-0.13
12/30/2007 4:15	0.26	-0.35
12/30/2007 4:20	0.37	-0.24
12/30/2007 4:25	0.47	0.08
12/30/2007 4:30	0.47	-0.02
12/30/2007 4:35	0.26	-0.02
12/30/2007 4:40	0.47	-0.13
12/30/2007 4:45	0.46	0.08
12/30/2007 4:50	0.76	0.29
12/30/2007 4:55	0.96	0.52
12/30/2007 5:00	0.76	0.52
12/30/2007 5:05	0.85	0.41

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/26/2007 2:45	1.65	0.43
10/26/2007 2:50	0.81	0.23
10/26/2007 2:55	26.10	0.02
10/26/2007 3:00	82.76	3.85
10/26/2007 3:05	76.42	7.72
10/26/2007 3:10	67.10	6.94
10/26/2007 3:15	77.90	8.85
10/26/2007 3:20	58.24	4.13
10/26/2007 3:25	42.85	-0.81
10/26/2007 3:30	31.97	-0.49
10/26/2007 3:35	28.04	-1.09
10/26/2007 3:40	30.49	-0.29
10/26/2007 3:45	32.15	0.02
10/26/2007 3:50	31.12	-0.07
10/26/2007 3:55	29.56	-0.27
10/26/2007 4:00	28.24	-0.38
10/26/2007 4:05	25.87	-0.68
10/26/2007 4:10	31.47	-0.08
10/26/2007 4:15	34.67	0.43
10/26/2007 4:20	30.44	-0.29
10/26/2007 4:25	21.92	-0.18
10/26/2007 4:30	14.49	-1.18
10/26/2007 4:35	9.99	-1.09
10/26/2007 4:40	12.92	-0.69
10/26/2007 4:45	22.47	0.12
10/26/2007 4:50	30.71	1.52
10/26/2007 4:55	32.31	1.83
10/26/2007 5:00	30.71	1.73
10/26/2007 5:05	27.78	0.92

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/30/2007 5:10	0.76	0.29
12/30/2007 5:15	0.66	0.29
12/30/2007 5:20	0.26	0.08
12/30/2007 5:25	0.76	0.29
12/30/2007 5:30	0.96	0.62
12/30/2007 5:35	0.85	0.41
12/30/2007 5:40	0.46	0.08
12/30/2007 5:45	0.26	-0.02
12/30/2007 5:50	0.06	-0.24
12/30/2007 5:55	0.35	0.08
12/30/2007 6:00	0.46	0.08
12/30/2007 6:05	0.56	0.29
12/30/2007 6:10	0.56	0.08
12/30/2007 6:15	0.35	-0.24
12/30/2007 6:20	0.06	-0.13
12/30/2007 6:25	0.06	-0.13
12/30/2007 6:30	-0.14	-0.46
12/30/2007 6:35	-0.04	-0.23
12/30/2007 6:40	-0.04	-0.44
12/30/2007 6:45	-0.33	-0.77
12/30/2007 6:50	-0.14	-0.35
12/30/2007 6:55	0.06	-0.23
12/30/2007 7:00	0.06	-0.23
12/30/2007 7:05	-0.04	-0.23
12/30/2007 7:10	-0.14	-0.44
12/30/2007 7:15	-0.14	-0.44
12/30/2007 7:20	0.06	-0.35
12/30/2007 7:25	0.26	-0.23
12/30/2007 7:30	0.06	-0.35

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/26/2007 5:10	22.72	0.22
10/26/2007 5:15	17.44	-0.50
10/26/2007 5:20	13.17	-1.20
10/26/2007 5:25	9.99	-1.51
10/26/2007 5:30	7.35	-0.39
10/26/2007 5:35	2.52	-0.29
10/26/2007 5:40	-0.65	-0.30
10/26/2007 5:45	-0.65	-0.40
10/26/2007 5:50	-0.65	-0.30
10/26/2007 5:55	-0.37	-0.40
10/26/2007 6:00	0.15	-0.20
10/26/2007 6:05	-0.65	-0.40
10/26/2007 6:10	-0.14	-0.20
10/26/2007 6:15	0.38	-0.30
10/26/2007 6:20	0.11	-0.61
10/26/2007 6:25	0.11	-0.71
10/26/2007 6:30	-0.14	-0.81
10/26/2007 6:35	0.38	-0.71
10/26/2007 6:40	0.10	-0.71
10/26/2007 6:45	0.35	-0.71
10/26/2007 6:50	0.10	-0.71
10/26/2007 6:55	0.86	-0.81
10/26/2007 7:00	0.35	-0.11
10/26/2007 7:05	0.85	-0.11
10/26/2007 7:10	0.33	-0.11
10/26/2007 7:15	0.58	0.00
10/26/2007 7:20	-0.23	-0.11
10/26/2007 7:25	0.04	-0.11
10/26/2007 7:30	0.58	-0.11

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/30/2007 7:35	0.16	-0.12
12/30/2007 7:40	0.16	-0.12
12/30/2007 7:45	0.46	0.2
12/30/2007 7:50	0.26	0.09
12/30/2007 7:55	0.06	-0.12
12/30/2007 8:00	-0.33	-0.35
12/30/2007 8:05	-0.33	-0.44
12/30/2007 8:10	-0.33	-0.66
12/30/2007 8:15	-0.44	-0.66
12/30/2007 8:20	0.62	0.47
12/30/2007 8:25	0.92	0.26
12/30/2007 8:30	1.03	0.58
12/30/2007 8:35	0.82	0.37
12/30/2007 8:40	-0.54	-0.89
12/30/2007 8:45	-0.14	-0.56
12/30/2007 8:50	-0.33	-0.77
12/30/2007 8:55	-0.24	-0.56
12/30/2007 9:00	-0.24	-0.56
12/30/2007 9:05	0.06	-0.56
12/30/2007 9:10	0.06	-0.23
12/30/2007 9:15	0.16	-0.23
12/30/2007 9:20	0.26	-0.02
12/30/2007 9:25	0.35	-0.02
12/30/2007 9:30	0.06	-0.23
12/30/2007 9:35	0.26	-0.23
12/30/2007 9:40	-0.04	-0.44
12/30/2007 9:45	1.22	0.58
12/30/2007 9:50	-0.14	-0.66
12/30/2007 9:55	-0.04	-0.56

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/26/2007 7:35	0.27	-0.11
10/26/2007 7:40	0.27	-0.31
10/26/2007 7:45	0.56	-0.11
10/26/2007 7:50	0.56	-0.21
10/26/2007 7:55	0.56	-0.31
10/26/2007 8:00	0.79	-0.41
10/26/2007 8:05	0.79	-0.21
10/26/2007 8:10	0.79	-0.43
10/26/2007 8:15	1.04	-0.32
10/26/2007 8:20	1.60	-0.43
10/26/2007 8:25	2.08	-0.32
10/26/2007 8:30	2.60	-0.22
10/26/2007 8:35	2.35	-0.22
10/26/2007 8:40	1.83	0.38
10/26/2007 8:45	1.83	0.38
10/26/2007 8:50	2.31	0.38
10/26/2007 8:55	2.31	0.59
10/26/2007 9:00	0.99	0.69
10/26/2007 9:05	-2.20	-0.77
10/26/2007 9:10	-1.14	-0.88
10/26/2007 9:15	-0.36	-0.98
10/26/2007 9:20	8.72	-0.77
10/26/2007 9:25	6.02	0.03
10/26/2007 9:30	1.21	0.84
10/26/2007 9:35	-0.64	0.84
10/26/2007 9:40	-0.64	0.93
10/26/2007 9:45	2.29	2.09
10/26/2007 9:50	1.99	1.79
10/26/2007 9:55	1.47	1.79

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Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
12/30/2007 10:00	-0.04	-0.23
12/30/2007 10:05	-0.14	-0.56
12/30/2007 10:10	1.03	0.58
12/30/2007 10:15	1.03	0.7
12/30/2007 10:20	0.05	-0.35
12/30/2007 10:25	0.05	-0.23
12/30/2007 10:30	0.35	-0.02
12/30/2007 10:35	0.35	-0.02
12/30/2007 10:40	0.05	-0.23
12/30/2007 10:45	0.35	0.09
12/30/2007 10:50	0.35	0.2
12/30/2007 10:55	0.15	-0.12
12/30/2007 11:00	0.26	0.31
12/30/2007 11:05	0.76	0.52
12/30/2007 11:10	-0.4	-0.62
12/30/2007 11:15	0.76	0.63
12/30/2007 11:20	0.35	0.09
12/30/2007 11:25	-0.14	-0.23
12/30/2007 11:30	-0.24	-0.44
12/30/2007 11:35	-0.24	-0.44
12/30/2007 11:40	-0.35	-0.44
12/30/2007 11:45	0.62	0.6
12/30/2007 11:50	0.41	0.16
12/30/2007 11:55	0.41	0.16
12/30/2007 12:00	0.01	-0.17

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/26/2007 10:00	17.42	1.89
10/26/2007 10:05	25.12	1.99
10/26/2007 10:10	17.94	1.59
10/26/2007 10:15	9.44	1.29
10/26/2007 10:20	2.77	0.88
10/26/2007 10:25	0.17	0.28
10/26/2007 10:30	0.42	-0.33
10/26/2007 10:35	-0.37	-0.93
10/26/2007 10:40	-0.12	-0.13
10/26/2007 10:45	-0.89	-0.43
10/26/2007 10:50	-0.89	-0.23
10/26/2007 10:55	0.17	-0.02
10/26/2007 11:00	0.97	0.37
10/26/2007 11:05	1.74	0.57
10/26/2007 11:10	-1.71	-0.89
10/26/2007 11:15	-1.46	-0.89
10/26/2007 11:20	-1.46	-0.79
10/26/2007 11:25	-1.46	-0.79
10/26/2007 11:30	1.47	0.37
10/26/2007 11:35	1.47	0.28
10/26/2007 11:40	1.20	0.18
10/26/2007 11:45	0.67	0.28
10/26/2007 11:50	1.47	0.37
10/26/2007 11:55	1.15	0.18
10/26/2007 12:00	1.15	0.28
10/26/2007 12:05	1.70	0.37
10/26/2007 12:10	1.44	0.27
10/26/2007 12:15	1.15	0.37
10/26/2007 12:20	0.63	0.27

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/26/2007 12:25	0.90	0.27
10/26/2007 12:30	0.33	0.16
10/26/2007 12:35	0.33	0.27
10/26/2007 12:40	0.06	0.37
10/26/2007 12:45	0.06	0.27
10/26/2007 12:50	0.33	0.47
10/26/2007 12:55	0.33	0.37
10/26/2007 13:00	0.61	0.37
10/26/2007 13:05	0.58	0.37
10/26/2007 13:10	0.58	0.27
10/26/2007 13:15	0.58	0.16
10/26/2007 13:20	0.29	0.27
10/26/2007 13:25	-0.51	0.27
10/26/2007 13:30	2.17	1.52
10/26/2007 13:35	1.89	1.52
10/26/2007 13:40	1.37	1.52
10/26/2007 13:45	2.41	1.52
10/26/2007 13:50	2.12	1.52
10/26/2007 13:55	2.41	1.52
10/26/2007 14:00	1.60	1.63
10/26/2007 14:05	1.85	1.43
10/26/2007 14:10	1.05	1.63
10/26/2007 14:15	1.05	1.52
10/26/2007 14:20	0.53	1.12
10/26/2007 14:25	0.51	1.02
10/26/2007 14:30	-0.04	1.02
10/26/2007 14:35	0.51	1.02
10/26/2007 14:40	-0.04	1.22
10/26/2007 14:45	3.41	2.68

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/26/2007 14:50	-0.29	0.72
10/26/2007 14:55	0.23	0.91
10/26/2007 15:00	0.51	0.72
10/26/2007 15:05	0.51	0.91
10/26/2007 15:10	-0.06	0.82
10/26/2007 15:15	-0.06	0.91
10/26/2007 15:20	-0.06	0.72
10/26/2007 15:25	-0.31	0.82
10/26/2007 15:30	-0.06	0.82
10/26/2007 15:35	-0.31	0.82
10/26/2007 15:40	-0.31	0.72
10/26/2007 15:45	-0.06	0.72
10/26/2007 15:50	-0.06	0.91
10/26/2007 15:55	-0.06	0.91
10/26/2007 16:00	-0.06	0.91
10/26/2007 16:05	-0.34	0.71
10/26/2007 16:10	-0.08	0.81
10/26/2007 16:15	-0.08	0.81
10/26/2007 16:20	-0.08	0.71
10/26/2007 16:25	-0.34	0.61
10/26/2007 16:30	2.31	1.86
10/26/2007 16:35	2.82	1.86
10/26/2007 16:40	2.57	1.77
10/26/2007 16:45	2.82	1.86
10/26/2007 16:50	-0.63	0.51
10/26/2007 16:55	-0.88	0.51
10/26/2007 17:00	-1.17	0.51
10/26/2007 17:05	-0.92	0.61
10/26/2007 17:10	-0.65	0.51

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/26/2007 17:15	-0.40	0.51
10/26/2007 17:20	-0.92	0.41
10/26/2007 17:25	2.54	1.77
10/26/2007 17:30	2.54	1.77
10/26/2007 17:35	2.29	1.77
10/26/2007 17:40	2.00	1.67
10/26/2007 17:45	1.73	1.67
10/26/2007 17:50	2.54	1.86
10/26/2007 17:55	2.23	1.67
10/26/2007 18:00	1.97	1.77
10/26/2007 18:05	1.45	1.86
10/26/2007 18:10	1.72	1.86
10/26/2007 18:15	1.72	1.86
10/26/2007 18:20	1.45	1.97
10/26/2007 18:25	1.72	1.77
10/26/2007 18:30	1.45	1.77
10/26/2007 18:35	1.97	1.66
10/26/2007 18:40	1.97	1.66
10/26/2007 18:45	1.45	1.66
10/26/2007 18:50	1.45	1.56
10/26/2007 18:55	1.45	1.56
10/26/2007 19:00	1.97	1.56
10/26/2007 19:05	1.72	1.66
10/26/2007 19:10	1.68	1.56
10/26/2007 19:15	2.75	1.56
10/26/2007 19:20	2.48	1.56
10/26/2007 19:25	-0.45	0.20
10/26/2007 19:30	-0.97	0.20
10/26/2007 19:35	2.48	1.56

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/26/2007 19:40	2.75	1.66
10/26/2007 19:45	2.48	1.56
10/26/2007 19:50	1.68	1.56
10/26/2007 19:55	1.68	1.66
10/26/2007 20:00	1.95	1.66
10/26/2007 20:05	1.95	1.86
10/26/2007 20:10	1.68	1.77
10/26/2007 20:15	1.68	1.66
10/26/2007 20:20	1.40	1.66
10/26/2007 20:25	1.66	1.56
10/26/2007 20:30	1.91	1.46
10/26/2007 20:35	1.66	1.66
10/26/2007 20:40	1.66	1.56
10/26/2007 20:45	2.18	1.46
10/26/2007 20:50	1.66	1.56
10/26/2007 20:55	1.91	1.56
10/26/2007 21:00	1.66	1.46
10/26/2007 21:05	2.18	1.56
10/26/2007 21:10	1.91	1.56
10/26/2007 21:15	1.91	1.56
10/26/2007 21:20	1.38	1.36
10/26/2007 21:25	2.18	1.46
10/26/2007 21:30	1.66	1.66
10/26/2007 21:35	1.91	1.66
10/26/2007 21:40	2.18	1.56
10/26/2007 21:45	1.66	1.66
10/26/2007 21:50	1.61	1.56
10/26/2007 21:55	1.90	1.56
10/26/2007 22:00	2.15	1.66

Date/Time	Uphill Piezometer Water Level (cm)	Downhill Piezometer Water Level (cm)
10/26/2007 22:05	1.34	1.56
10/26/2007 22:10	1.90	1.56
10/26/2007 22:15	1.90	1.56
10/26/2007 22:20	1.61	1.46
10/26/2007 22:25	2.15	1.46
10/26/2007 22:30	2.15	1.36
10/26/2007 22:35	1.90	1.46
10/26/2007 22:40	1.90	1.36
10/26/2007 22:45	1.90	1.46
10/26/2007 22:50	2.15	1.46
10/26/2007 22:55	1.90	1.36
10/26/2007 23:00	2.15	1.56
10/26/2007 23:05	1.90	1.46
10/26/2007 23:10	2.15	1.36
10/26/2007 23:15	1.84	1.36
10/26/2007 23:20	2.65	1.36
10/26/2007 23:25	2.13	1.56
10/26/2007 23:30	1.59	1.46
10/26/2007 23:35	1.84	1.36
10/26/2007 23:40	1.84	1.36
10/26/2007 23:45	1.59	1.46
10/26/2007 23:50	1.07	1.36
10/26/2007 23:55	1.59	1.25