Performance and Feasibility Study of Vegetated Roadsides as a Low-Impact-Development Practice for Linear Transportation Systems

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ABSTRACT

Water quality improvement, constituent mass transport mitigation, and hydraulic performance of vegetated roadsides were evaluated over 16 storm events for two vegetated roadside strips along Lorton Road, Fairfax County, Virginia. Automated, flow-weighted sampling practices were employed to develop composite samples and event mean concentrations representative of an entire storm event. Lorton Road and two vegetated roadside strips were monitored for flow rate and volume to determine hydraulic performance, as well as thermal monitoring of the runoff to determine thermal load mitigation. Collected samples were analyzed for 13 water quality constituents: total suspended solids, total nitrogen, nitrates, phosphate, oil and grease, chemical oxygen demand, total coliform bacteria, *E. coli*, cadmium, chromium, copper, lead, and zinc. Varying vegetation management practices were employed at each vegetated strip to determine the impact of vegetation management on vegetated roadside performance. The managed and unmanaged vegetated strips achieved a mean peak flow reduction of 76.3% and 89.5%, respectively, while achieving a mean total flow reduction of 80.7% and 87.3%, respectively. The relatively high degree of stormwater infiltration allowed for moderate to high mass loading mitigation for each of the 13 water quality constituents monitored. A Sign test analysis of the constituent mass load data revealed that the effluent of both vegetated strips were statistically lower than the Lorton Road runoff for all 13 constituents and both hydraulic parameters. Thermal load was substantially reduced in both the managed and unmanaged vegetated strip effluent. The unmanaged vegetated strip effluent had statistically lower peak flows and mass loads of total nitrogen, phosphate, copper, and zinc compared to the managed vegetated strip.

Keywords: Low Impact Development, Vegetated Roadsides, Highway Runoff, Stormwater Monitoring, Stormwater Quality, Vegetation Management

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Contents

1.0 INTRODUCTION

Concerns regarding highway stormwater runoff quality have steadily increased over recent years as more roads are built or widened, and the impervious surface areas of watersheds increases. In addition, increased vehicle miles traveled on highways potentially provide additional load source of pollutants to highway surfaces, with potential for further decreasing water runoff quality. According to the National Cooperative Highway Research Program, the prevention or mitigation of discharge of pollutants from highways has become a primary goal from many jurisdictions, including state departments of transportation (NCHRP 2006).

To mitigate the effects of highway runoff on receiving waters, low impact development (LID) stormwater management systems are being employed as a de-centralized, hydraulic and non-point-source control alternative to centralized best management practices (BMPs) treatment. The U. S. Environmental Protection Agency describes low impact development strategies as site design strategy with the goal of maintaining or replicating the pre-development hydrologic regime through the use of design techniques to create a functionally equivalent hydrologic landscape. Hydrologic functions of storage, infiltration, and groundwater recharge, as well as the volume and frequency of discharges are maintained through the use of integrated and distributed micro-scale stormwater retention and detention areas, reduction of impervious surfaces, and the lengthening of flow paths and runoff time (U. S. EPA 2000 and Coffman 2000). By means of infiltration, evapotranspiration, and reuse of water LID techniques manage water and water pollutants at the source and thereby reduce the impact of development on rivers, lakes, streams, coastal waters, and groundwater (U. S. EPA 2007).

The use of vegetated roadsides as a viable LID practice would allow state transportation departments an additional cost-effective stormwater management practice to better protect receiving streams. The results of this vegetated roadside study provide data essential to determining the stormwater mitigation performance potential of vegetated roadsides which were not designed for stormwater management. It is necessary to understand the performance of LID systems above and beyond the performance of vegetated roadsides in order to properly evaluate the feasibility and value of constructing, operating, and maintaining LID systems. If vegetated roadsides show performance comparable to engineered LID systems, the feasibility, value, and performance of LID systems above and beyond that of existing vegetated roadsides may be diminished. Similarly, the feasibility of incorporating vegetated roadsides as an accepted LID practice for linear transportation systems may be improved.

A previous study has evaluated the “first flush” water quality treatment performance of vegetated roadsides (Li et al. 2008) finding some runoff constituent concentration reductions attributed to vegetated roadsides. An additional study performed flow-weighted sampling of a vegetated highway median swale (Barrett et al. 1998) which was found to be effective at reducing pollutant mass loadings. Additional studies have evaluated various engineered LID systems’ feasibility for linear transportation infrastructure (Armeni 2010, Barrett 1997, Barrett 1998, Caltrans 2007, Conlon and Journey 2008, Line and Hunt 2009, Maurer 2009, Mitchell 2010, NCHRP 2006, Storey et al. 2009, Walsh et al. 1997, Yu et al. 1993, Yu and Kaighn 1995,) which were generally found to be effective, particularly for peak flow reduction and total suspended solids removal.

1.1 Background

In response to the increased concerns regarding highway stormwater runoff and its impacts to receiving waters, many state regulators have incorporated some level of LID practice into use as an accepted BMP treatment of highway runoff to protect receiving waters. Runoff from agriculture, industrial, and urban areas accounts for almost 50% of the total water pollution in the developed world (Novotny and Harvey 1994). Highway runoff has been suspected of being a major factor in stream quality degradation. Some studies have suggested that even though highways may only compose some 5-8% of an urban catchment area, highway drainage area can contribute as much as 50% of total suspended solids, 16% of total hydrocarbons, and between 35% and 75% of the total metal input budgets to the receiving stream (Ellis et al. 1987, as cited by Ellis et al. 1994).

1.2 Pollutants of Concern

The pollutants of most concern to transportation, environmental, and regulating agencies include, but are not limited to, total suspended solids, chemical oxygen demand, nitrates, total Kjeldahl nitrogen, total phosphorus, copper, lead, and zinc (Storey et al. 2009). In Virginia, phosphorus is the keystone pollutant of concern statewide. The Chesapeake Bay as well as some local total maximum daily loads (TMDLs) also require reductions in nitrogen and sediment loads. In addition to having a detrimental effect on receiving watercourses in its own right, sediment in highway runoff has been shown to correlate strongly with individual pollutant loads (Jones et al. 2008, Sansalone et al. 1998, Zanders 2004). Up to 85% of pollutants are to be found as, or adsorbed on, or absorbed by sedimentary particles (Jones et al. 2008 and Luker and Montague 1994).

1.3 Factors Potentially Affecting the Performance of LIDs

It is likely that newly constructed LID systems with low soil nutrient concentrations will have a significantly higher tendency to adsorb constituents in runoff to the soil resulting in higher than expected removal performance while LIDs systems constructed with high soil nutrient concentrations are more likely to desorb constituents resulting in an export of pollutants from the LID during the first year following construction. Line and Hunt (2009) attributed high nutrient concentrations of a bioretention cell's effluent to its relatively new construction and the use of fertilizer and mulch to establish plant growth. Other factors which may affect LID performance over time are the accumulation of pollutants in the soils which could exhaust the LID's ability to further remove pollutants and the loss of infiltration rate as sediments and metals fill void spaces of the soil matrix (National Cooperative Highway Research Program 2006). Reduced infiltration rate would have a noticeable impact on an LID's ability to reduce runoff volume, detain runoff to reduce peak flow, and reduce pollutant loading though infiltration.

Seasonal changes are attributed to substantial differences in LID performance. According to the Iowa Stormwater Management Handbook regarding vegetated swales, in temperate climates, fall and winter temperatures force vegetation into dormancy thereby reducing uptake of runoff pollutants, and removing an important method of runoff reduction. Decomposition in the fall and the absence of grass cover in the winter can often produce an outwelling of nutrients, and exposes the swale to erosion during high flows, increasing sediment load downstream (Iowa Stormwater Management Manual 2007). Pollutant removal efficiencies for many constituents can be markedly different during the growing and dormant periods (Driscoll and Mangarella, 1990).

1.4 Additional Concerns Regarding LID Use

The maintenance requirements and operating costs required to maintain ideal performance of LID systems is a concern which has been expressed by the Virginia Department of Transportation (VDOT) and is likely shared by other state transportation departments. Thermal load mitigation is a common objective of states with cold water streams and lakes with habitats subject to alteration by elevated water temperatures (Storey et al. 2009). Concerns regarding impacts to groundwater as a result of LID infiltration of runoff have been expressed in previous studies (National Cooperative Highway Research Program 2006). Caltrans BMP retrofit study (Caltrans 2004) found no impacts to groundwater for runoff infiltration devices but suggested a longer study would be necessary to produce conclusive research.

2.0 LITERATURE REVIEW

The following sections provide a review of the state of the industry and supportive information and data related to highway runoff and low impact development performance data obtained from previous research. These sections are provided to help understand the issues of highway runoff, how LID systems' removal mechanisms function, and how vegetated roadsides compare to other LID practices.

2.1 Constituents in Highway Runoff

The pollutants of most concern to transportation, environmental, and regulating agencies include, but are not limited to, total suspended solids, chemical oxygen demand, nitrates, total Kjeldahl nitrogen, total phosphorus, copper, lead, and zinc (Storey et al. 2009). Washington State Department of Transportation makes the important comment that some of the data on highway runoff constituent concentrations is from the 1980’s and early 1990’s and, therefore, may not accurately represent today’s highway runoff concentrations. For example, since 1973 the U. S. Environmental Protection Agency began phasing out lead in gasoline products (U. S. EPA 1996). As a result, studies have shown a dramatic decrease in lead concentrations in highway runoff. However, lead is still being deposited on highway surfaces such as paints used on the right-of-ways, through atmospheric deposition, and automotive lead-acid batteries (WSDOT 2006, FHWA 1999 and U. S. EPA 2010). Table 1 provides concentration ranges of these constituents that have been previously reported in the scientific literature.

Table 1: Concentrations of Constituents in Stormwater Runoff as Reported by Multiple Sources

	Barrett et al. 1998a	Li et al. 2008	Walsh et al. 1997	Yu and Kaighn 1995	Yu et al. 1993
	Event Mean Concentration	Mean Concentration Range From Six Sites	Mean Concentration Range From Two Sites	Mean Concentration Range from Three Sites	Mean Concentration at One Site
Total Suspended Solids (mg/L)	204	116-173	157 – 190	32.8 – 112.9	112.9
Chemical Oxygen Demand (mg/L)	90.6	64-100	94 – 109	61.1 – 295.4	295.4
Total Organic Carbon (mg/L)	32	NA	33.9 – 41.3	Not Analyzed	Not Analyzed
Oil and Grease (mg/L)	Not Analyzed	Not Analyzed	Not Analyzed	Not Analyzed	22.8
Nitrate (mg/L)	1.24	0.22-1.06	0.91 – 1.27	Not Analyzed	1.13
Total Kjeldahl Nitrogen (mg/L)	1.59	1.13-2.13	2.17 – 2.61	Not Analyzed	7.08
Phosphorus (mg/L)	0.356	0.13-0.28	0.24 – 0.55	1.08 – 3.71	3.71
Ortho-Phosphate (mg/L)	Not Analyzed	Not Analyzed	Not Analyzed	Not Analyzed	1.27
Copper (μg/L)	Not Analyzed	14.33-29.75	Not Analyzed	Not Analyzed	66
Lead (μg/L)	Not Analyzed	5.66-14.72	93 – 138	Not Analyzed	105
Zinc (μg/L)	143	112-175	129 – 347	100 - 650	650

2.1.1 Heavy Metals

Heavy metals associated with highway runoff include cadmium, chromium, copper, iron, lead, manganese, and nickel. Metals exist in both the dissolved form as well as the particulate and sorbed states. The preference for dissolved to particulate state will depend upon the partitioning characteristics of a particular metal. The primary source of pollutant metal build-up on road surfaces is vehicular traffic. This would suggest the average daily traffic (ADT) and antecedent dry period (ADP) as the primary predictors of pollutant concentrations, however, a study by Li, et al., 2008, raises questions regarding the mechanisms of pollutant build-up and transport. Table 2 provides a summary of metal pollutant sources in highway runoff.

Table 2: Sources of Heavy Metals in Runoff

Metal	Sources
Cadmium	Tire wear, lubricants, and insecticide application
Chromium	Metal plating, moving engine parts, and brake liners
Copper	Metal plating, bearing and bushing wear, moving engine parts, brake lining wear, deicers, fungicides and insecticides
Iron	Auto body rust, steel highway structures such as bridges and guardrails, brake lining wear, deicers, and moving engine parts
Lead	Leaded gasoline from auto exhaust, tire wear, lubricating oil and grease, bearing wear and atmospheric deposition
Manganese	Moving engine parts and fuel additive
Nickel	Diesel fuel and gasoline, lubricating oil, deicers, metal plating, bushing wear, brake lining wear and asphalt paving
Zinc	Tire wear, brakes, motor oil and grease

Source: Mitchell et al. (2010), from Barber et al. (2006), originally summarized by East-West Gateway Coordinating Council (2000) and Granato et al. (2003)

2.1.2 Nutrients

Nutrients as a pollutant generally refer to nitrogen and phosphorus due to their effects on phytoplankton populations. Excessive population levels of phytoplankton, commonly referred to as eutrophication, typically result in decreased water quality. The primary adverse effects of eutrophication are low dissolved oxygen levels that result in hypoxia and unappealing aesthetic quality as streams develop a green tint caused by chlorophyll. Nitrogen forms typically associated with stormwater monitoring are inorganic nitrogen which include nitrite and nitrate (commonly referred to jointly as nitrates), total Kjeldahl nitrogen (TKN) which includes ammonia and organic nitrogen, and total nitrogen. It is often desirable to monitor all nitrogen nutrient forms due to their differing behavior with respect to removal mechanisms. Forms of phosphorus associated with stormwater include orthophosphate, soluble phosphate (which includes orthophosphate and organic phosphate), and total phosphate. Orthophosphate and total phosphate are the forms most commonly monitored in stormwater runoff to characterize phosphate in its bioavailable form as well as total phosphate.

2.1.3 Thermal Load

According to the National Cooperative Highway Research Program because of limited infiltration capacity and expedited transport of runoff, paved surfaces provide a variety of indirect water quality problems such as higher temperature of discharge and increased risk of flooding (NCHRP 2006). Multiple stressors, including impervious surfaces, effluent from industrial facilities and power plants, as well as destruction of riparian vegetation, increase stream temperature (Winston et al. 2011, LeBlanc et al. 1997, Van Buren et al. 2000b, Wilkerson 2006, Encina et al. 2008). Increases in stream temperature can have profound impacts on stream ecology, including increased oxygen solubility and increased metabolic rates, raising the susceptibility of organisms to heavy metals, parasites, and disease (Winston et al. 2011, Jones 1975, Wahli et al. 2002). Studies have shown that thermal impacts from stormwater runoff can be exacerbated by traditionally designed best management practices (Winston et al. 2011, Galli 1990, Lieb and Carline 2000, Van Buren et al. 2000a, Kiesser et al. 2004, Herb et al. 2009, Jones and Hunt 2010). Winston et al. (2011) studied the mitigation of stormwater runoff thermal loading from an urban catchment using two vegetated strips and level spreaders. The study found that the use of vegetated filter strips resulted in statistically significant reductions in thermal load of the stormwater runoff. Runoff temperatures exceeded 29°C for a highway in

Louisiana (Sansalone et al. 2005) and 30°C for a parking lot in North Carolina (Jones and Hunt 2009).

2.2 Variability of Constituent Load

A number of factors impact the removal efficiency of LID systems. In particular, decreasing influent concentration generally results in decreased removal performance as the separation between influent and effluent concentrations becomes less pronounced. Therefore, factors which impact highway runoff pollutant concentrations strongly affect LID performance. Variance in factors which impact pollutant concentrations between different study sites, or even between individual storms at a specific study site, has resulted in high levels of variation with respect to LID performance and pollutant removal efficiency. Factors which impact pollutant concentrations in highway runoff can be the result of highway specific characteristics such as average daily traffic (ADT) and the use of curb and gutter systems for stormwater collection or climate characteristics such as antecedent dry period (ADP), rainfall depth, and rainfall intensity. High ADT volume and long ADP in conjunction with a curb and gutter system allow for high levels of pollutant build up on road surfaces. The exclusion of curb and gutter collection systems may allow for dispersion of pollutants from road surfaces due to natural and vehicle-induced winds (Li et al. 2008).

2.3 First Flush

The phenomenon commonly referred to as “first flush” describes the initial stormwater runoff characteristics associated with a particular storm event. This generally involves a relatively large portion of total pollutant load mass transport occurring within a relatively small percentage of the total runoff volume generated from a particular rainfall event. The term first flush is used inconsistently and typically does not describe a specific runoff volume or pollutant mass percentage. According to the New South Wales Environmental Protection Authority, pollutants deposited on an exposed area can become dislodged and entrained by the rainfall-runoff process. Usually the stormwater that initially runs off an area will be more polluted than the stormwater that runs of later, after the rainfall has "cleansed" the catchment. The stormwater containing this high initial pollutant load is called the "first flush" (EPA NSW 2013). The existence of this first flush of pollutants provides an opportunity for controlling stormwater from a broad range of land uses. First flush collection systems are employed to capture and isolate this most polluted runoff, with subsequent runoff being diverted directly to the stormwater system (EPA NSW 2013). Many LID systems are designed to maximize pollutant load removal efficiency by capturing the initial relatively low volume, high concentration first flush runoff rather than treating a similar runoff volume distributed throughout the entire rainfall event.

The California Department of Transportation uses a mass first flush (MFF) ratio to quantify first flush. The MFF quantifies the mass of emitted pollutants as a function of storm progress, as indicated by a normalized runoff volume (e.g. 0 to 1 with 1 being the total volume). It is defined as follows:

$$MFF_n = \frac{\frac{\int_0^{t_1} C(t)Q(t)dt}{M}}{\frac{\int_0^{t_1} Q(t)dt}{V}}$$

Where, MFF is the mass first flush ratio; n is the index or point in the storm, and corresponds to the percentage of the runoff; M is the total mass of the emitted pollutant; V is the total runoff volume; C(t) and Q(t) are the concentration and runoff volume as functions of time (Caltrans 2005).

2.4 Treatment of Highway Runoff

There are a number of LID designs and practices currently in use for managing stormwater runoff and improving water quality of stormwater runoff conveyed to receiving waters. The following sections describe removal mechanisms by which LID practices attenuate flow volumes and/or improve water quality. Hydraulic control is intended to achieve either peak shaving (the reduction of the peak flow rate of runoff), total volume reduction, or both. The mechanisms responsible for hydraulic control are infiltration, retention, detention, interception, conveyance, and evapotranspiration.

Infiltration is the reduction of runoff volume resulting from the downward migration of surface runoff into subsurface soils. Many factors influence an LID's infiltration capacity, including: soil type, depth to groundwater, and preferential pathways such as those created by vegetation. According to the U. S. Department of Agriculture, depending on the amount and type of clay minerals, many clayey soils develop shrinkage cracks as they dry, creating a direct conduit for water to enter the soil. These clay soils have high infiltration capacities as water moves into the shrinkage cracks, although at other times, when cracks are not present, their infiltration rate is characteristically slow (USDA 2008). Infiltration is influenced by factors such as soil type, vegetative cover, and groundwater conditions at the site (NCHRP 2006 and Urbonas and Stahre 1993).

Large storm events can make it difficult to retain all of the runoff generated on-site by using infiltration and storage practices. In these situations, conveyance practices are used to route excess runoff through and off the site. In LID designs, conveyance systems can be used to slow flow velocities, lengthen the runoff time of concentration, and delay peak flows that are discharged off-site (U. S. EPA 2007).

As described by the National Cooperative Highway Research Program, interception is a form of detention storage that occurs when leaves, stems, branches, and leaf litter temporarily store runoff. Interception is considered to be detention storage if raindrops drain off vegetation by “throughfall” (dripping off a leaf onto the ground) or by streamflow (flowing down stems or trunks). The percentage of rainfall that is intercepted increases with the density of vegetation, including all vertical layers from canopy to leaf litter. At maximum density, both trees and grasses may intercept 10 to 20% of precipitation from an individual storm (NCHRP 2006). Per unit of ground area, some grass species have the same leaf area as many trees (Dunne and Leopold 1978).

Detention is the temporary storage of stormwater runoff. Rainfall runoff is generally stored in ponds or in subsurface soil pores and released slowly over several hours or days after a rainfall event. For small, frequently occurring storms, the release of detained water will not usually result in flooding as the rate at which stormwater runoff enters stormwater systems is much lower than if detention systems were not in place (NCHRP 2006). Retention is the permanent capture of stormwater. The potential methods responsible for retention of runoff volume are interception, evaporation, transpiration, and reuse (NCHRP 2006) as well as deep infiltration into groundwater. Retention and detention are the key components to increases in time of concentration (U.S. EPA 2000).

Evaporation (transformation of liquid water to water vapor) and transpiration (water vapor emission for from plant surfaces) are outflow processes of water budgets. Evapotranspiration is the combined process of water surface evaporation, soil moisture evaporation, and plant transpiration. Stormwater management applications may include water surfaces, vegetation, or both, and therefore may require an estimation of evaporation, transpiration, or both, to estimate water level changes between storms (Gulliver et al. 2010).

Best management practice technologies are typically defined based on their fundamental process category (FPC) and these processes influence a respective system's pollutant removal mechanisms and efficiency. FPCs incorporate both unit operations (treatment in which the application of physical forces predominates) and unit processes (treatment in which chemical or biological processes predominate) (NCHRP 2006 and Metcalf and Eddy 2003). In many cases, the primary FPC utilized is not well determined, and thus the efficiency of any of the unit processes may depend upon static and state variables (NCHRP 2006 and Quigley et al. 2002). Some static variables include the system design parameters (e.g., volumes, dimension, and bypass systems), watershed location, size, slope, imperviousness, vegetated canopy, and soil type and compaction (NCHRP 2006 and Huber et al. 2006).

Settling and sedimentation is a physical process associated with the separation of particles downward because of a difference in densities between water and solids (NCHRP 2006 and Minton 2005). Total suspended solids and larger sediments, as well as adsorbed constituents such as heavy metals, are the primary pollutants associated with sedimentation (NCHRP 2006). The primary removal mechanism in vegetative controls is sedimentation and the secondary mechanisms include infiltration and adsorption (Rammohan 2006 and Dorman et al. 1996).

The National Cooperative Highway Research Program describes filtration is a process identified by the physical straining of particles through a porous medium and sorption as the individual unit processes of both adsorption and absorption. Absorption is a physical process whereby a substance of one state is incorporated into a substance of another state. Adsorption is the physiochemical adherence or bonding of ions and molecules onto the surface of another molecule (NCHRP 2006). In order to function well, devices that rely on both filtration and adsorption must remain in an aerobic state. If anaerobic conditions occur, the oxidation-reduction (redox) state will change, and sorbed metal will be released (NCHRP 2006 and Sansalone 2003).

Microbially mediated transformations are the unit processes of microbial activity that promote or catalyze redox reactions and transformations. These processes include the degradation of organic pollutants as well as the oxidation or reduction of inorganic pollutants. Microbially mediated transformations are chemical transformations performed primarily by bacteria, algae, and fungi that exist in the water column, soil, root zone of plants, and on wetted surfaces such as leaves (NCHRP 2006, Kadlec and Knight 1996, Karthikeyan and Kulakow 2003, and Minton 2005).

2.4.1 Vegetated Roadsides and Non-engineered Controls

Vegetated roadsides designed for aesthetics, driver safety, and erosion control have shown an ability to improve water quality of highway runoff and to decrease runoff volume. Vegetated roadsides differ from engineered LID practices such as grass filter strips in the sense that vegetated roadsides are not specifically designed for stormwater management. Vegetated roadsides may have variable slopes, some of which may have a high degree of slope, which may not be considered suitable for a grass filter strip. Grass filter strips and other vegetated LID systems also require specific routine maintenance for vegetation management and slope and erosion maintenance which is not typically a requirement for vegetated roadsides. Grass channels designed for water conveyance have also shown an ability to improve water quality, with limited runoff volume reduction (Barrett et al. 1998a). Vegetated roadsides, although not designed for stormwater management, provide water quality improvement and volume reduction according to the same physical processes as grass filter strips, i.e. flow velocity reduction due to low slope and flow resistance offered by dense vegetation which promotes sedimentation and infiltration, as well as physical filtration of particulates through vegetation (Li et al. 2008).

2.4.2 Vegetated Filter Strip

Vegetated filter strips, also commonly referred to as grass filter strips, vegetated buffers, and vegetated buffer strips are areas of sloped vegetative cover which receive stormwater under sheet flow conditions. Vegetated filter strips are the most similar engineered LID system to vegetated roadsides in relation to physical layout, function, and removal mechanics. The characteristic differences between vegetated filter strips and vegetated roadsides are the engineered design and intended use. Vegetated filter strips go through typical engineering design process and are designed specifically for stormwater management. Vegetated roadsides, however, are designed primarily for driver safety.

The vegetation and low slope provide a reduction to flow velocity which promotes sedimentation of suspended particles and infiltration of stormwater into subsurface soils. Particle removal is further enhanced by filtration of particulates by vegetative matter. Consistency of soils and vegetation as well as an evenly sloped flow surface are important to minimize flow channeling which reduces travel time and can cause erosion, resulting in the formation of gullies. The use of a level spreader may be employed to facilitate the even distribution of flow over vegetated filter strips.

Vegetated filter strips are commonly employed as a pre-treatment to subsequent BMP systems. A filter strip's ability to remove primarily larger diameter suspended-sediment particles reduces maintenance requirements and improves longevity of downstream BMPs. Total suspended solids and larger sediments, as well as absorbed constituent such as heavy metals, are the primary constituents associated with this removal mechanism (NCHRP 2006). Dynamic removal under turbulent conditions is generally dependent upon surface hydraulic loading, TSS particle-settling velocities, particle size, and fluid viscosities (which is affected by temperature) (NCHRP 2006 and Urbonas 1995). Typically, sedimentation is a highly effective removal mechanism when higher pollutant concentrations (>400 mg/L) and larger particle sizes (>50 μ) are encountered (NCHRP 2006, Urbonas 1995, and Minton 2005).

In a study conducted in North Carolina, it was determined that the restriction of requiring 1 to 2 meters of separation between many LIDs and the seasonally high water table was not a required restriction for vegetated filter strips (North Carolina Department of Environment and Natural Resources (NCDENR), Division of Water Quality, 2007, and Davis et al. 2009). Therefore, vegetated filter strips were seen as a possible solution where other LIDs may not be possible due to seasonally high water tables (Hunt et al. 2010). An additional finding of the North Carolina study was that of the 23 storm events monitored, only 3 produced outflow. All events of that study which produced outflow exceeded 1.6 inches of rainfall. Cumulative volume reduction associated with the events was 85%, which compared favorably with other LID structural practices tested in the region (Hunt et al. 2010). Peer reviewed studies of vegetated filter strips for urban areas are limited. However, vegetated filter strip performance for agricultural runoff volume reduction and pollutant capture is well researched (Abu-Zrieg et al. 2004; Magette et al. 1989; Schmitt et al. 1999), and vegetated filter strips are regarded to perform rather well (Hunt et al 2010).

Studies have shown that vegetative cover density influences performance efficiency and that efficiency rapidly declines as vegetation density drops below 80%. Due to the lack of retention volume, vegetated filters are limited to relatively small drainage areas. Vegetated filter strips are particularly feasible for highway runoff treatment due to their linear nature and lack of obstructions which may jeopardize driver safety. A summary of removal efficiencies of vegetated filter strips from previous studies is provided in Table 3. From Table 3 it can be seen that vegetated filter strips can provide high pollutant removal efficiency for total suspended solids, metals, and bacteria, low-to-negative removal of nitrogen species, and a high export of phosphate.

Table 3: Removal Efficiencies of Vegetated Filter Strips

Constituent	Mean Event Mean Concentration Reduction Efficiency from 4 Sites (%) (Caltrans 2004)	Mean Concentration Reduction Efficiency (%) (Line and Hunt 2009)	Mean Percent Change in Concentration (Yu and Kaighn 1995)
Total Suspended Solids	69	70	63.9
Chemical Oxygen Demand	Not Analyzed	Not Analyzed	59.3
Nitrate	-30	11	Not Analyzed
Total Kjeldahl Nitrogen	-5	17	Not Analyzed
Total Nitrogen	-10	14	Not Analyzed
Reactive Phosphate	-216	Not Analyzed	Not Analyzed
Phosphorus	-46	-11	-21.2
Total Copper	85	Below Detection Limit	Not Analyzed
Total Lead	88	70	Not Analyzed
Total Zinc	72	74	87.6
Fecal Coliform	92	Not Analyzed	Not Analyzed

2.4.3 Vegetated Swales and Dry Swales

Vegetated swales, also commonly referred to as grassy swales and grass lined channels, are described by the EPA as a vegetated, open-channel channel management practice designed specifically to treat and attenuate runoff for a specified water quality volume (EPA 2000). In addition to water quality improvement, vegetated swales provide concentrated flow stormwater conveyance. Pollutant removal is primarily achieved by sedimentation and filtration of particulate matter. High density vegetative cover provides resistance to flow, decreasing flow velocity and thereby providing increased sedimentation efficiency.

Vegetated swales are particularly well suited for implementation with highways and rural roads due to their linear nature. Vegetated swales are also recommended for conveying water between individual BMP systems of a treatment train, due to the opportunity for volume reduction and water quality improvement. In a study of vegetated swales in Texas, a removal efficiency of 35% for total nitrogen and 37% for total phosphorus was observed (Walsh et al. 1997). Davis et al. (2012) found that vegetated swales, enhanced by check dams, significantly reduced runoff volume during rain events totaling less than 3 cm of rainfall. Larger rain events resulted in virtually no runoff reduction, acting instead as a means of stormwater conveyance. A 2 year study of a vegetated swale treating runoff from a Florida parking lot showed on average a 30% reduction of runoff volume (Rushton 2001). A study by Stagge and Davis (2006) reported event mean concentration removal efficiency of 65-71% of total suspended solids and 30-60% of zinc. Grass swale field sites studied by Backstrom (2003) found the grass swales reduced zinc concentration by 66%. Figure 1 shows a typical grassy swale, provided by ATCS and adapted from the Virginia Stormwater Management Handbook.

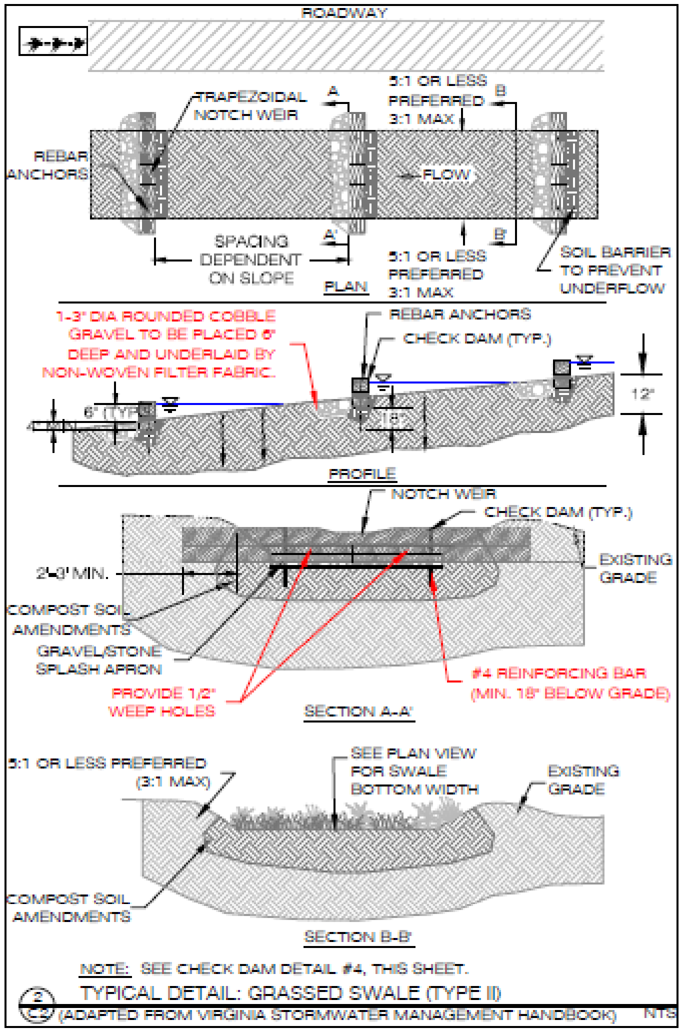

Figure 1: Typical grassy swale plan, profile, and cross section, Source: ATCS, adapted from the Virginia Stormwater Management Handbook

Dry swales, also commonly referred to as bioswales, are constructed with an underlying engineered soil media for enhanced runoff volume reduction due to an improved infiltration rate, additional retention volume provided by the void space of the soil media and typically an underlying gravel sump, as well as improved water quality as the infiltrated stormwater is filtered by the soil matrix. Native soils and construction fill used in roadside construction generally do not provide sufficient infiltration rates to adequately dewater the engineered soil media. An underdrain system consisting of perforated pipe within a gravel sump is often used to ensure adequate drainage, particularly for sites with C- or D- category soils. The underdrain discharges directly to a storm sewer system or to receiving waters. Figure 2, provided by ATCS and adapted from the Virginia Stormwater Management Handbook, shows a typical dry swale.

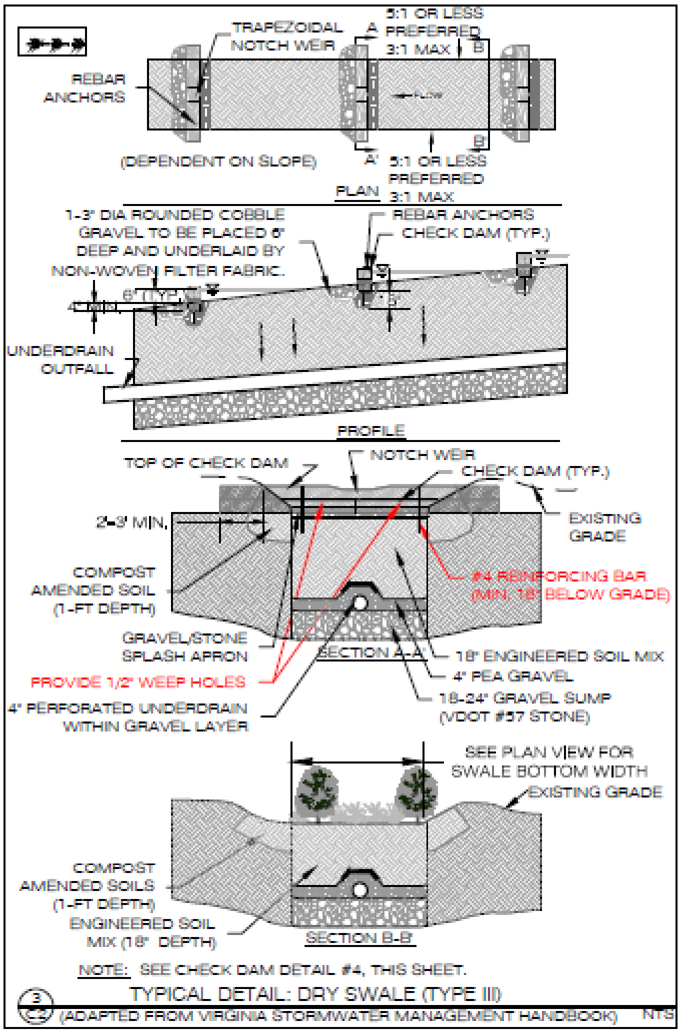

Figure 2: Typical dry swale plan, profile, and cross section, Source: ATCS, adapted from the Virginia Stormwater Management Handbook

A summary of pollutant removal efficiencies from previous studies is provided in Table 4. Vegetated swales provide moderate to high removal of total suspended solids and metals and moderate removal of nitrogen species. However, vegetated systems in the Caltrans 2004 study showed a high phosphate export, which may be attributable to the specific vegetation which was used for swale cover.

Table 4: Removal Efficiencies of Vegetated Swales

Constituent	Mean Event Mean Concentration Removal Efficiency from 6 Sites (Caltrans 2004)	Median Removal Efficiency (%) (EPA 1999)	Mean Percent Change in Concentration (Yu and Kaighn 1995)
Total Suspended Solids	49	81	29.7
Chemical Oxygen Demand	Not Analyzed	Not Provided	-5.6
Nitrate	27	38	Not Analyzed
Total Kjeldahl Nitrogen	31	Not Provided	Not Analyzed
Total Nitrogen	30	Not Provided	Not Analyzed
Reactive Phosphate	-218	Not Provided	Not Analyzed
Phosphorus	-106	9	-0.4
Total Copper	63	51	Not Analyzed
Total Lead	68	67	Not Analyzed
Total Zinc	77	71	11.1
Fecal Coliform	-30	Not Provided	Not Analyzed

2.4.4 Bioretention filters

A bioretention filter is a stormwater best management practice which detains stormwater runoff in a shallow, vegetated depression and then rapidly infiltrates into an underlying layer of engineered soil media. Bioretention filters are designed to allow for a maximum of 6 to 12 inches of ponding above the topsoil layer. Infiltration through the engineered soil media provides an environment for pollutant removal due to filtration, plant uptake, and biological activity. In addition to effective reduction of event mean concentration of suspended solids, nutrients, and metals, bioretention filters achieve moderate to high levels of runoff reduction, which further decrease pollutant load transport to receiving waters.

The Virginia Department of Conservation and Recreation's (VDCR) Stormwater Design Specification describes bioretention as a good environment for runoff reduction, filtration, biological uptake, and microbial activity, and provides high pollutant removal, as well as providing an attractive landscaping feature with high amenity value and community acceptance. According to the VDCR design specification, bioretention filters are capable of achieving 40% runoff reduction, 40% total nitrogen removal efficiency, and 25% target total phosphorus removal efficiency for a level one design and 80% runoff volume reduction, 60% total nitrogen removal efficiency, and 50% target total phosphorus removal efficiency for a level two design. Figure 3, provided by ATCS and adapted from the Fairfax County Public Facilities Manual, shows a typical bioretention filter plan view. A summary of pollutant removal efficiency for bioretention filters from previous studies is provided in Table 5.

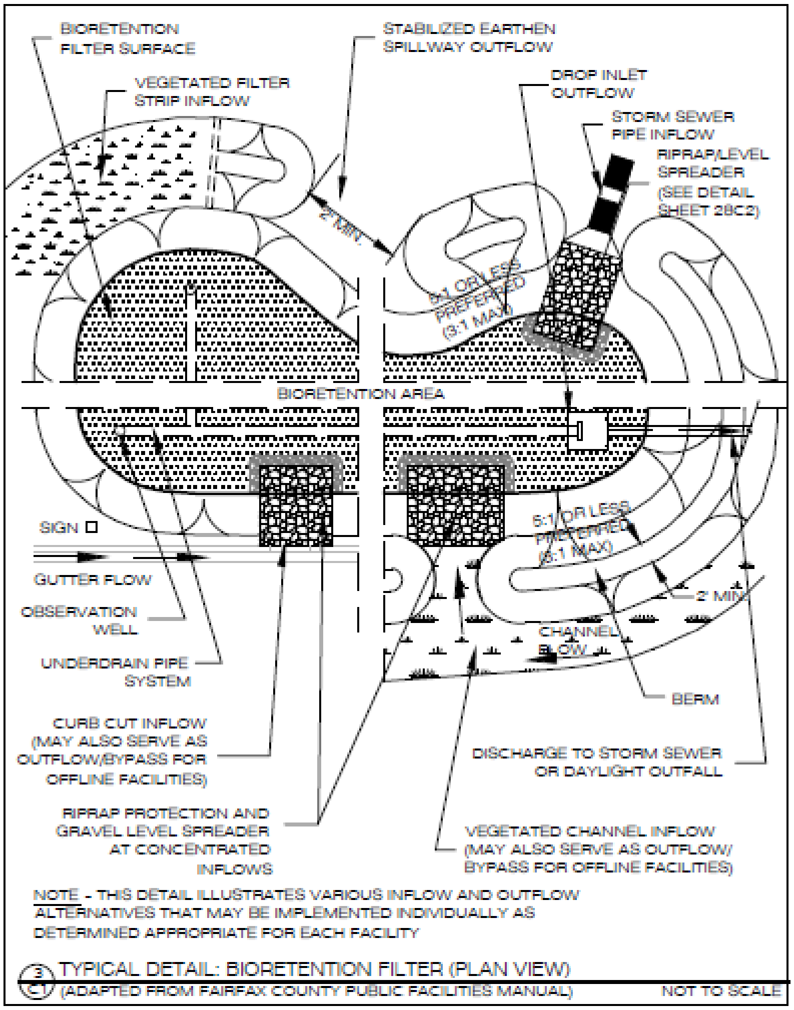

Figure 3: Typical bioretention filter plan view, Source: ATCS, adapted from the Virginia Stormwater Management Handbook

Table 5: Removal Efficiencies of Bioretention Filters

Constituent	Mean Concentration Reduction Efficiency (Line and Hunt 2009)	Mean Concentration Reduction Efficiency (Armeni 2010)	Mean Concentration Reduction Efficiency of Five Pilots Boxes (Li et al. 2010)
Total Suspended Solids	79	24	42.9
Nitrates	-257	Not Analyzed	-1896
Total Kjeldahl Nitrogen	28	Not Analyzed	Not Analyzed
Total Nitrogen	-3	Not Analyzed	-256
Reactive Phosphate	Not Analyzed	Not Analyzed	Not Analyzed
Phosphorus	44	Not Analyzed	-1873
Total Copper	Below Detection Limit	92	-12.6
Total Lead	64	67	71.4
Total Zinc	82	73	61.6
Total Cadmium	Not Analyzed	51	Not Analyzed
Total Chromium	Not Analyzed	45	Not Analyzed
Total Iron	Not Analyzed	44	Not Analyzed
Total Nickel	Not Analyzed	74	Not Analyzed
E. Coli	Not Analyzed	Not Analyzed	87.3

2.4.5 Enhanced Extended Detention Basin

Extended detention basins (EDB) and enhanced extended detention basins both provide temporary stormwater runoff detention in order to achieve water quality improvement, receiving channel erosion protection, and/or flood prevention. Both extended detention basin designs achieve water quality improvement primarily through sedimentation of suspended particles. Extended detention basins tend to have low removal efficiency when evaluated over time due to the occurrence of sediment re-suspension resulting from high influent velocities of larger storm events. Enhanced extended detention basins incorporate a shallow marsh to reduce sediment re-suspension and increase pollutant removal by vegetative filtration, adsorption, and plant uptake.

The Virginia Stormwater Management Handbook assigns a target phosphorus removal efficiency of 35% for an extended detention basin and 50% target phosphorus removal efficiency for an enhanced extended detention basin. The detention volume of an extended detention basin may be increased above the water quality treatment volume to provide additional runoff volume detention to achieve stream protection for larger, less frequent storms. Through extended detention, flow velocities below the critical erosive velocity based on the slope and channel lining of receiving channels may be maintained for a range of storm event frequencies.

2.4.6 Bioslope

Bioslopes according to the Fairfax County Draft LID BMP Fact Sheet (Fairfax County 2005), also referred to as ecology embankments, incorporate an engineered soil media design to a standard grass filter strip. The engineered soil media provides a soil layer with higher permeability and larger void ratio for runoff retention than typical native soils or construction fill. The inclusion of an engineered soil media enhances water quality improvement through filtration, adsorption, and biological activity of infiltrated runoff, runoff volume reduction, and reduced tendency for slope erosion. In this way bioslopes have a similar removal mechanism as the dry swale and bioretention filter. Bioslopes have a similar site application as grass filter strips and are feasible for use in low slope areas such as highway or rural roadsides. Contrary to most LID designs which are mostly dependent on rainfall depth, bioslopes are designed according the maximum anticipated intensity of a water quality storm event. For storm intensities below design intensity, drainage of the engineered soil media is sufficient to allow for continued infiltration. In many cases the underlying native or construction fill soils do not provide sufficient permeability to fully infiltrate runoff within the engineered soils. In such cases an underdrain system is installed at the base of the bioslope to facilitate dewatering of the soil media and conveyance of treated runoff to an outfall, a stormwater sewer system, or to an additional BMP. The runoff retention volume of a bioslope may be increased through the inclusion of a gravel sump at the base of the bioslope. If design intensity is exceeded, void spaces of the soil media become saturated and additional runoff is conveyed by sheet flow along the vegetated slope. Bioslopes should be limited to sheet flow conveyance over stable slopes of 4 horizontal to 1 vertical.

The Washington State Department of Transportation has found that bioslopes are capable of achieving 60% removal of phosphorus, 77% of metals, and 88% of total suspended solids (Fairfax County 2005 and WSDOT 2004). Figure 4, provided by ATCS and adapted from the National Cooperative Highway Research Program 565 and the Washington Department of Transportation Highway Runoff Manual, shows a typical bioslope cross section.

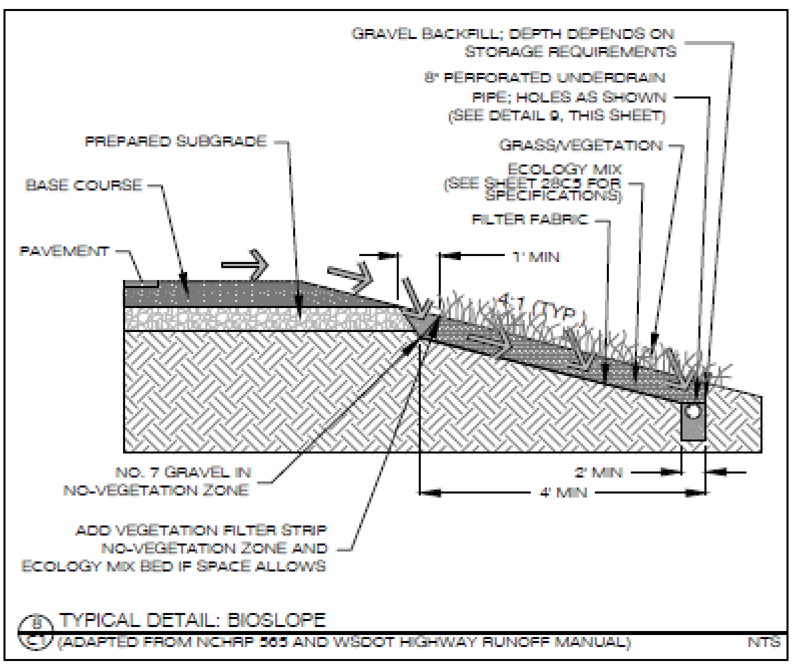

Figure 4: Typical bioslope cross section, Source: ATCS, adapted from the NCHRP 565 and WSDOT Highway Runoff Manual

2.4.7 Compost-Amended Soils

Compost-amended soils as described by the Virginia Department of Conservation and Recreation Stormwater Design Specification Number 4, referred to as soil compost-amendment or soil restoration, is the practice of tilling compost into native topsoil to a minimum depth of 12 inches to increase the void ratio and permeability of native soils to enhance their retention volume and infiltration capability. Compost-amended soils are particularly feasible for use in conjunction with grass filter strips or grass channels with C or D category soils. The application of amended soils can improve the runoff volume reduction of grass filter strips to 50% and increase the runoff volume reduction of grass channels from 10% reduction without soil amendment to 30% reduction with soil amendment. Compost-amended soil practice may also be used to increase the runoff retention volume of LID practices which incorporate a retention volume component, such as dry swales and bioretention filters, by amending the native soils below the engineered soil media or gravel sump to provide a soil layer of increased pore volume.

2.5 Site Description

This study was performed in 2014 to provide the following three data sets: the characterization of Lorton Road runoff quantity and quality, the performance of vegetated roadsides, and the effects on performance of various vegetation management and maintenance routines. The study site was located in Fairfax County, Virginia adjacent to the east bound lanes of Lorton Road between Furnace Road and Silverbrook Road, west of I-95. Lorton Road is a two lane road which services approximately 8,000 vehicles per day (VDOT 2014). The site location can be seen in Figure 5. Lorton Road would be classified as a secondary road, the greatest linear mileage of roadway in Virginia which VDOT is responsible for. Of the 57,868 miles of roadway in Virginia which VDOT is responsible for, 48,305 miles are secondary roads. An additional 12, 238 miles of roads in Virginia are maintained by other entities (VDOT 2014).

Figure 5 Approximate location of Lorton Road study site Source: U.S. Geological Survey

The study sites were located adjacent to the east bound lanes of Lorton Road between Furnace Road and Silverbrook Road. This location was selected in part due to its inclusion in phase 3 of the multi-phased construction schedule. Phase 3 of the current construction schedule is expected to begin spring 2015 and, therefore, has allowed ample time to perform a full characterization of Lorton Road runoff, a full evaluation of the performance of vegetated roadsides, and a complete evaluation of the impact of vegetation management routines before construction activities begin. The location of the vegetated roadside study strips are shown below in Figure 6. Although both sites A and B were initially evaluated for study, Site A was ruled out due to the close proximity of Lorton Road widening construction activities which would likely have interfered with the study. All vegetated roadside studies, as well as the characterization of Lorton Road, were performed at Site B.

Figure 6: Initial study site locations evaluated for feasibility, Source: Google Maps

3.0 Experimental Materials and Methods

The following sections describe the materials used during the study, the monitoring and sampling methods of evaluating and sampling stormwater runoff and storm events, and the analytical methods used to determine the water quality of highway runoff and vegetated roadside effluent, and the methods for data analysis.

3.1 Flow Monitoring and Sampling

In order to monitor and sample sheetflow runoff, 30-feet long PVC troughs with aluminum flashing were installed at three locations to channel the sheetflow into a concentrated discharge. One sheetflow collector was installed directly adjacent to Lorton Road for collection of the road runoff sample. An additional sheetflow collector was installed at two separate monitoring locations to collect the vegetated roadside's effluent. Each vegetated roadside effluent collector is 18-foot long parallel to flow path and 30-feet wide. A photograph of the Lorton Road runoff sheetflow collector is presented as Figure 7.

Figure 7: Lorton Road stormwater runoff PVC and aluminum sheetflow collector

The vegetated strips had a slope of 49 percent for the first four feet adjacent to the road and an average of 8 percent for the remainder of the vegetated strips. Concentrated road and vegetated roadside runoff are conveyed through additional 4 inch PVC piping approximately 22 feet for the effluent of the vegetated roadside strips and approximately 40 feet for the Lorton Road runoff. Each concentrated pipe flow is conveyed to a 0.4 HS velocity flume for flow monitoring and sampling, as seen in Figure 8.

Figure 8: 0.4 HS velocity flume used for sample collection and flow monitoring

Multiple years of road runoff had resulted in a buildup of sediment adjacent to the road which had created a hydraulic barrier preventing road runoff from flowing onto the vegetated strips. The sediment barrier, as well as several small sections of the road stripping, were removed to allow for a uniform sheetflow of the road runoff onto the vegetated strips, as seen in Figure 9. The removed sediment was relocated elsewhere on the study site, away from the vegetated strips.

Figure 9: Removal of hydraulic barrier due to sediment buildup

Flow depths within the flumes were measured using a submersible depth sensor housed within a probe well. The potential beneficial impacts of a more rigorous vegetation management routine were evaluated during the course of the vegetated roadside study. In order to study the effects of vegetation management on vegetated roadsides' performance, two vegetated roadside strips were monitored concurrently under differing vegetation management routines. The unmanaged vegetation strip, consisting of relatively woody vegetation and wild blackberry, was subjected only to typical VDOT roadside vegetation management. The vegetated roadside strips can be seen in Figure 10.

Figure 10: Vegetated roadside strips and effluent sheetflow collectors

VDOT's vegetation management involved one summer mowing event that cut vegetation back approximately 4 feet from the road without any removal of the cuttings. The managed vegetated strip had a herbaceous vegetated cover, was cut to approximately 4 inches along the entire vegetated strip, and the cuttings were removed to prevent nutrient release from vegetation decay. Vegetation management was performed by hand using non-motorized equipment to prevent contamination of the managed vegetated strip due to fuel exhaust. The removal of cut vegetation has been shown to prevent re-release of nutrients as cut vegetation decays, decreasing the nutrient load impacting receiving waters due to runoff (Tate et al. 2004). A simple site schematic showing the layout of stormwater sheetflow collectors and sampling equipment may be found below as Figure11.

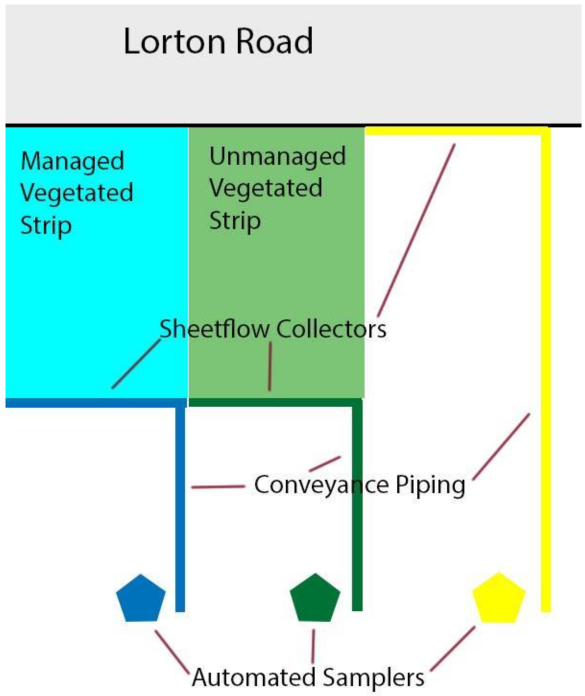

Figure 11: Site Schematic of Lorton Road, vegetated roadside strips and sampling layout

Samples were collected using Sigma 900 MAX portable sample systems for sample collection and flow monitoring. Each system is capable of collecting flow-weighted samples to produce up to a 2.5-gallon composite sample. Flow weighted sampling allows for a distribution of samples to create a composite sample which is representative of an entire storm event, as opposed to collecting “first flush” samples which often contain higher concentrations of pollutants during initial runoff periods. In order to develop composite samples representative of an entire storm event, it was required that no sample aliquot represent more than 25 percent of a storm event. For that reason it was necessary that at least 5 sample aliquots are collected from the monitoring site for each storm event and that flow logging begins when flow is first present in the velocity flumes and continues until flow is no longer present in order to ensure flow weighted sampling is conducted throughout the entire storm event.

Two storm events over the course of the study were disqualified as runoff generating storm events due to low total rainfall depths generating insufficient runoff for 5 road runoff sample aliquots. Although the same requirement for sampling throughout an entire storm event was included for both vegetated roadside strips, there was no requirement for minimum number of sample aliquots per storm event. This was necessary since the vegetated roadside strips would frequently infiltrate all runoff and no samples could be collected despite sufficient road runoff having been generated to qualify as a storm event.

In order to distinguish between rain events, a period of 12 hours was selected as the minimum period between measurable precipitation to qualify as a new event. Any additional precipitation within less than 12 hours would be considered a continuation of the original storm event. However, in practice this this minimum time separation requirement was challenging since samples were retrieved at the conclusion of a storm event without any certainty of when the next rain event would begin. In addition, at the time of sample collection it was difficult to know precisely when storm events occurred until the data could later be analyzed. During the course of the study, two rain events were separated by only 10 hours, 40 minutes but were comprised of separate sampling events and were treated as separate events.

A malfunction with the depth sensors was observed during the October 4^{th} and October 10^{th} storm events. Although the cause of the malfunction is unknown, the malfunction prevented the sensors from properly returning to their zero reference point following the storm event resulting in continued sampling despite no runoff flow present. However, it was possible to estimate the flows with accuracy and confidence since the periods when flow was present could be determined by successful sampling of the runoff flow. Unsuccessful sampling events, (sampling attempts when no flow was present), were used to determine when no flow was present and the runoff from the storm event had ended. To properly preserve samples, each sampler was packed with ice prior to each storm event. Samples were collected within 24 hours and transported on ice to the Water Quality Laboratory at the University of Virginia where they were stored under refrigeration and preserved with sulfuric acid to a pH less than 2 until analysis. Two field blanks were taken during the study but the DI water used in creating the field blanks was later discovered to be contaminated, making the results of the field blanks meaningless.

Total rainfall depth and rainfall intensity of each monitored storm event was monitored using a tipping gauge rain gauge and the rainfall data were recorded in 5 minute intervals using the a Sigma 900 Max automated sampler. The average rainfall intensity was calculated by dividing the total rainfall depth by the duration of the storm event. This does include periods of no rainfall for rain events which are composed of multiple periods of rainfall during the total rainfall event duration. Therefore, the average rainfall intensity may be considerably lower than the intensity observed during periods of rainfall.

Thermal data were collected using a thermal probe within the stormwater sheetflow collector and was logged using an Omega OM-CP-QUADRTD model data logger. The sheetflow collectors were selected as the monitoring point, as opposed to the velocity flume, to prevent any thermal transfer from the pvc conveyance piping between the sheetflow collectors and the velocity flume. Runoff temperatures were logged every one minute throughout an entire storm event for five storm events between September 12th and October 14th. These data were collected to determine if vegetated roadsides had potentially beneficial or negative effects on runoff temperatures and, consequently, on receiving waters. The temperature data were correlated to the flow data logged during storm events to determine total thermal loads potentially impacting receiving waters. Mean temperature of runoff per storm event was calculated for Lorton Road, the managed roadside vegetation strip, and the unmanaged roadside vegetation strip.

Soil core samples were collected using a split spoon hand auger down to 24 inches. Collected soil cores were 2 ¼ inch diameter and six inches in length. The 12 to 18 inch soil core was analyzed for grain size using a series of sieves. The sieves were placed on a mechanical shaker for 30 minutes prior to measuring the retained weights for each sieve. The sieves were returned to the mechanical shaker for an additional 5 minutes and re-weighed to ensure the change in retained weight for each sieve was less than one percent.

3.2 Analytical Methods

Laboratory analyses of total suspended solids, chemical oxygen demand, metals, nutrients, and oil and grease were conducted for all collected water samples. As noted previously, water sample types were either samples collected directly as they left the roadside, or samples that had been transported across managed or unmanaged vegetation. These analyses determined the pollutant removal efficiency of the two vegetated roadside strips. The USEPA generally categorizes pollutants associated with urban runoff as solids, oxygen-demanding substances, nutrients, pathogens, organics associated with fuel and other petroleum products, metals, and synthetic organics (USEPA 1999). Using the USEPA categories of pollutants, the analytical capabilities of the University of Virginia Water Quality Laboratory, and a literature review of previous investigations of stormwater characterization of highway runoff and LID performance (Armeni 2010, Barrett et al. 1997, Barrett et al. 1998, Barrett et al. 1998, Caltrans 2004, Conlon and Journey 2008, Li et al. 2008, Li et al. 2010, Line and Hunt 2009, Maurer 2009, Mitchell et al. 2010, NCHRP 2006, Storey 2009, USEPA 1999, Walsh et al. 1997, Yu et al. 1993, Yu and Kaighn 1995,), the following constituents were selected for analysis to determine water quality improvement performance of LID systems: total suspended solids (TSS), chemical oxygen demand (COD), nutrients (nitrite and nitrate, total nitrogen, and total phosphate), metals (copper, lead, zinc, chromium, cadmium, and iron), oil and grease, and total coliform bacteria and *Escherichia coli* (*E. coli*).

Analytical methods employed in this study include filtration and gravimetric determination of total suspended solids, colorimetric analysis using spectrophotometry for nutrients and chemical oxygen demand, atomic absorption spectrophotometry of metal concentrations, spectrophotometric determination of oil and grease, and most probable number method for *E. coli* and total coliform. A summary of analytical methods can be found in Table 6.

TABLE 6 Water Quality Constituents of Concern and Relevant Analytical Methods

Pollutant	Method	Practical Quantifiable Limit
Copper	EPA 220.2	5.0 µg/L
Lead	EPA 239.2	5.0 µg/L
Zinc	EPA 289.2	0.2 µg/L
Cadmium	EPA 213.2	0.5 µg/L
Chromium	EPA 218.2	5.0 µg/L
Total Suspended Solid	EPA 160.2	4.0 mg/L
Chemical Oxygen Demand	EPA 410.4	3.0 mg/L
Oil and Grease	EPA 413.2	0.2 mg/L
Nitrates	EPA 353.3	0.01 mg/L
Total Nitrogen	CCAL 33A.2	0.01 mg/L
Total Phosphorus	EPA 365.1	0.01 mg/L
Escherichia Coli (*E. Coli*)	Standard Method 9223 B	1 Most Probable Number per 100 mL
Total Coliform Bacteria	Standard Method 9223 B	1 Most Probable Number per 100 mL

3.3 Data Analysis

Performance of each vegetated roadside strip was evaluated based on its hydraulic characteristics and ability to reduce pollutant event mean concentrations and pollutant loads. Pollutant event mean concentration is assumed to be equal to the pollutant concentration of the composite sample. Pollutant concentration reduction efficiency is the percentage of reduction of the effluent event mean concentration relative to the influent event mean concentration, calculated as:

$$\frac{EMC_{Influent} - EMC_{Effluent}}{EMC_{Influent}} \times 100$$

Pollutant load is equal to the event mean concentration multiplied by the total flow volume per storm event for the Lorton Road runoff and effluent of the vegetated roadsides.

Pollutant load reduction efficiency is considered to be better representative of BMP performance since infiltration of stormwater within the BMP often transports pollutants to subsurface soils and flow volume reduction reduces total pollutant mass transport to receiving waters. Pollutant load reduction efficiency is calculated as:

$$\frac{Load_{Influent} - Load_{Effluent}}{Load_{Influent}} \times 100$$

Hydraulic performance characteristics include runoff volume reduction and peak flow reduction. Runoff volume reduction is the percentage of reduction of effluent flow volume relative to the influent, resulting primarily due to infiltration within the vegetated roadside, but could also be attributed to evapotranspiration. Runoff volume reduction is calculated as the influent volume subtracted by effluent volume divided by the influent volume for a given storm event. Peak flow reduction is the reduction percentage of peak effluent flow rate relative to the influent peak flow rate. Peak flow reduction is achieved by the reduction of flow velocity by slope design and/or vegetation or the temporary storage of runoff volume and is calculated as the peak influent flow rate subtracted by the peak effluent flow rate divided by the peak influent flow rate.

Thermal load of runoff was calculated using the logged temperature and flow data in the following equation:

$$W=Q \text{ x } \rho \text{ x } T \text{ x } C \text{ x } t$$

Where W = thermal load (J); Q = flow rate (m^3/s); ρ = density of water (assumed constant at 1,000 kg/m^3); T = water temperature (°C); C = heat capacity of water (assumed constant at 4,186 J/kg/°C); and t = time (s). Thermal load allowed for the evaluation of total thermal load migrated from the road surface to receiving waters. Thermal load analysis accounts for thermal transport mitigation due to infiltration of heat bearing surface runoff within the vegetated roadside strips, thereby preventing infiltrated thermal runoff loads from impacting receiving waters.

To determine statistically significant differences between Lorton Road runoff and vegetated roadside effluent, (i.e. if a vegetated roadside is achieving significant removal), a non-parametric Sign test analysis was performed for pollutant load. Pollutant load Sign testing was also performed comparing the two vegetated roadsides to determine if a statistically significant difference exists due to differences in vegetation management. Sign testing was selected over other statistical methods for two reasons. Sign testing allows for paired comparisons between data sets. This was an important factor due to the large degree of variance introduced between events by factors such as storm characteristics and antecedent dry period, among others. Sign testing was also selected as the statistical method due to a lack of assumptions related to sample distributions required of other statistical methods. The primary assumptions which were not assumed to be true of the runoff water quality or runoff loads was the assumption of normally distributed data and the assumption of symmetry about the median. It was seen during data analysis that the median value of many parameters associated with the vegetated roadsides was zero due to frequent full infiltration of road runoff. Therefore, since no values could be negative, the values about the median were not symmetric.

Linear regression was employed as a method of modeling the relationship of both rainfall characteristics and vegetative roadside strip influent with vegetative roadside strip effluent. The rainfall characteristics of total rainfall and rainfall intensity were used as independent variables to predict the dependent variables of Lorton Road runoff quantity and quality and vegetative roadside effluent quantity and quality. The Lorton Road runoff water quality characteristics of constituent concentration and constituent mass loading were also used as independent variables as the vegetative roadside strips' influent water quality to predict the vegetative strips' effluent water quality. Data collected over the course of the study were used as observed data for developing the linear relationship to predict previously described stormwater runoff parameters. Through the use of linear regression it is possible to predict any of the previously described dependent variables by selecting any given independent variable. Linear regression can also be used to compare vegetative roadside strips' performance by selecting a value of an independent variable. In the case of this study the event mean concentration averaged over the course of the study was used for predicting the performance of the vegetative strips evaluated in this study.

4.0 RESULTS AND DISCUSSION

The following sections present the results of the study and a discussion of the findings. The following sections are presented: soil analysis,

4.1 Soil Analysis

A 2 ¼ inch diameter, six-inch-long soil core was sampled from the study site six feet from the vegetated roadside and 12 inches to 18 inches below grade. The soils sample was removed using a hand auger split spoon. A sieve analysis was performed on the soils core to determine the grain size analysis. Additional method description can be found in the sampling methods section. The results of the grain size analysis are provided in Table 7.

TABLE 7 Grain Size Analysis of Vegetated Roadside Soil Core Collected 12” to 18” Below Grade

Sieve Size (inch)	Weight Retained (gram)	Percent Retained
0.1839	150.1	33.1
0.0787	53.4	11.8
0.0469	41.1	9.1
0.0331	29.5	6.5
0.0098	28.9	6.4
0.007	81.1	17.9
Fines	69.8	15.4

This soil type would be classified by the United States Department of Agriculture (USDA) National Resource Conservation Service as a type B hydrologic group based on the greater than 50 percent sand and gravel content and less than 20 percent clay content (NRCS 2007). A type B soil would be expected to achieve 0.57 to 1.42 inch per hour of infiltration under saturated soil conditions (NRCS 2007). Although the exact percentage of surface area in Virginia with a type B soil is difficult to estimate, the NRCS Web Soil Survey appears to show type B soils present in approximately 40 percent of the sites surveyed (NRCS 2013). Fairfax County describes the soil near the study site as Marumsco soil which may contain bands of marine clay resulting in the formation of shrinkage craking (Northern Virginia Soils and Water Conservation District 2015). It is also likely that the hydrologic soil type at the Lorton Road site has changed over the years since the initial installation of Lorton Road. The compaction of soils due to the use of heavy equipment during road construction typically results in a low infiltration type D soil. The infiltration rate generally improves over time as the vegetation creates flow paths as well as other mechanisms for increasing soil permeability. However, the rate at which soil infiltration rates rebound is highly variable and difficult to predict.

4.2 Event Mean Concentration

The average of each constituent of concern was calculated from the event mean concentrations for each sampling location from 16 storm events occurring May 1, 2014 to November 27, 2014. The peak flow and total flow volume for each storm event were averaged over the 16 monitored events. The results are presented in Table 8. With the exception of total suspended solids (TSS), Lorton Road runoff constituent concentrations are reasonably comparable to concentrations found in previous research (Armeni 2010, Barrett et al. 1997, Barrett et al. 1998, Barrett et al. 1998, Caltrans 2004, Conlon and Yu et al. 1998, Journey 2008, Li et al. 2008, Li et al. 2010, Line and Hunt 2009, Maurer 2009, Mitchell et al. 2010, NCHRP 2006, Storey et al. 2009, USEPA 1999, Walsh et al. 1997, Yu and Kaighn 1995,).

Heavy application of salt and road aggregate during the spring of 2014, combined with the soil disturbance resulting from the installation of sheetflow collectors, resulted in highly elevated TSS concentrations during the initial storm events of the study. Although the constituent concentrations of Lorton Road runoff and vegetated roadsides' effluent is useful for characterizing water quality and understanding vegetated roadsides' removal mechanisms, constituent concentrations alone do not account for infiltration of runoff and, therefore, do not accurately represent vegetated roadside removal performance. The constituent concentration reduction efficiency of the managed and unmanaged strips was calculated to determine vegetated roadsides' potential for reducing constituent concentrations of the effluent. Negative concentration reduction efficiency represents an increased constituent concentration found in the vegetated strips effluent. However, increased constituent concentration does not necessarily indicate an increase of constituent mass impacting receiving waters since infiltration of the runoff volume may mitigate mass migration. A graphical representation of the concentration reduction efficiency is presented in Figure 12.

The managed and unmanaged vegetated roadsides appear to be most effective at reducing the concentration of total suspended solids, nitrates, and total coliform. The vegetated strips show a moderate reduction of oil and grease and the metals cadmium, chromium, copper, and lead concentrations. Vegetated roadsides showed little effect on average on the concentration of chemical oxygen demand while only the unmanaged vegetated roadside appears capable of consistently reducing the concentration of phosphate. Both vegetated roadside strips increased the concentration of total nitrogen and zinc. The unmanaged vegetated strip appeared to increase *E. coli* concentration while the managed vegetated strip effectively reduced the *E. coli* concentration.

TABLE 8: Average of Hydraulic Parameters, Event Mean Concentrations, and Standard Deviations of Lorton Road Runoff, Managed Vegetation Effluent, and Unmanaged Vegetation Effluent

	Road Runoff		Managed Vegetation		Unmanaged Vegetation	
Parameter	Hydraulic Parameter	Standard Deviation	Hydraulic Parameter	Standard Deviation	Hydraulic Parameter	Standard Deviation
Average Peak Flow Per Event (gpm)	2.3	2.4	0.9	2.3	0.3	0.8
Average Flow Volume Per Event (Liters)	429.3	544.1	222.3	669.2	204.4	752.6
	Road Runoff		Managed Vegetation		Unmanaged Vegetation	
Constituent	Event Mean Concentration	Standard Deviation	Event Mean Concentration	Standard Deviation	Event Mean Concentration	Standard Deviation
Total Suspended Solids (mg/L)	1870.3	3791.0	130.1	179.7	231.3	474.6
Total Nitrogen (mg/L-N)	1.9	1.4	2.5	3.1	3.1	5.2
Nitrates (mg/L-NO_3)	0.7	0.6	0.2	0.4	0.2	0.5
Total Phosphate(mg/L -PO_4^{-3})	1.0	1.0	1.0	1.3	0.6	1.1
Oil and Grease (mg/L)	9.2	11.6	0.8	9.6	5.7	9.8
Chemical Oxygen Demand (mg/L)	91.3	45.9	97.5	108.8	90.7	118.6
Total Coliform (cfu/100mL)	8378	9962	3570	9199	2845	7058
E. coli (cfu/100mL)	4.7	10.5	0.5	0.7	8.9	27.6
Cadmium (µg/L)	0.9	1.3	0.5	0.5	0.4	0.4
Chromium (µg/L)	9.4	6.8	5.1	6.8	6.1	10.5
Copper (µg/L)	38.1	45.0	24.4	46.6	12.4	16.5
Lead (µg/L)	7.9	11.0	5.3	8.3	6.1	9.2
Zinc (mg/L)	0.4	0.5	0.5	0.6	0.6	0.9

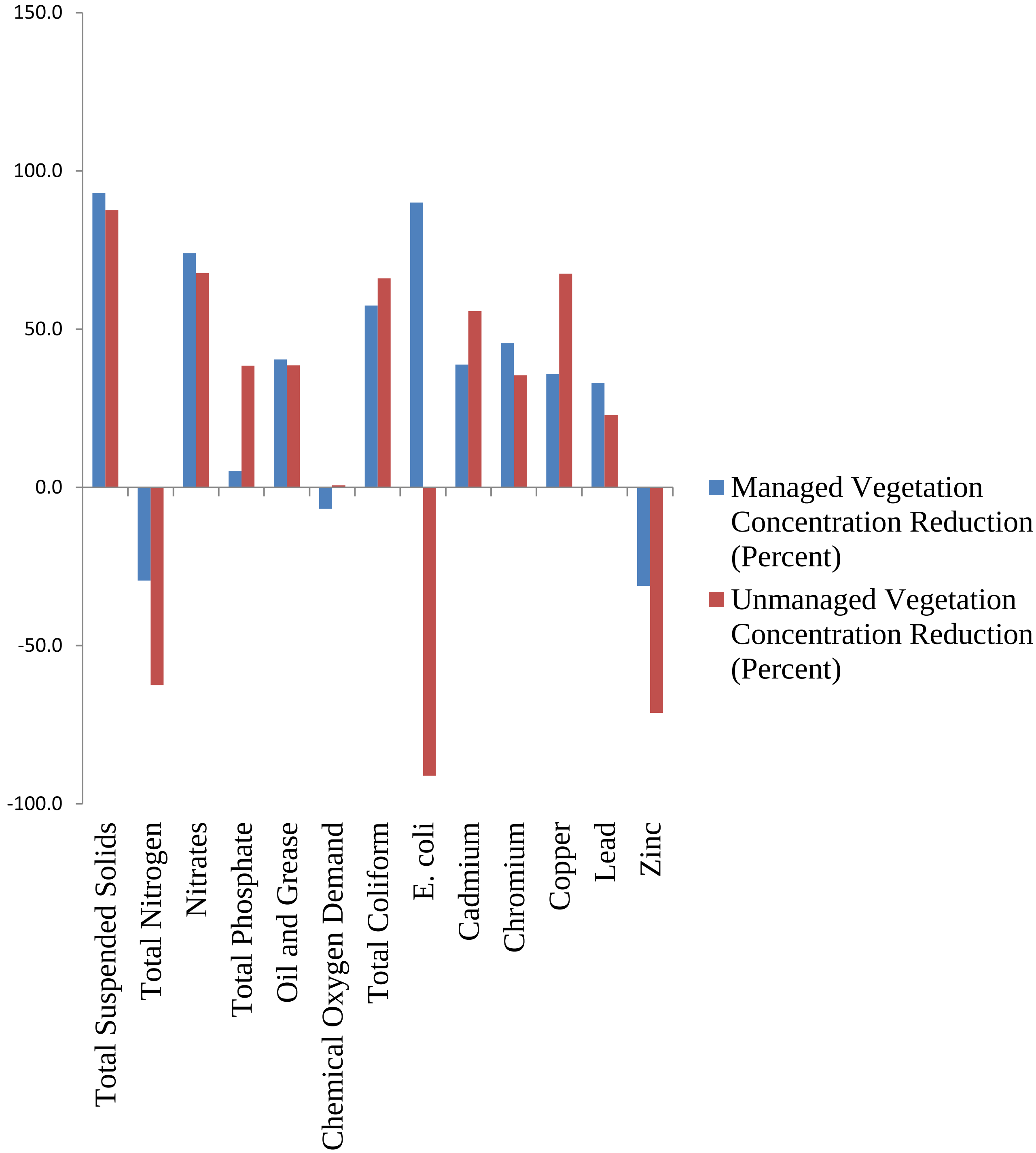

Figure 12: Mean constituent concentration reduction efficiency of the managed and unmanaged vegetative strips

A table of the mean constituent concentration reduction efficiency of the managed and unmanaged vegetated strips is provided as Table 9 for detailed comparison of concentration reduction efficiencies.

Table 9: Mean Constituent Concentration Reduction Efficiency of the Managed and Unmanaged Vegetative Strips

Parameter	Managed Vegetation Concentration Reduction (Percent)	Unmanaged Vegetation Concentration Reduction (Percent)
Total Suspended Solids	93.0	87.6
Total Nitrogen	-29.5	-62.5
Nitrates	73.9	67.7
Total Phosphate	5.1	38.4
Oil and Grease	40.4	38.6
Chemical Oxygen Demand	-6.8	0.6
Total Coliform	57.4	66.0
E. coli	90.0	-91.1
Cadmium	38.8	55.7
Chromium	45.5	35.4
Copper	35.9	67.5
Lead	33.0	22.8
Zinc	-31.1	-71.3

4.3 Hydraulic Parameters and Event Mass Load

The average of event constituent mass migrated from the road surface and through the vegetated strips is presented in Table 10. The event constituent mass describes the actual mass which migrates from the road surface and could potentially impact receiving waters. The constituent mass migrated is proportional to the volume of road runoff generated for a given constituent concentration. Therefore, reduction of flow volume in the vegetated strips through infiltration reduces the total constituent mass which migrates from the road surface, through the vegetated strips, and potentially to receiving waters.

Table 10: Average of Event Mean Mass Migrated and Standard Deviation from Lorton Road Runoff, Managed Vegetation Effluent, and Unmanaged Vegetation Effluent

	Road Runoff		Managed Vegetation		Unmanaged Vegetation	
Constituent	Event Mean Mass	Standard Deviation	Event Mean Mass	Standard Deviation	Event Mean Mass	Standard Deviation
Total Suspended Solids (g)	1818.0	6116.7	75.1	206.0	68.3	245.5
Total Nitrogen (mg-N)	1031.1	2409.1	1631.4	5589.6	1085.3	4091.0
Nitrates (mg-NO_3)	380.1	863.5	37.9	97.0	2.8	6.7
Total Phosphate(mg-PO_4)	387.8	520.7	326.0	1003.0	406.2	1599.1
Oil and Grease (mg)	3936.9	6485.4	568.3	1301.1	452.4	1178.3
Chemical Oxygen Demand (g)	44.7	86.1	28.8	74.1	34.7	128.5
Total Coliform (Million cfu)	14	15	9	22	14	44
E. coli (Thousand cfu)	22.4	39.7	2.5	7.7	1.0	2.1
Cadmium (µg)	407.5	1104.1	138.3	362.49	241.8	941.1
Chromium (µg)	5052.7	8559.8	1215.6	3450.2	660.5	2425.2
Copper (µg)	27174.0	76036.9	4933.1	15571.6	5020.5	19268.3
Lead (µg)	6771.3	16791.7	1223.0	4075.6	693.1	1927.1
Zinc (mg)	130.6	234.6	81.6	208.0	51.1	178.9

In order to develop a representative account of vegetated roadsides' potential for constituent migration mitigation, constituent mass loads were calculated for each constituent of concern. Constituent mass loading accounts for road runoff infiltration and the resulting reduction of flow volume impacting receiving streams. The hydraulic mitigation and mean constituent percent mass reduction results calculated from constituent mass loadings are presented in Figure 13. A table of the mean hydraulic and constituent mass reduction efficiency of the managed and unmanaged vegetated strips is provided as Table 11 for detailed comparison of mass reduction efficiencies.

Vegetated roadsides' hydraulic and water quality mitigation performance was found to be comparable to engineered LID systems used for linear transportation (Yu et al. 1993, Yu and Kaighn 1995, Walsh et al. 1997, Barrett et al. 1997, Barrett et al. 1998, Conlon and Journey 2008, Line and Hunt 2009, Storey et al. 2009, Maurer 2009, Mitchell 2010, NCHRP 2006). The heavy vegetative growth of the unmanaged vegetative roadside strip was capable of achieving higher peak flow reduction and total flow reduction relative to the managed vegetation strip. A mean peak flow reduction of 89.5% and 76.3% of the unmanaged and managed vegetative strips, respectively, provides hydraulic protection of the receiving stream reducing the frequency of the stream flow reaching erosive velocities. The total flow volume was reduced by 87.3% due to the unmanaged vegetative strip while the managed vegetative strip achieved a 80.7% reduction of total flow volume. The relatively high degree of runoff infiltration prevents migration of constituents of concern to receiving waters and results in moderate to high pollutant load mitigation. The unmanaged vegetative strip was a consistently more effective practice achieving higher removal efficiencies for each constituent of concern. Although not a statistically significant difference of runoff volume reduction between the managed and unmanaged vegetated strips, the unmanaged vegetated strip did show a higher average runoff volume reduction efficiency. The increased removal efficiency of the unmanaged vegetative strip is mostly attributed to higher infiltration rate due to increased flow resistance and possibly increased preferential flow pathways in the soil root zone caused by woodier plants in the unmanaged vegetated strip.

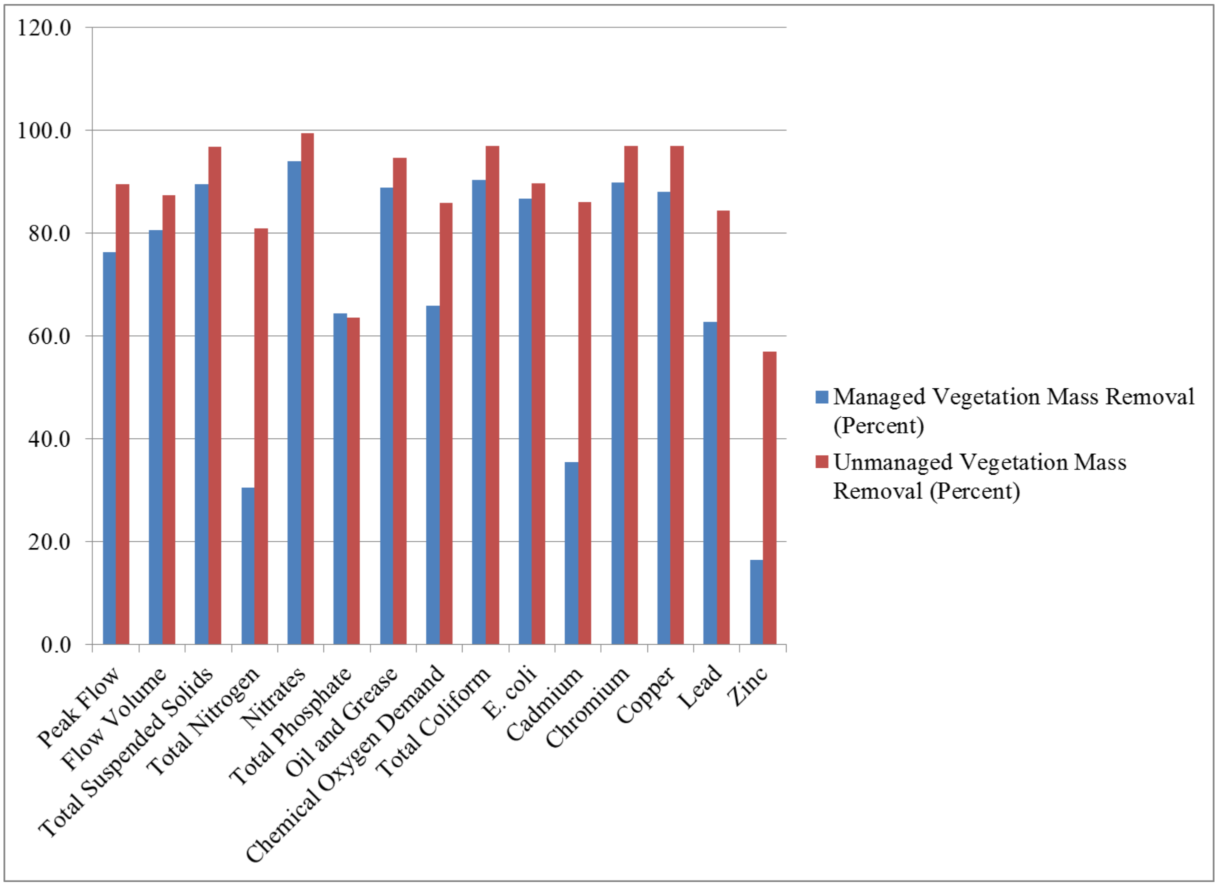

Figure 13 Mean hydraulic and constituent mass reduction efficiency of the managed and unmanaged vegetated strips

Table 11: Mean hydraulic and constituent mass reduction efficiency of the managed and unmanaged vegetated strips

Parameter	Managed Vegetation Mass Removal (Percent)	Unmanaged Vegetation Mass Removal (Percent)
Peak Flow	76.3	89.5
Flow Volume	80.7	87.3
Total Suspended Solids	89.5	96.8
Total Nitrogen	30.6	81.0
Nitrates	94.1	99.4
Total Phosphate	64.3	63.6
Oil and Grease	88.8	94.6
Chemical Oxygen Demand	65.8	85.8
Total Coliform	90.4	97.0
E. coli	86.7	89.8
Cadmium	35.5	86.0
Chromium	89.9	96.9
Copper	88.1	97.0
Lead	62.8	84.3
Zinc	16.4	57.0

Total flow volumes per storm event from both road runoff and vegetated roadside effluent can be seen in Figure 14. Vegetated roadsides showed less infiltration during the early spring months (while vegetation was still dormant) relative to late summer and fall. Although most of the year showed a substantial decrease in vegetated roadside effluent volume compared to Lorton Road runoff volume, early spring months showed an increase in stormwater runoff generated from the vegetated strips. This is suspected to be the result of the combined watershed area of Lorton Road and the vegetated roadside strip which provides a greater surface area relative to the watershed area of only Lorton Road. The surface areas of the vegetated roadsides appear to function as a low permeability surface during periods of the year when vegetation is dormant, which appears to generate additional runoff volume. During the summer and fall the vegetation appears to increase the permeability of the soil (Li et al. 2010) allowing for infiltration of not only rainfall onto the vegetated strips but also the Lorton Road runoff.

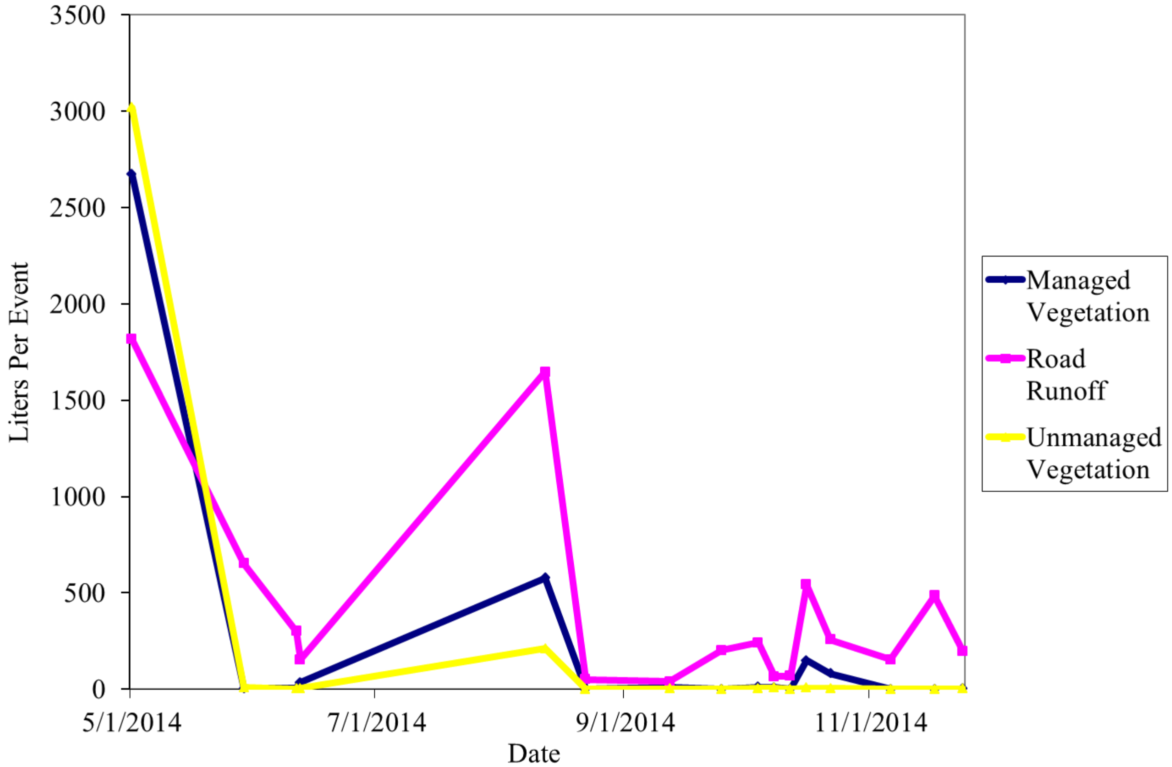

Figure 14: Total flow volumes from Lorton Road runoff and vegetated roadside strips of 18 storm events

4.4 Storm Event Monitoring

As described in the methods section, total rainfall depth and rainfall intensity of each monitored storm event was monitored using a tipping gauge rain gauge and the rainfall data were recorded in 5 minute intervals using the a Sigma 900 Max automated sampler. The average rainfall intensity was calculated by dividing the total rainfall depth by the duration of the storm event. This does include periods of no rainfall for rain events which are composed of multiple periods of rainfall during the total rainfall event duration. Therefore, the average rainfall intensity may be considerably lower than the intensity observed during periods of rainfall. Total rainfall depth and average rainfall intensity are provided in Table 12.

Table 12 Total rainfall depth and average rainfall intensity for each monitored storm event

Date	Total Rainfall Depth (inch)	Average Rainfall Intensity (inch/hour)
5/1/2014	3.49	0.07
5/29/2014	0.88	0.05
6/11/2014	0.74	0.03
6/12/2014	0.29	0.20
8/12/2014	2.82	0.15
8/22/2014	0.21	0.32
9/12/2014	0.13	0.26
9/25/2014	0.74	0.04
10/4/2014	0.37	0.05
10/8/2014	0.22	0.08
10/12/2014	0.38	0.02
10/16/2014	1.26	0.13
10/22/2014	0.91	0.04
11/6/2014	0.37	0.03
11/17/2014	0.76	0.07
11/24/2014	0.47	0.06

4.5 Non-Parametric Statistical Analysis

Sign test analysis was performed to determine whether Lorton Road runoff, managed vegetation strip effluent, or unmanaged vegetation strip effluent had statistically higher pollutant mass loadings. The Sign test analysis comparing the effluent of managed vegetated strip to the effluent of the unmanaged vegetated strip is provided below in Table 12. The Sign test analysis comparing Lorton Road runoff to the managed vegetated strip effluent is provided as Table 13. The Sign test analysis comparing the Lorton Road runoff to the unmanaged vegetated strip is provided as Table 14. The results of the Sign test show the mass loading of the Lorton Road runoff was statistically higher for every constituent of concern and hydraulic parameter when compared to both the managed and unmanaged vegetative roadside strip. The managed vegetated strip was statistically higher for the following four constituents of concern: total nitrogen, total phosphate, copper, and zinc, as well as peak flow.

TABLE 13: Sign Test Analysis of Mass Loading Comparing Managed and Unmanaged Vegetated Strips

Managed Versus Unmanaged	Significant	N value	p-value	Site That is Statistically Greater
Peak Flow	Yes	11	0.0005	Managed
Total Flow	no	12	0.073	Neither
Total Suspended Solids	no	7	0.5	Neither
Total Nitrogen	yes	9	0.002	Managed
Phosphate	yes	9	0.0176	Managed
Nitrate	no	6	0.344	Neither
Chemical Oxygen Demand	no	9	0.09	Neither
Total Coliform	no	4	0.688	Neither
E. coli	no	4	0.688	Neither
Cadmium	no	9	0.09	Neither
Chromium	no	9	0.09	Neither
Copper	yes	9	0.018	Managed
Lead	no	9	0.5	Neither
Zinc	yes	9	0.018	Managed
Oil and Grease	no	10	0.172	Neither

Table 14 Sign Test Analysis of Mass Loading Comparing the Lorton Road Runoff to the Managed Vegetation Effluent

Managed Vegetation Versus Road Runoff	Significant	N value	p-value	Site That is Statistically Greater
Peak Flow	yes	16	0.0002	Road
Total Flow	yes	16	0.0002	Road
Total Suspended Solids	yes	16	1.52588E-05	Road
Total Nitrogen	yes	16	0.0105	Road
Phosphate	yes	16	1.52588E-05	Road
Nitrate	yes	16	0.0007	Road
Chemical Oxygen Demand	yes	15	0.011	Road
Total Coliform	yes	10	0.001	Road
E. coli	yes	8	0.035	Road
Cadmium	yes	16	0.0156	Road
Chromium	yes	16	3.8147E-06	Road
Copper	yes	16	3.8147E-06	Road
Lead	yes	16	7.24792E-05	Road
Zinc	yes	16	0.0038	Road
Oil and Grease	yes	16	1.52588E-05	Road

Table 15 Sign Test Analysis Comparing the Lorton Road Runoff to the Unmanaged Vegetated Strip Effluent

Unmanaged Vegetation Versus Road Runoff	Significant	N value	p-value	Site That is Statistically Greater
Peak Flow	yes	16	7.24792E-05	Road
Total Flow	yes	16	7.24792E-05	Road
Total Suspended Solids	yes	16	1.52588E-05	Road
Total Nitrogen	yes	16	7.24792E-05	Road
Phosphate	yes	16	7.24792E-05	Road
Nitrate	yes	16	0.0007	Road
Chemical Oxygen Demand	yes	15	7.24792E-05	Road
Total Coliform	yes	10	0.001	Road
E. coli	yes	8	0.0039	Road
Cadmium	yes	16	3.8147E-06	Road
Chromium	yes	16	3.8147E-06	Road
Copper	yes	16	3.8147E-06	Road
Lead	yes	16	7.24792E-05	Road
Zinc	yes	16	7.24792E-05	Road
Oil and Grease	yes	16	1.52588E-05	Road

4.6 Thermal Load

As described in the methods section, runoff temperatures were logged every one minute throughout an entire storm event for five storm events between September 12th and October 14th. These data were collected to determine if vegetated roadsides had potentially beneficial or negative effects on runoff temperatures and, consequently, on receiving waters. The temperature data were correlated to the flow data logged during storm events to determine total thermal loads potentially impacting receiving waters. Mean temperature of runoff per storm event was calculated for Lorton Road, the managed roadside vegetation strip, and the unmanaged roadside vegetation strip. These data are presented as Figure 15. Averaged over the five storm events, the managed vegetated roadside strip reduced runoff temperature by 3.3 percent. The unmanaged vegetated roadside strip reduced runoff temperature by 3.0 percent. However, infiltration in the vegetated strips of flow volume which could potentially migrate heat from the road surface to receiving waters reduced the thermal load potentially impacting receiving waters. The managed vegetated strip reduced the thermal load of the effluent by 83.0 percent compared to the Lorton Road runoff. The unmanaged vegetated strip reduced the thermal load of the effluent by 98.2 percent. From the collected data it can be seen that the temperature of the effluent of the vegetated roadside strips was less than the temperature of the Lorton Road runoff for each of the five storm events. It should be noted that there was no effluent from the unmanaged vegetated strip for the October 14th event due to complete infiltration of all runoff. With the assumption that the Lorton road runoff is higher temperature than the receiving stream, the data suggest that vegetated roadsides have a beneficial impact on runoff temperatures which could help protect aquatic organisms vulnerable to thermal change. Thermal load was calculated as described in the section titled “Data Analysis” and is presented in Figure 16.

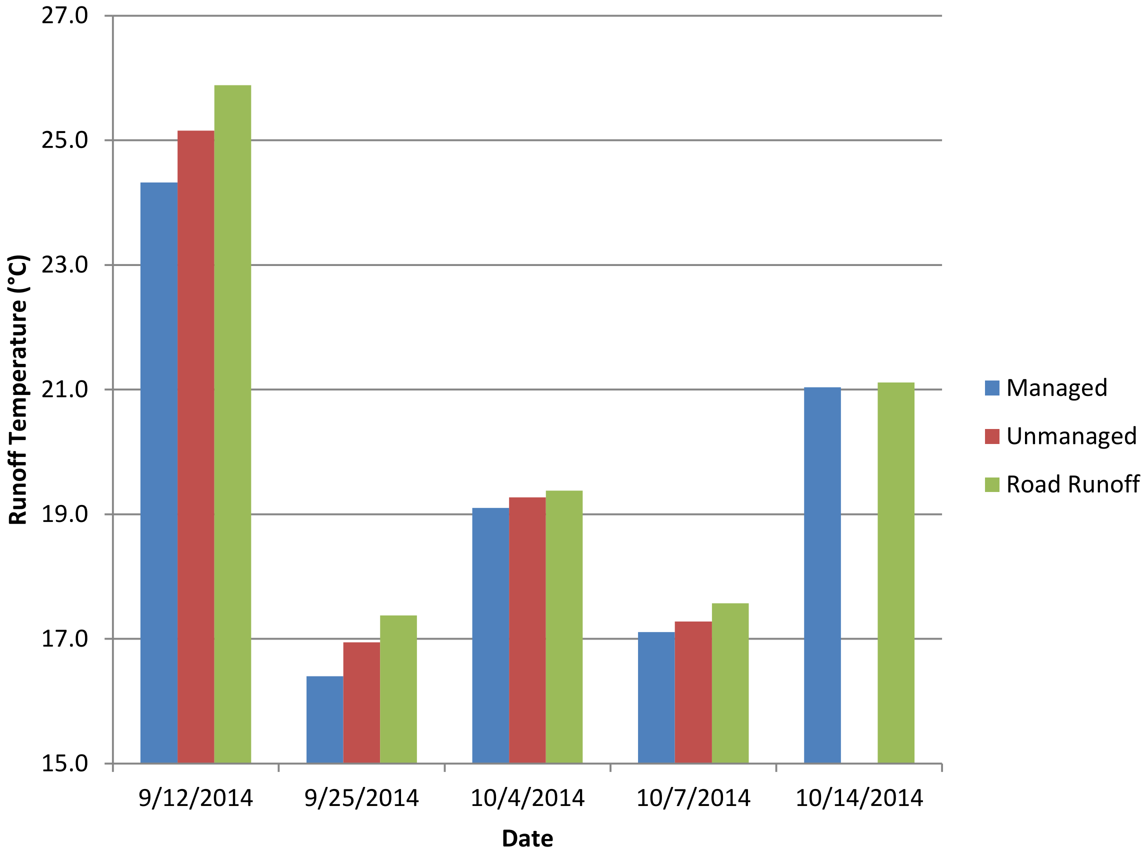

Figure 15: Stormwater runoff temperature from Lorton Road, managed roadside vegetation, and unmanaged roadside vegetation per storm event

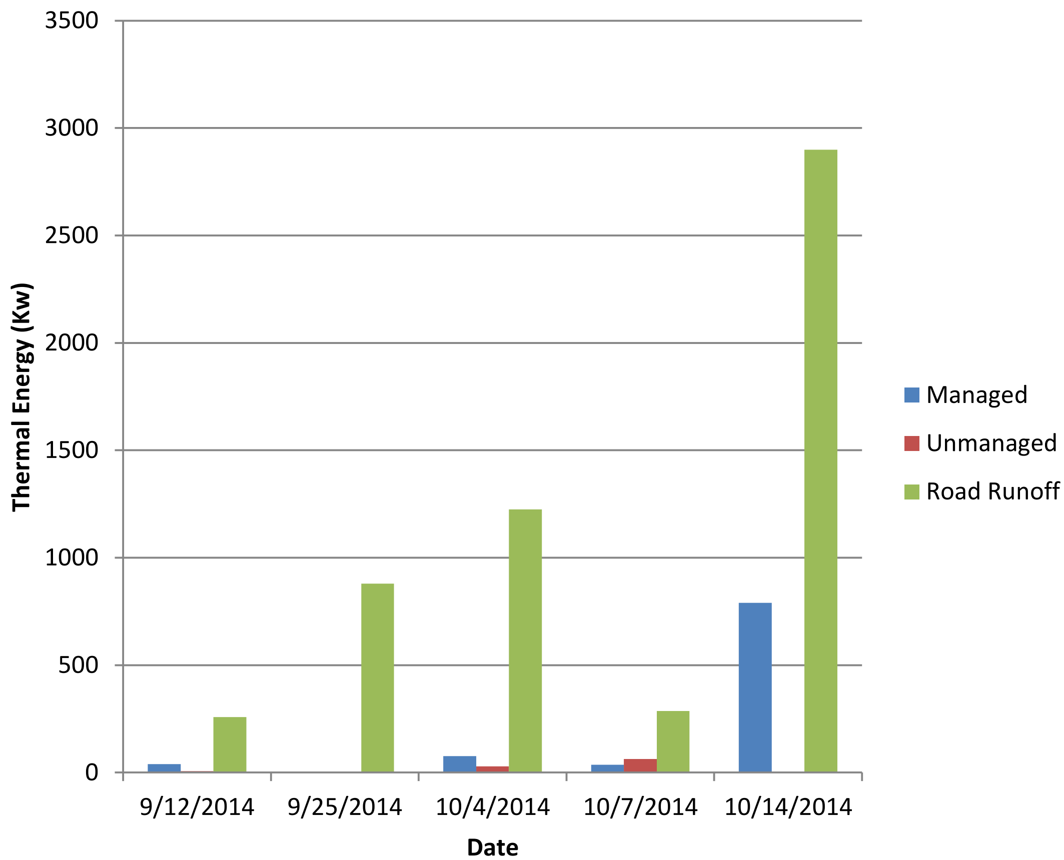

Figure 16: Thermal energy of runoff from Lorton Road, managed roadside vegetation, and unmanaged roadside vegetation per storm event

4.7 Linear Regression Modeling

Linear regression was employed as a method of modeling the relationship of both rainfall characteristics and vegetative roadside strip influent with vegetative roadside strip effluent. Hydraulic and water quality modeled predictions were made using the observed rainfall and Lorton Road runoff data collected during the study as independent variable data and observed vegetated roadside effluent data as observed dependent variables. The May 1st storm event had a total rainfall depth of 3.49 inches and was responsible for a relatively large percentage of the total mass migrated from the road surface throughout the entire study. Therefore, the mass load for that storm event has a large influence on the liner regression models for mass load.

Consideration had been given to removal of the data from that storm event, particularly when considering that LID systems are not designed to improve the water quality of storms of that magnitude. However, given the importance of the storm event in determining the overall performance of vegetated strips the decision was made to keep the data as part of the linear regression models.

The relationship relating total rainfall depth to total flow volume of runoff from Lorton Road was modeled to predict total runoff volume for a given storm event and, therefore, the vegetated roadside influent volume for any given storm event. Similarly, average rainfall intensity to peak flow rate of Lorton Road runoff was modeled to predict hydraulic flow rates which may cause erosive velocities of receiving streams for given rainfall intensities. The developed linear regression models for relating total rainfall depth to total flow volume and average rainfall intensity to peak flow rate are shown in Figure 17 and Figure 18. Using a total rainfall depth average from the observed 16 storm events of 0.88 inch the linear regression model predicts a total flow volume of 436.5 liters of runoff from Lorton Road compared to the observed average of 429.3 liters. Using an average rainfall intensity averaged from the observed 16 storm events of 0.10 inch per hour the linear regression model predicts a peak runoff flow rate of 2.67 gallons per minute compared to the observed average peak flow rate of 2.35 gallons per minute. However, the relatively flat slope of the linear regression does not suggest a strong correlation relating the average rainfall intensity to Lorton Road runoff peak flow rates.

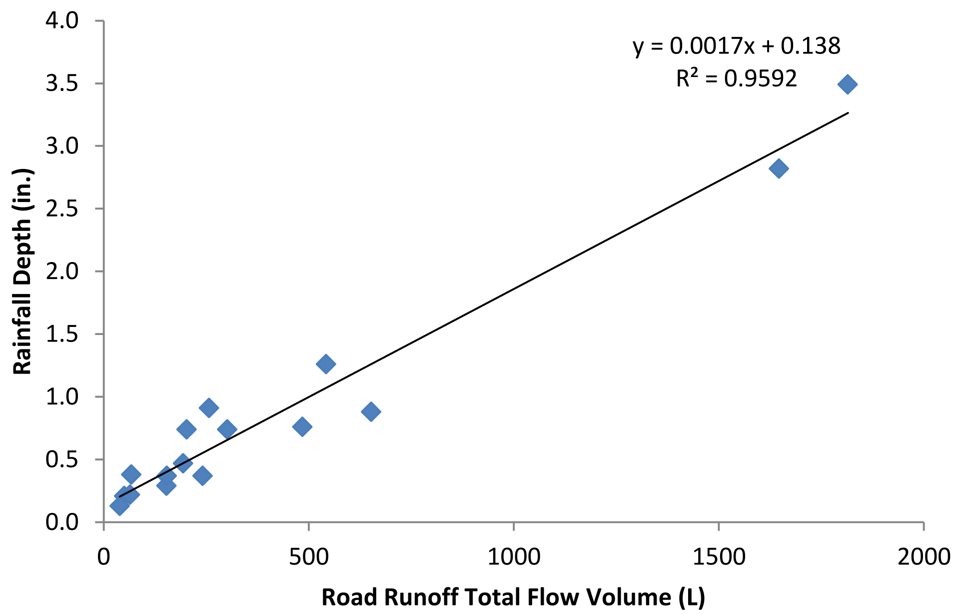

Figure 17: Total rainfall depth per storm event versus total road runoff flow volume

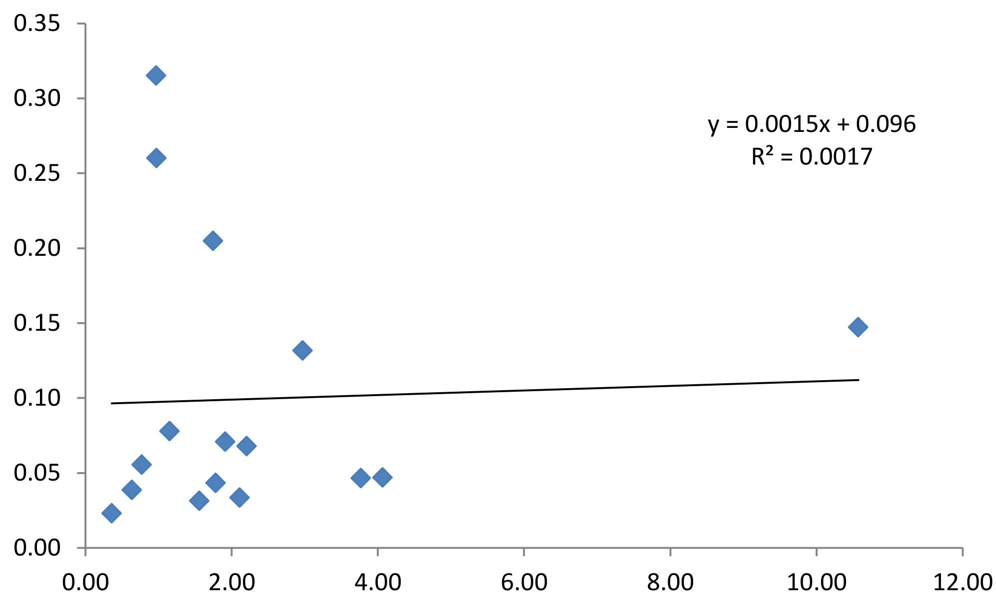

Figure 18: Average rainfall intensity per storm event versus Lorton Road runoff peak flow rates

Linear regression modeling of both the managed and unmanaged vegetative strips was developed as a tool to predict hydraulic properties of vegetated roadside effluent for known or assumed storm event total rainfall depth and average rainfall intensity. The linear regression models are also used to determine the effectiveness of vegetative roadsides for hydraulic management of stormwater runoff and comparing the relative effectiveness of managed and unmanaged vegetative roadsides. The linear regression models for total rainfall depth versus managed and unmanaged vegetation effluent total flow volumes are shown in Figure 19 and Figure 20, respectively, while the average rainfall intensity versus managed and unmanaged vegetated strip effluent peak flow rates are shown in Figure 21 and Figure 22, respectively. The average rainfall depth over the course of the study of 0.88 inch was used for predicting the total effluent volume of the managed and unmanaged vegetative strips. The predicted total flow volume of the managed vegetative strip is 226.1 liters compared to the observed average total effluent flow volume of 222.3 liters. The predicted total flow volume of the unmanaged vegetative strip is 202.0 liters compared to the observed average total effluent flow volume of 204.4 liters.

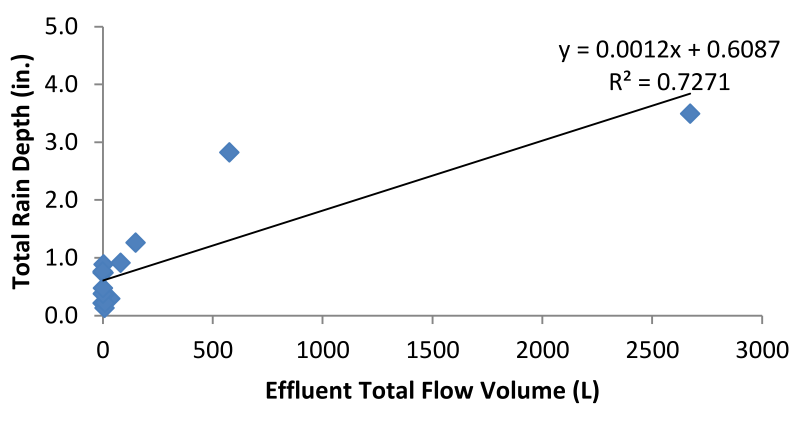

Figure 19: Total rainfall depth per storm event versus total effluent flow volume of the managed vegetated roadside strip

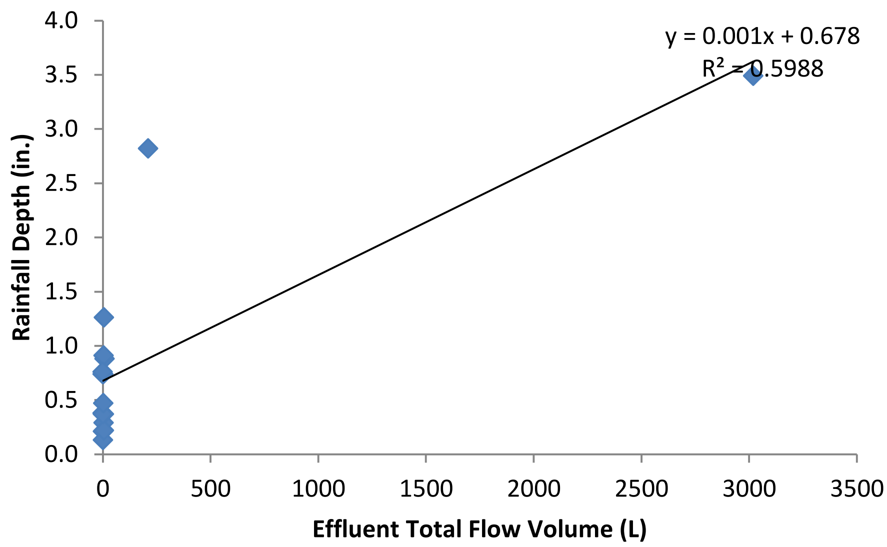

Figure 20: Total rainfall depth per storm event versus total effluent flow volume of the unmanaged vegetated roadside strip

The average rainfall intensity per storm event, averaged over the course of the study, of 0.10 inch per hour was used to predict the effluent peak flow of the managed and unmanaged vegetative strip. A peak effluent flow rate of 1.04 gallons per minute is predicted for the managed vegetative strip compared to the observed average of 0.93 gallons per minute while a peak effluent flow rate of 0.71 gallons per minute compared to the observed average of 0.33 gallons per minute. However, the relatively flat slope of the average rainfall intensity versus peak effluent flow rate suggests there is little correlation relating average rainfall intensity to peak effluent flow rate. This is likely due to averaging of rainfall intensities over the course of a rain event which likely hides the peak rainfall intensity which would be more directly correlated to peak flow rate.

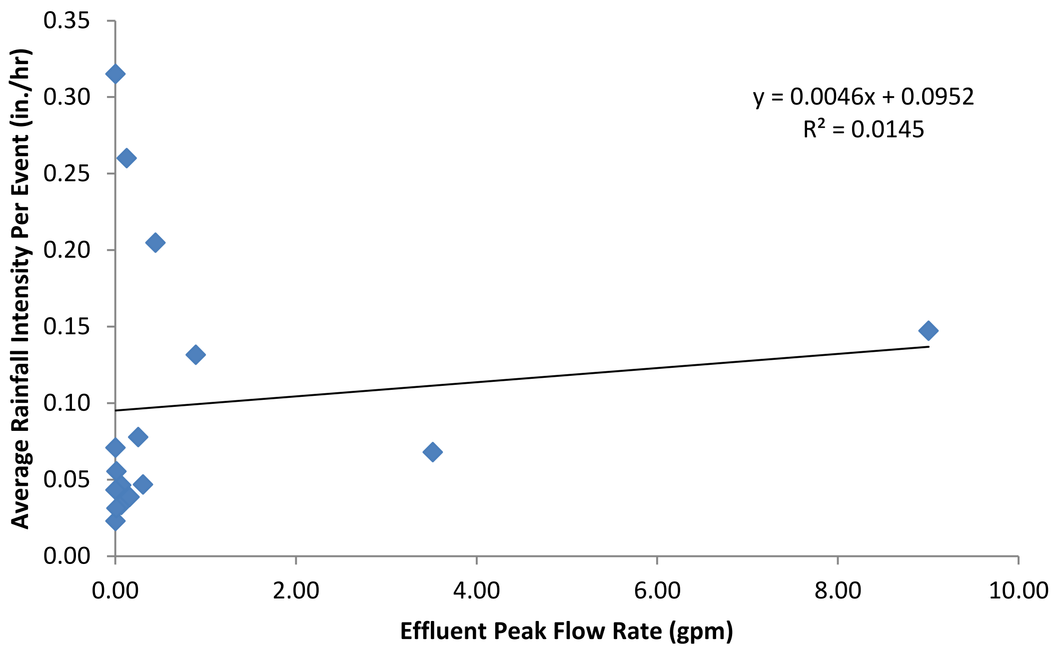

Figure 21: Average rainfall intensity per storm event versus effluent peak flow rate of managed vegetation strip

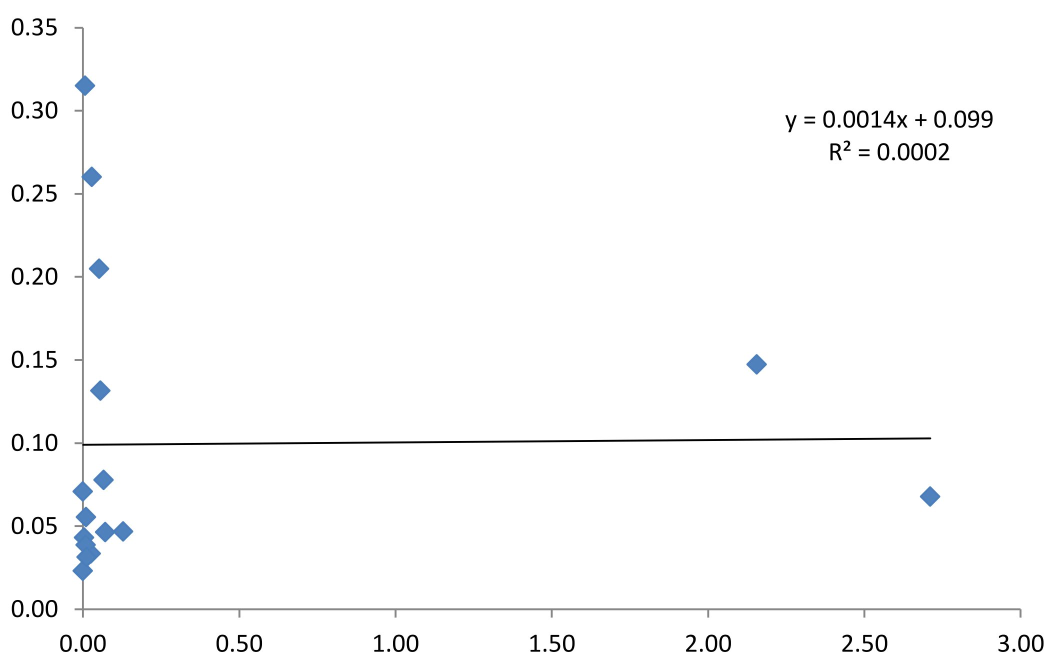

Figure 22: Average rainfall intensity per storm event versus peak flow rate of unmanaged vegetated strip

Linear regression modeling was developed relating Lorton Road runoff to the effluent of the managed and unmanaged vegetated roadside strips for both total suspended solids concentrations and mass loading. These models were developed to not only predict vegetated roadside effluent water quality given a known or assumed road runoff quality but also for determining the effectiveness of vegetated roadsides for total suspended solids mitigation. The results of the linear regression modeling of the managed vegetated strip and unmanaged vegetated strip total suspended solids concentration are shown in Figure 22 and Figure 23, respectively. Using the total suspended solids event mean concentration of the Lorton Road runoff, averaged over the course of the study, as the vegetated strip influent concentration 1870.3 mg/L the managed vegetated strip linear regression model predicts a concentration of 130.1 mg/l compared to the observed averaged concentration of 130.1 mg/L. The linear regression model of the unmanaged vegetated strip predicts a total suspended solids concentration of 231.3 mg/L compared to the observed average concentration of 231.3 mg/L. The managed vegetated strip linear regression model predicts an average total suspended solids reduction efficiency of 93.0 percent while the unmanaged vegetated strip predicts an average reduction efficiency of 87.6 percent.

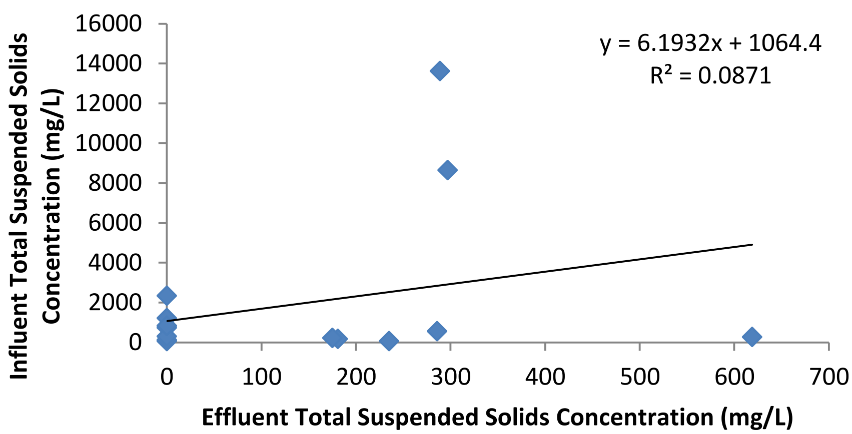

Figure 23: Linear regression model of the total suspended solids concentration of the managed vegetated strip

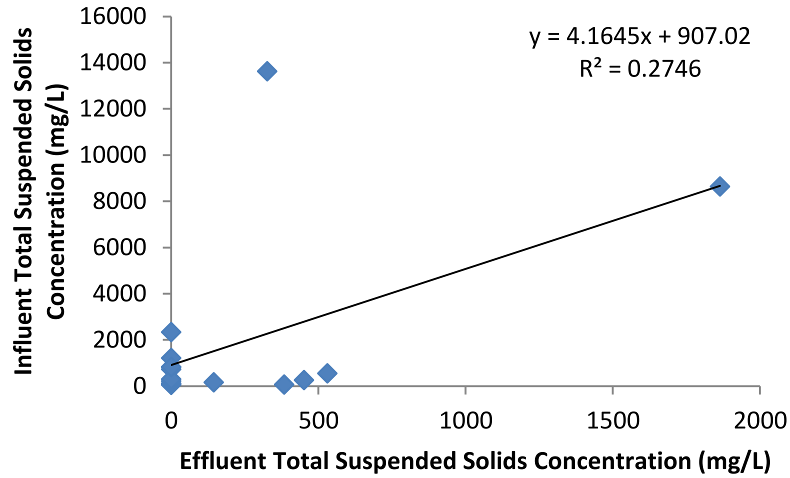

Figure 24: Linear regression of the total suspended solids concentration of the unmanaged vegetated strip

Linear regression modeling of the total suspended solids mass loading for the managed vegetated strip and unmanaged vegetated strip are shown in Figure 25 and Figure 26. Using the average observed mass load of 1818.0 grams, determined from the Lorton Road runoff as the mass loading influent, the linear regression model of the total suspended solids mass loading of the managed vegetated strip predicts an effluent mass loading of 60.3 grams. The unmanaged vegetated strip, given the same influent conditions, predicts an effluent mass loading of 68.3 grams. Although the model predicts a substantially higher effluent concentration of total suspended solids of the unmanaged vegetated strip, the total suspended solids mass loading of the unmanaged vegetated strip is less than that of the managed vegetated strip. This is likely attributed to the increased infiltration of the Lorton Road runoff within the unmanaged vegetated strip. Linear regression modeling predicts and average mass load reduction of total suspended solid mass by 96.7 percent for the managed vegetated strip and 96.4 percent for the unmanaged vegetated strip.

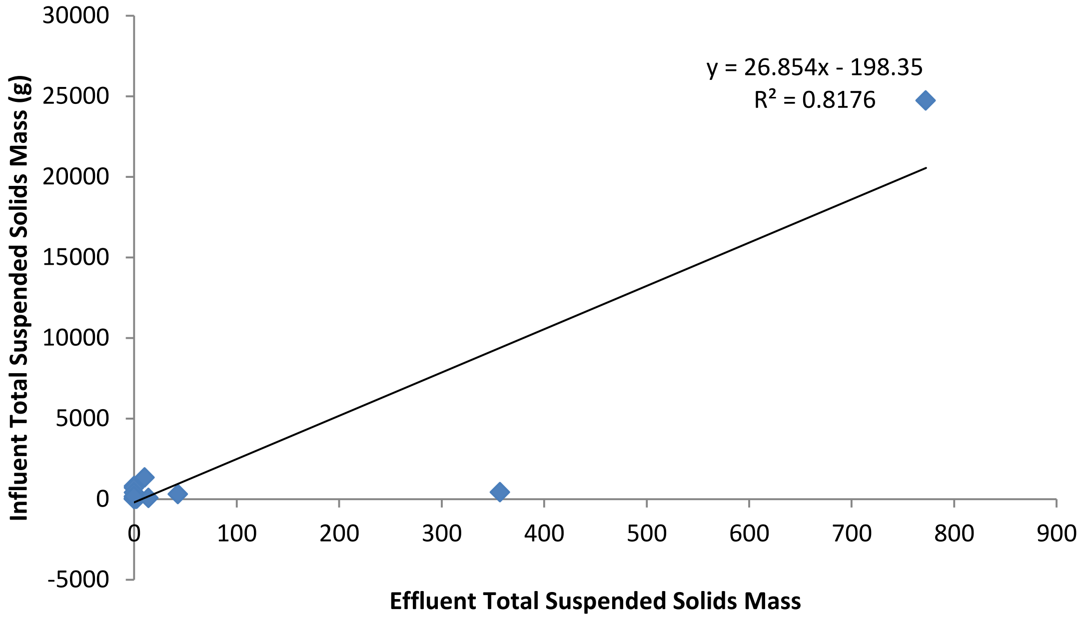

Figure 25: Linear regression model of the total suspended solid mass loading of the managed vegetated strip

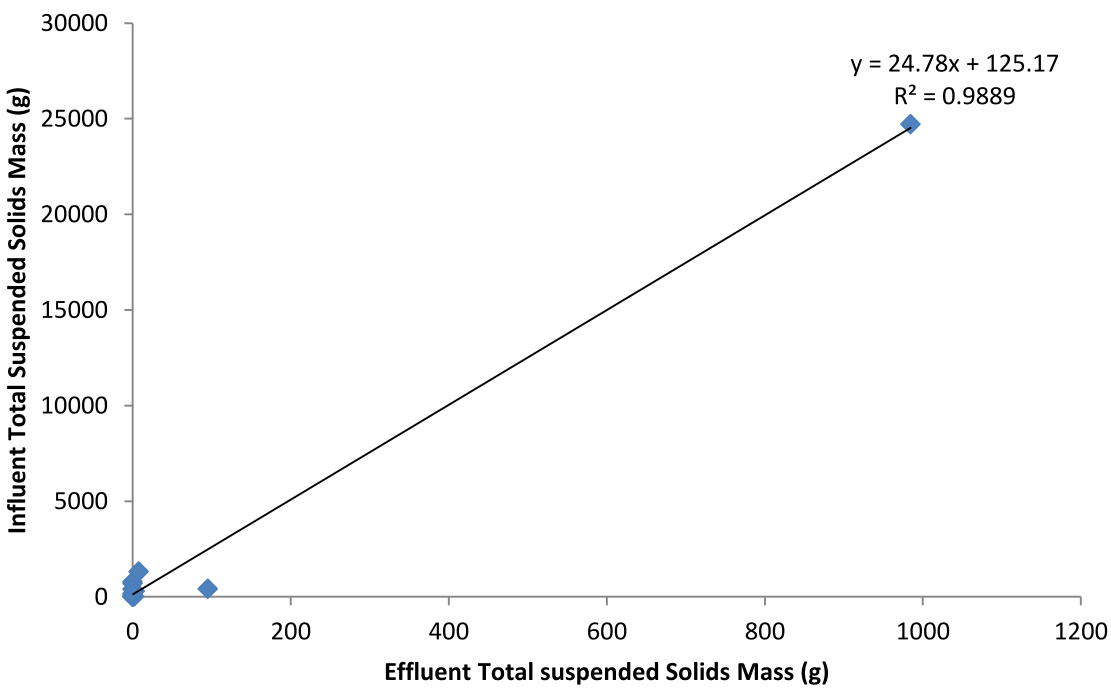

Figure 26: Linear regression model of the total suspended solids mass loading of the unmanaged vegetated strip

Linear regression modeling was performed for nitrate concentration and mass loading for the managed and unmanaged vegetated strips evaluated in this study. The results of the nitrate concentration modeling of the managed vegetation strip are presented in Figure 27. The results of the nitrate concentration modeling of the unmanaged vegetated strip are presented in Figure 28. The observed Lorton Road runoff nitrate concentration of 0.73 mg/l averaged from the 16 storm events monitored during this study was used as the influent concentration to develop the linear regression nitrate concentration models. A concentration of 0.20 mg/l is predicted as the nitrate effluent concentration for the managed vegetated strip compared to the observed average nitrate concentration of 0.19 mg/l. A concentration of 0.26 mg/l is predicted as the nitrate concentration for the unmanaged vegetated strip compared to the observed average of 0.23 mg/l. Linear regression modeling predicts an average nitrate concentration reduction efficiency of 72.6 percent for the managed vegetated strip and 64.4 percent for the unmanaged vegetated strip.

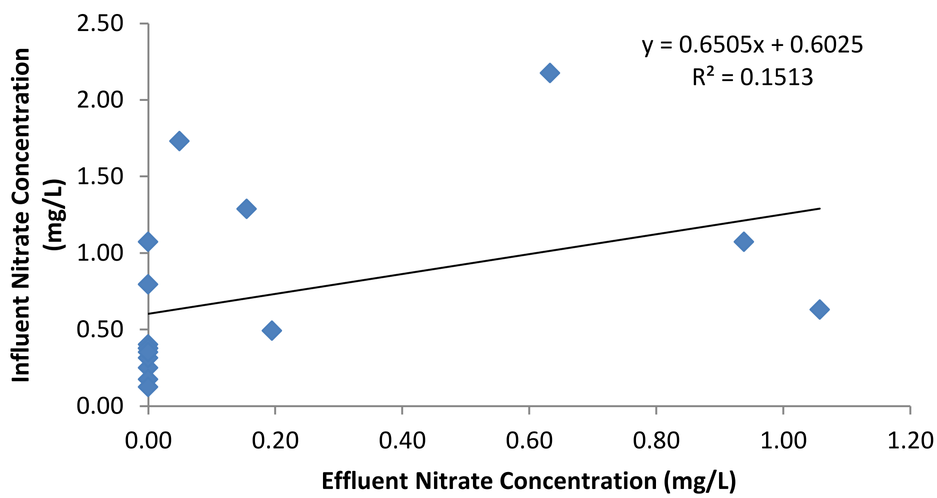

Figure 27: Linear regression modeling of nitrate concentrations of the managed vegetated strip

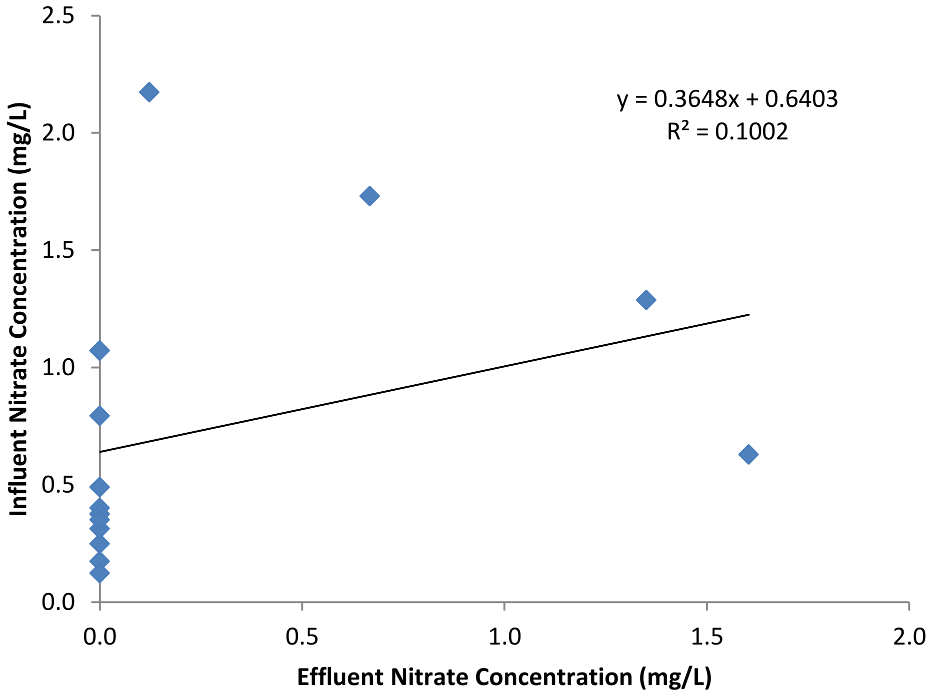

Figure 28: Linear regression modeling of the nitrate concentration of the unmanaged vegetated strip

Linear regression models of the nitrate mass loading of the managed and unmanaged vegetated strips are presented in Figure 29 and Figure 30, respectively. The averaged Lorton Road runoff mass loading of 380.1 mg was used to calculate average predicted values for the managed and unmanaged vegetated strips for model validation and evaluation and comparison of each vegetated roadside strip. An average predicted nitrate mass loading of 38.0 mg was calculated for the managed vegetated strip while a nitrate mass loading of 2.76 mg was calculated for the unmanaged vegetated strip. These predicted values can be compared to the observed mass loadings of 37.9 mg for the managed vegetated strip and 2.76 mg for the unmanaged vegetated strip. These results suggest that both vegetated roadside strips are capable of reducing mass loading of nitrate regardless of the vegetation management routine employed. However, the unmanaged vegetated strip was capable of achieving higher reductions of mass loading despite having higher effluent concentrations. This is likely the result of increased infiltration of Lorton Road runoff volume within the unmanaged vegetated strip. Linear regression modeling predicts an average nitrate mass reduction efficiency of 90.0 percent for the managed vegetated strip and 99.3 percent for the unmanaged vegetated strip.

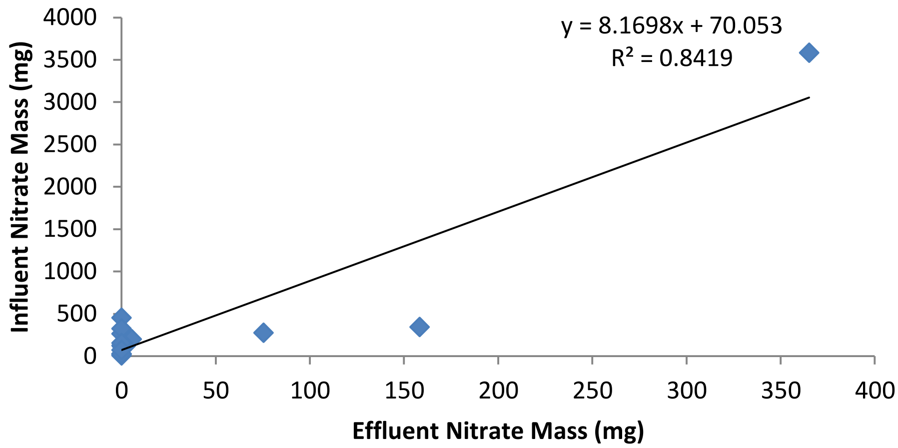

Figure 29: Linear regression of nitrate mass loading of the managed vegetated strip

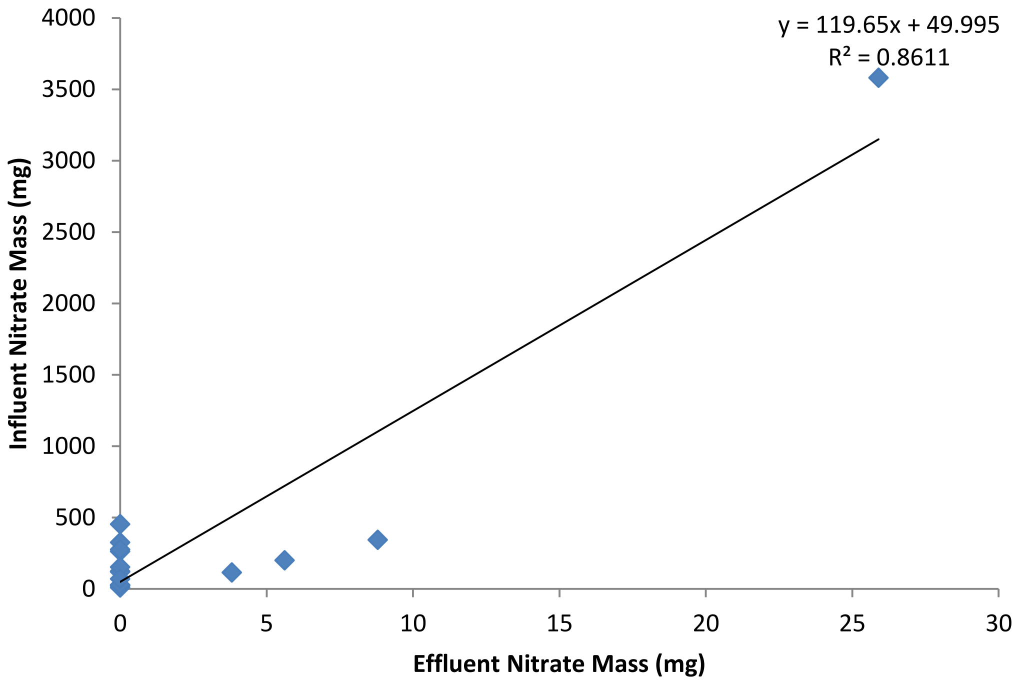

Figure 30: Linear regression modeling of nitrate mass loading of the unmanaged vegetated strip

Linear regression modeling was performed for total nitrogen concentration and mass loading of the managed and unmanaged vegetated strips evaluated in this study. The total nitrogen linear regression concentration models are presented in Figure 31 for the managed vegetative strip and Figure 32 for the unmanaged vegetated strip. The total nitrogen concentration of the Lorton Road runoff, averaged over the 16 storm events, of 1.93 mg/l was used as the influent concentration for the linear regression models of the managed and unmanaged vegetated strips. The linear regression model predicts an effluent total nitrogen concentration of 3.20 mg/l for the managed vegetative strip compared to the observed average of 2.50 mg/l. An effluent concentration of 3.30 mg/l of total nitrogen is predicted for the unmanaged vegetative strip compared to the observed averaged concentration of 3.14 mg/l. The relatively flat slope of the regression model suggests that the influent concentration is near or below the total nitrogen reducible concentration for vegetated roadsides regardless of the vegetation management routine employed. Therefore, effluent total nitrogen concentrations would be expected to be near to or higher than those of the influent for the managed and unmanaged vegetated strips. Linear regression modeling predicts an average increase of total nitrogen mass by 65.8 percent for the managed vegetated strip and 71.0 for the unmanaged vegetated strip.

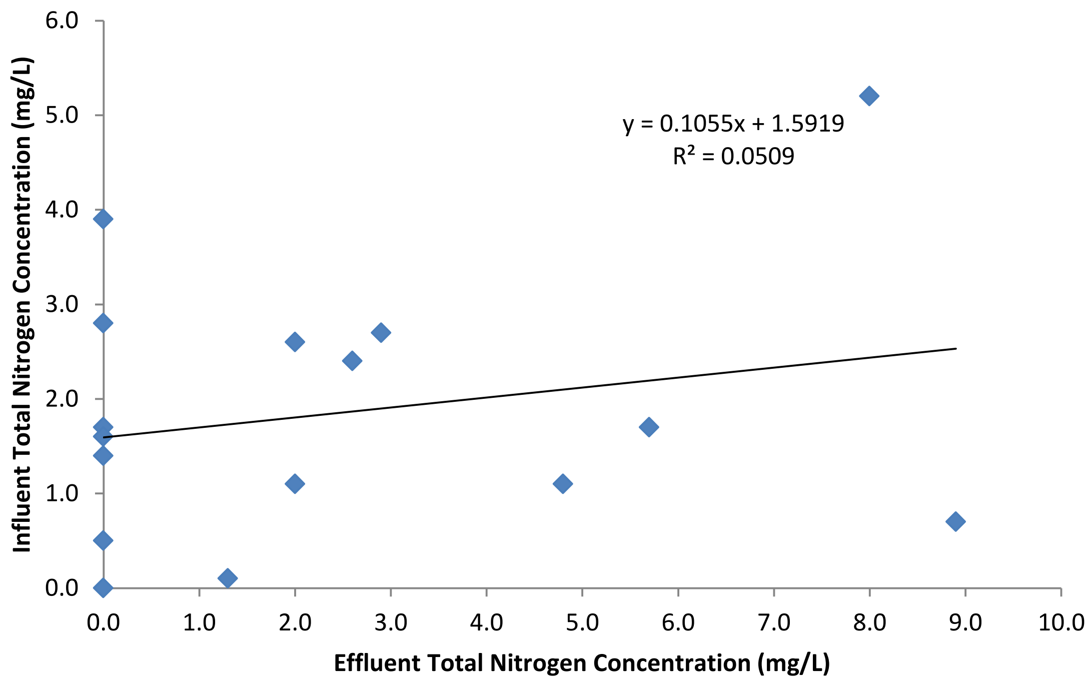

Figure 31: Linear regression model of total nitrogen of the managed vegetated strip

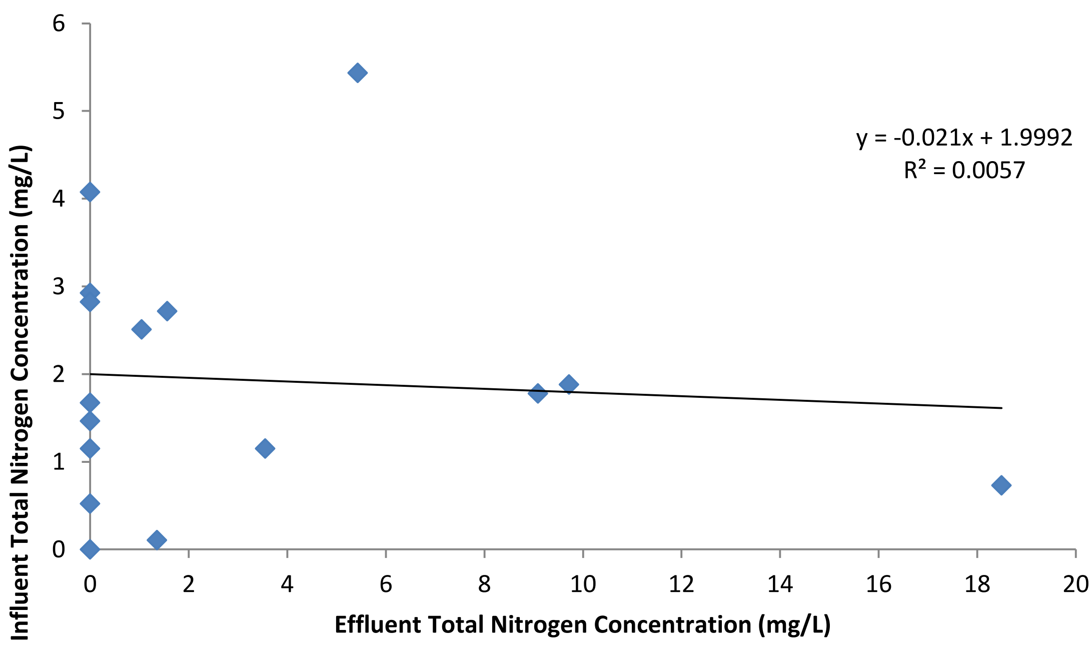

Figure 32: Linear regression model of total nitrogen concentration of the unmanaged vegetated strip

Linear regression models for the total nitrogen mass loading are shown for the managed vegetated strip and unmanaged vegetated strip in Figure 33 and Figure 34, respectively. The observed total nitrogen mass loading of the Lorton Road runoff, averaged over the 16 storm events monitored during this study, of 1031.2 mg was used as the influent mass loading for the managed and unmanaged vegetated strips to calculate the predicted average total nitrogen mass loading. The predicted average total nitrogen mass loading of the managed vegetated strip effluent was calculated to be 1631.6 mg compared to the observed average of 1631.4 mg. The predicted average total nitrogen mass loading of the unmanaged vegetated strip effluent was calculated to be 1085.3 mg compared to the observed average total nitrogen loading of 1085.3 mg. The results of the linear regression model suggest that vegetated roadsides perform as a nitrogen export as opposed to mitigating nitrogen despite infiltration conditions reducing total runoff volumes. However, the mass reduction performance calculated per storm event averages out to a 30.6 percent and 81.0 percent reduction of total nitrogen mass in the effluent of the managed and unmanaged vegetated strip, respectively. This may be due to the extreme outlying total nitrogen mass in the effluent of the managed and unmanaged vegetated strips in the May 1st, 2014 storm event.

The total nitrogen mass of the managed vegetated strip effluent for the May 1st storm event was responsible for 85.9 percent of the total nitrogen mass of the managed vegetated strip effluent measured throughout the entire study and 94.5 percent of the unmanaged effluent total nitrogen mass measured throughout the study. The Lorton Road runoff total nitrogen mass loading of the May 1st storm event was responsible for 60 percent of the total mass of total nitrogen migrated from the road surface during the course of this study. This was the first storm event monitored for all three monitoring locations, the Lorton Road runoff and both vegetated strips. The total rainfall for the May 1st event was 3.41 inch, the largest rainfall depth of any rain event monitored throughout the study. The May 1st storm event accounted for 24.9 percent of the total rainfall depth of the 16 monitored storms. Given that this was one of the first rain events of the spring it is conceivable that nutrient build up from decayed fall vegetation as well as other sources throughout the winter would be released at a high concentration during the first large spring rain event, resulting in a large mass transport through the vegetated strips. It should be noted that although the managed vegetated strip was did undergo a vegetation management routine during the study, no vegetation management routine was performed prior to beginning the monitoring program. Therefore, it is not possible to say whether vegetation management of the previous year would have prevented the extreme outlier or whether the vegetation management of performed during this study may have prevent a large nitrogen export from taking place during the following spring.

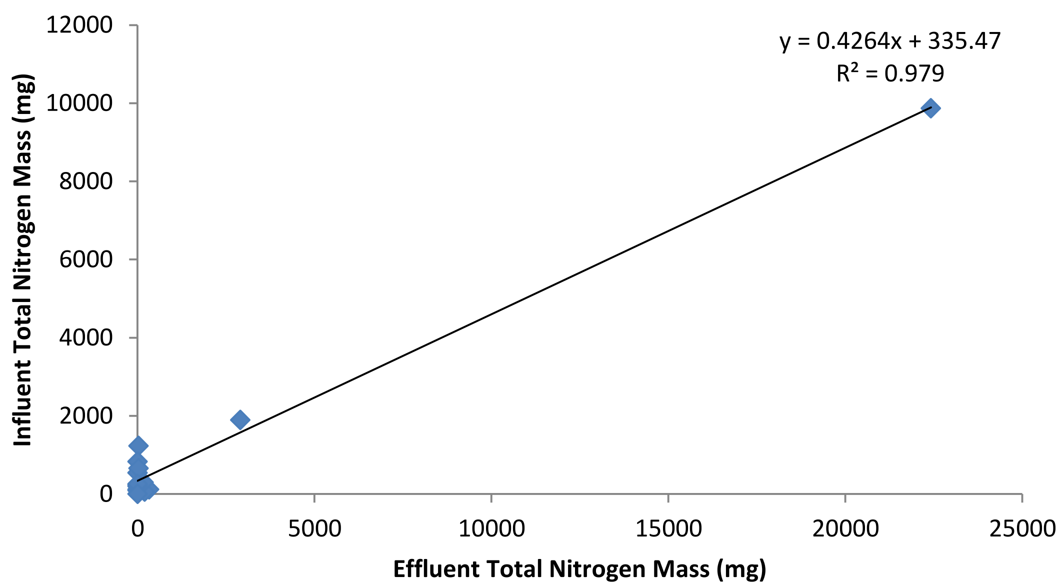

Figure 33: Linear regression model of total nitrogen mass of the managed vegetated strip

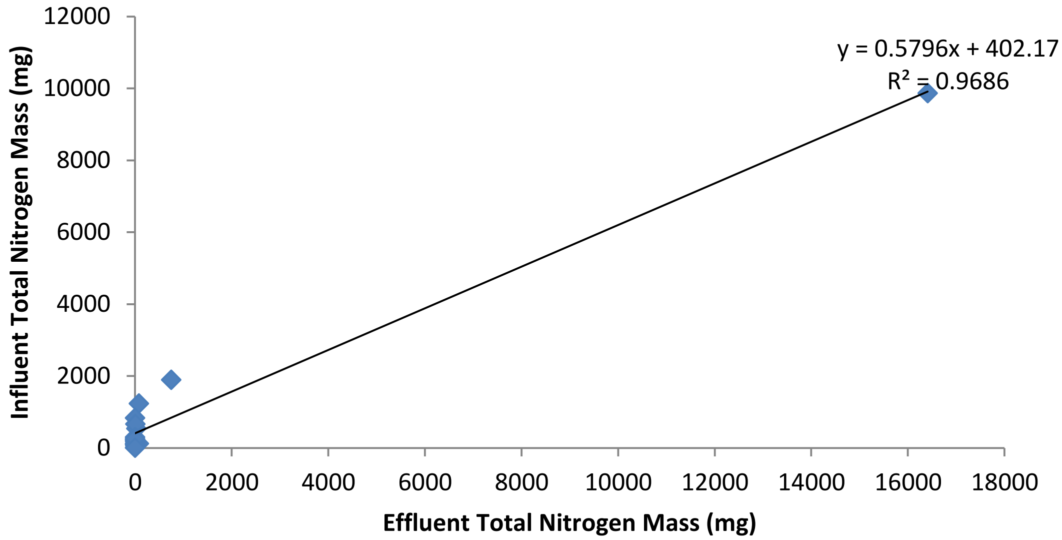

Figure 34: Linear regression model of total nitrogen of the unmanaged vegetated strip

Linear regression modeling was performed for total phosphate concentration and mass loading of the managed and unmanaged vegetated strips evaluated in this study. The total phosphate concentration of 1.03 mg/l from the Lorton Road runoff, averaged over the 16 storm events monitored was used as the influent concentration of the managed and unmanaged vegetated strips. The result of the linear regression model is shown in Figure 35 and Figure 36 for the total phosphate concentration of the managed vegetated strip and unmanaged vegetated strip, respectively. The linear regression model for total phosphate of the managed vegetated strip predicts an effluent concentration of 0.98 mg/l compared to the observed average effluent concentration of 0.98 mg/l. The linear regression model of the unmanaged vegetated strip predicts an effluent concentration of 0.64 mg/l compared to the observed average effluent concentration of 0.63 mg/l. Linear regression modeling predicts an average total phosphate concentration reduction of 4.9 percent for the managed vegetated strip and 37.9 percent fro the unmanaged vegetated strip.

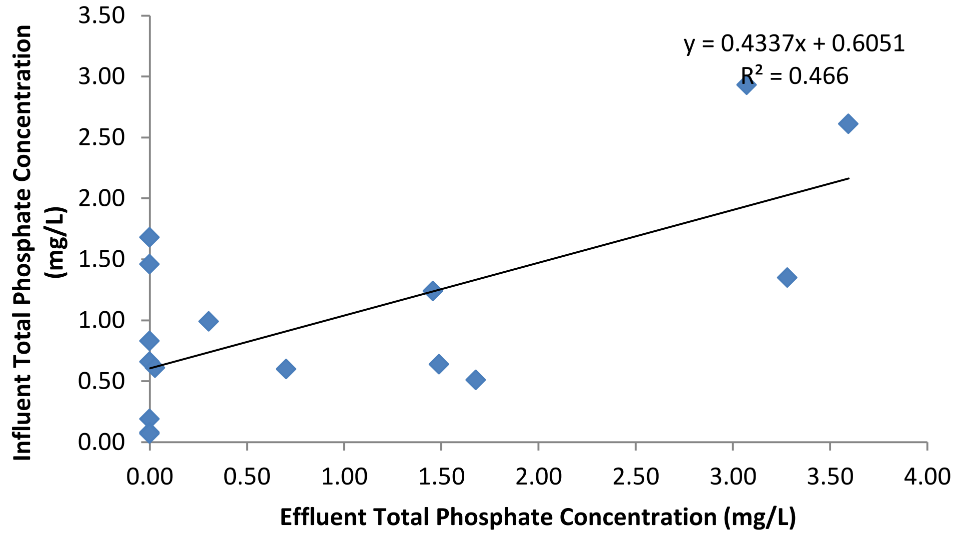

Figure 35: Linear regression model of total phosphate concentration for the managed vegetated strip

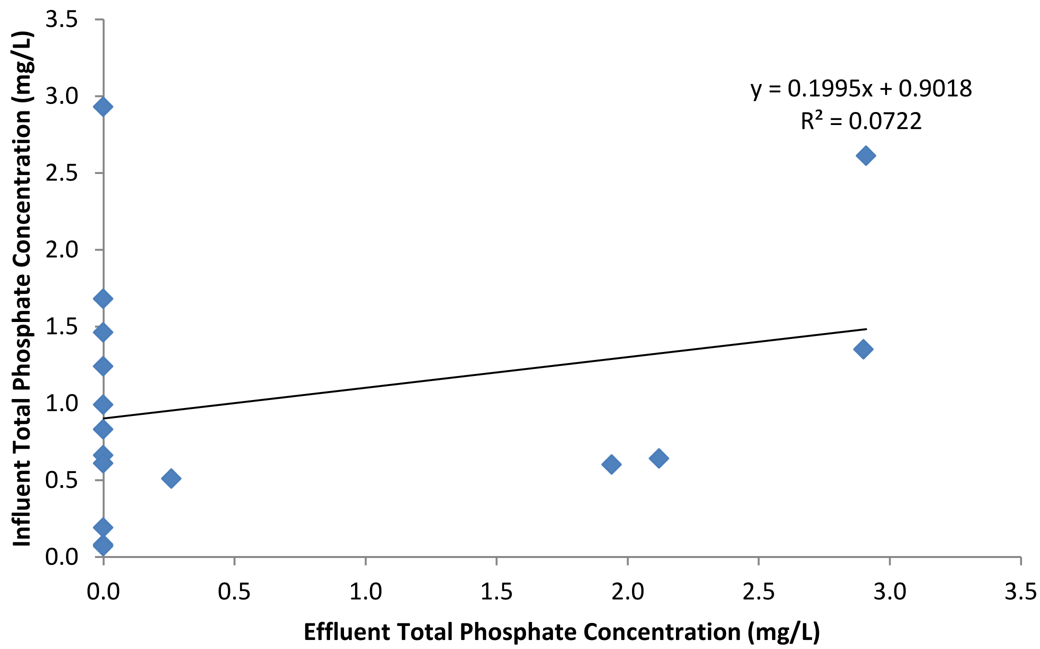

Figure 36: Linear regression model of total phosphate concentration of the unmanaged vegetated strip

The total phosphate mass loading of 387.8 mg, determined from the Lorton Road runoff and averaged over the 16 monitored storm events, was used as the influent mass loading of the managed and unmanaged vegetated strips. The result of the linear regression model of the managed vegetated strip is shown in Figure 37 and the unmanaged vegetated strip linear regression model is shown in Figure 38. Linear regression modeling performed for the managed vegetated strip predicts an effluent total phosphate mass loading of 459.3 mg compared to the observed average effluent mass loading of 326.0 mg. Linear regression modeling of the unmanaged vegetated strip predicts a mass loading of 405.9 mg compared to the observed average effluent mass loading of 406.2 mg. Linear regression modeling predicts and average phosphate mass load increase of 18.4 percent for the managed vegetated strip and 4.7 percent for the unmanaged vegetated strip. Phosphate mass loading appears to show a similar phenomenon as that observed in the total nitrogen mass loading with an large percentage of the total mass of total phosphate migrating from the vegetated strips during the first monitored storm event occurring on May 1st, 2014.

The May 1st storm event accounted for 76 percent and 99 percent of the total phosphate mass loading migrated from the managed vegetated strip and unmanaged vegetated strip, respectively. The total phosphate mass load migrated from the Lorton Road surface from the May 1st event was 19 percent of the total phosphate mass load migrated from the Lorton Road surface throughout the entire study. The results of the total phosphate mass load migration of the May 1st storm event further suggest that although no evidence improved performance resulting from increased vegetation management was observed during this study, the possibility appears to still be present and would require a multi-year study to either confirm or deny that possibility.

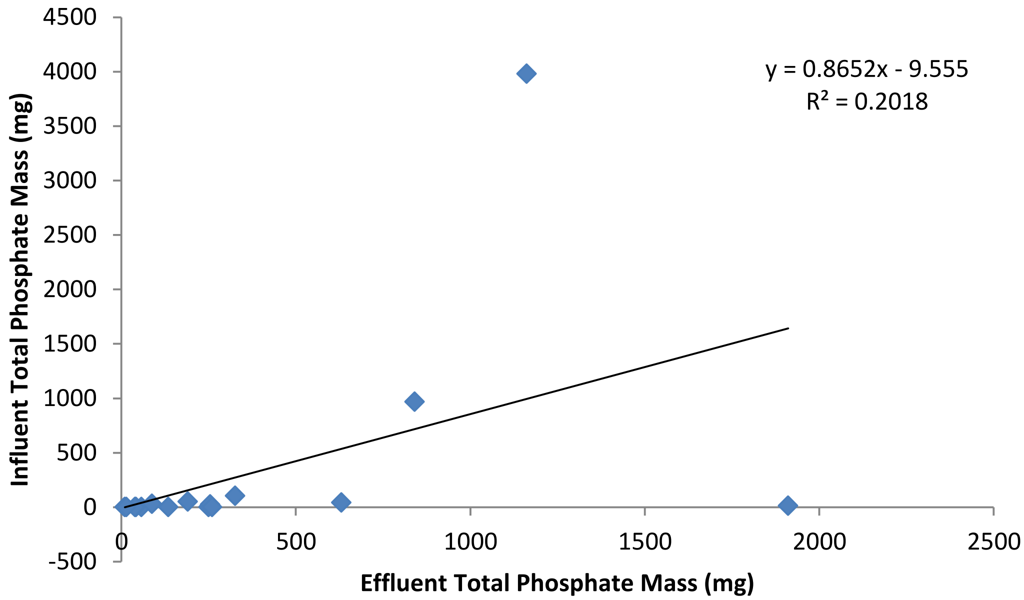

Figure 37: Linear regression model of total phosphate mass loading of managed vegetated strip

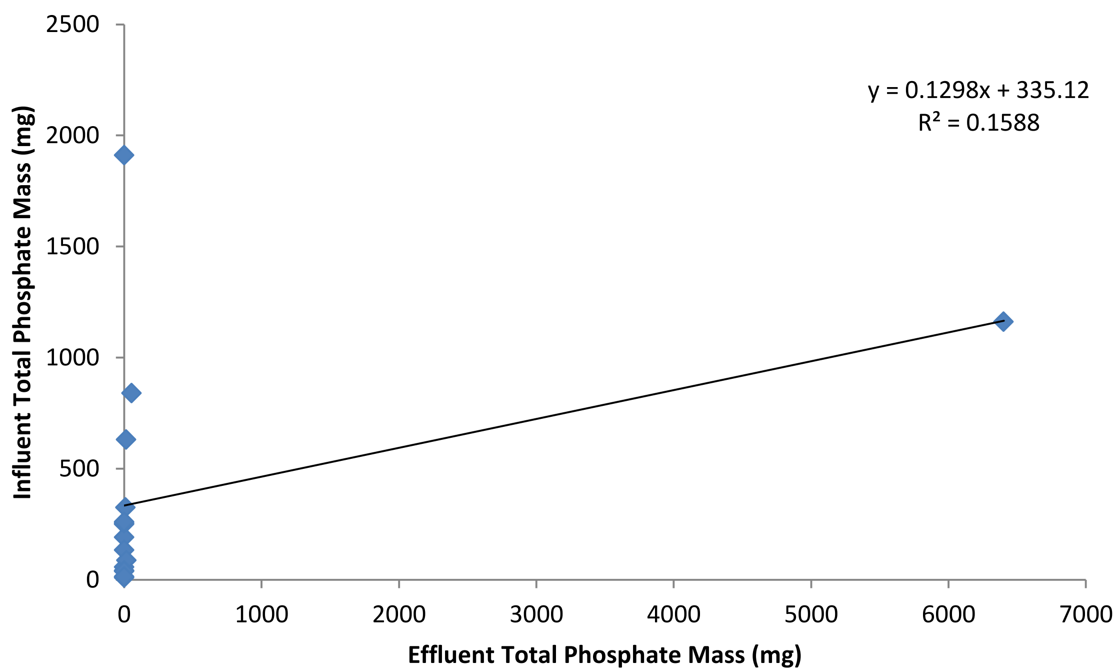

Figure 38: Linear regression model of total phosphate mass loading of unmanaged vegetated strip

Linear regression modeling was performed for chemical oxygen demand (COD) and COD mass loading for the managed vegetated strip and unmanaged vegetated strip. The linear regression model of the managed vegetated strip COD per liter of runoff is presented in Figure 39 while the linear regression model of the unmanaged vegetated strip COD per liter of runoff is presented in Figure 40. The Lorton Road runoff COD of 91.3 mg/l averaged over 15 storm events monitored during this study was used as the influent COD for the managed and unmanaged vegetated strips. The linear regression model predicts an average COD effluent of the managed vegetated strip of 108.3 mg/l compared to the observed average COD of 97.5 mg/l. The predicted average COD effluent of the unmanaged vegetated strip is 81.4 mg/l compared to the observed average COD of 90.7 mg/l. Linear regression modeling of COD suggests that the average influent COD seen in this study is at or below the reducible COD for a managed vegetated strip as evidenced by the relatively flat linear regression slope and is therefore not generally capable of achieving additional reduction of the COD. The linear regression model of the managed vegetated strip predicts an average COD increase of 18.6 percent while the unmanaged vegetated strip showed an average reduction of COD by 10.8 percent

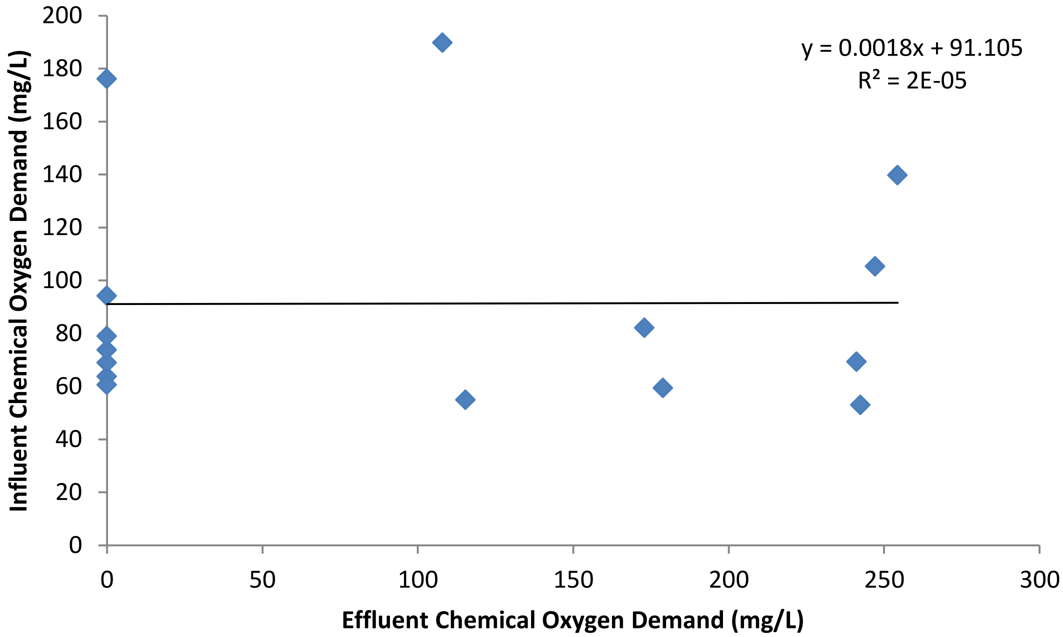

Figure 39: Linear regression model of chemical oxygen demand for the managed vegetated strip

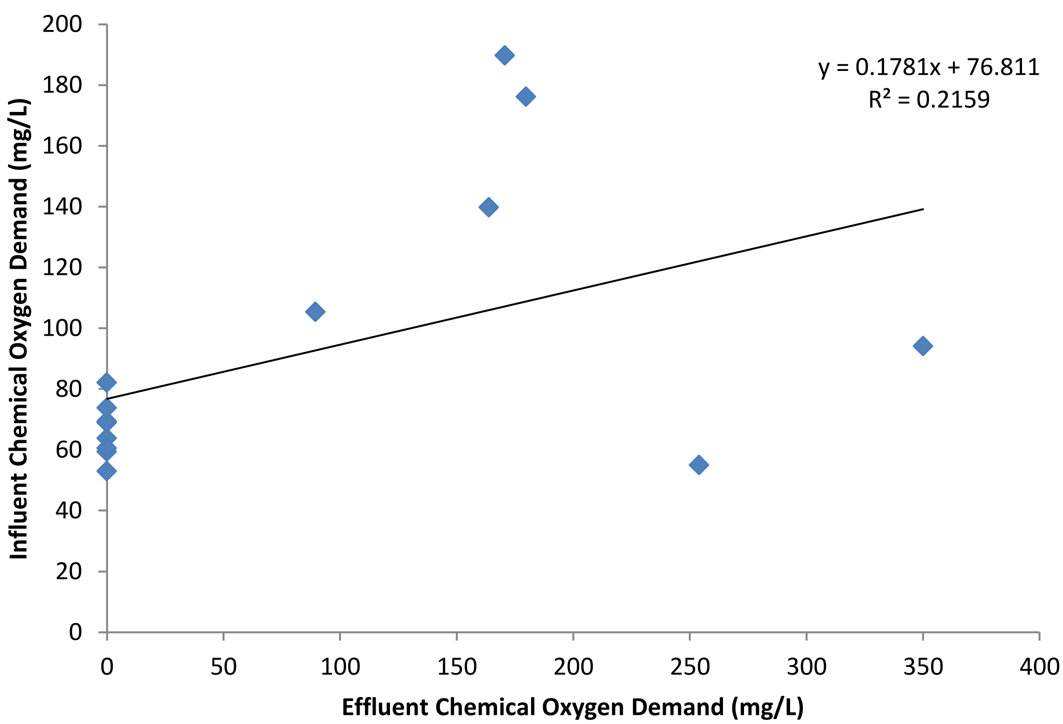

Figure 40: Linear regression model of chemical oxygen demand for the unmanaged vegetated strip

Linear regression models of chemical oxygen demand for the managed and unmanaged vegetated strips are presented in Figure 41 and Figure 42, respectively. The Lorton Road runoff mass load of 44.7 grams averaged over the 16 monitored storm events was used as the influent mass load for the managed and unmanaged vegetated strips. The linear regression model for chemical oxygen demand of the managed vegetated strip predicts a COD effluent mass load of 30.7 grams compared to the observed average of 28.8 grams. The predicted COD effluent mass load of the unmanaged vegetated strip is 36.2 grams compared to the observed average of 34.7 grams. Linear regression modeling of COD mass load predicts an average removal efficiency of 31.3 percent and 35.6 percent for the managed and unmanaged vegetated strips, respectively.

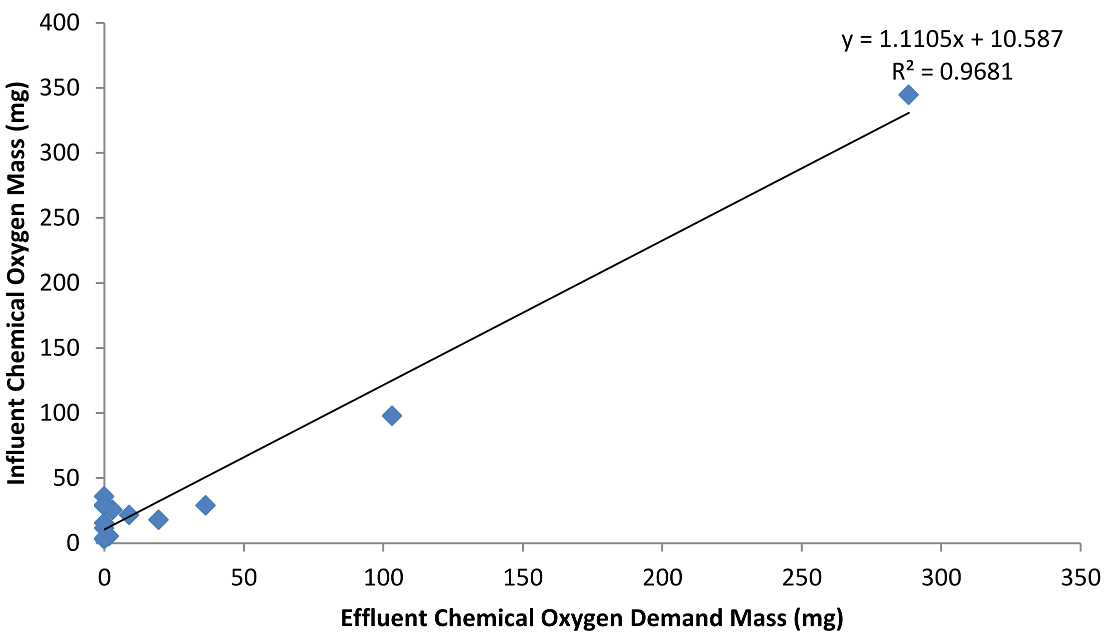

Figure 41: Linear regression model of chemical oxygen demand mass load of the managed vegetated strip

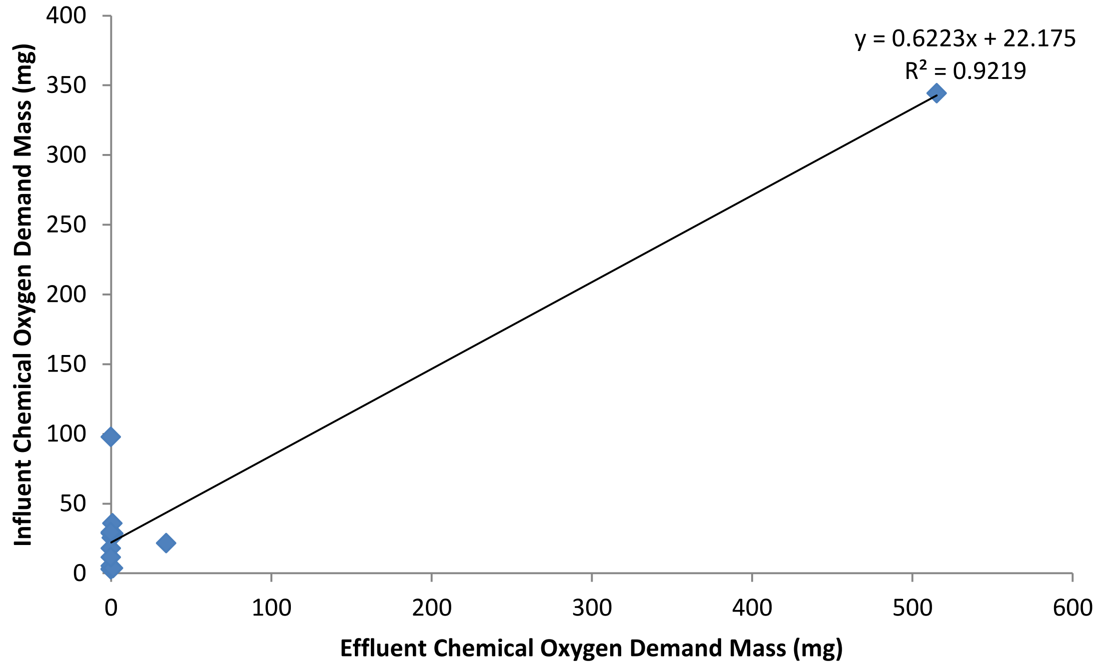

Figure 42: Linear regression model of chemical oxygen demand of the unmanaged vegetated strip

Linear regression modeling was performed for both oil and grease concentration and mass loading of the managed and unmanaged vegetated strips. The oil and grease concentration of 9.25 mg/l, determined from the Lorton Road runoff averaged over the 16 storm events evaluated in this study, was used as the observed average influent concentration. The oil and grease concentration linear regression model of the managed vegetated strip is presented in Figure 43 while the linear regression model of the unmanaged vegetated strip is presented in Figure 44. The linear regression model of the managed vegetated strip oil and grease concentration predicts an average effluent concentration of 5.51 mg/l compared to the observed average effluent concentration of 5.51 mg/l. The linear regression model of the unmanaged vegetated strip oil and grease concentration predicts an average effluent concentration of 5.68 mg/l compared to the observed average effluent concentration of 5.75 mg/l. The linear regression model predicts the managed vegetated strip achieves an oil and grease concentration reduction of 40.4 percent while the unmanaged vegetated strip achieves a reduction of 38.6 percent.

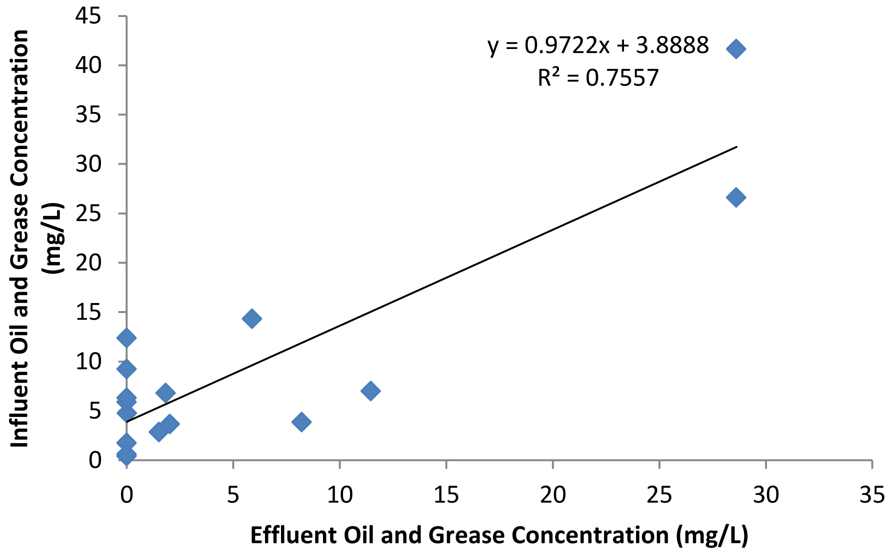

Figure 43: Linear regression model of oil and grease concentration of the managed vegetated strip

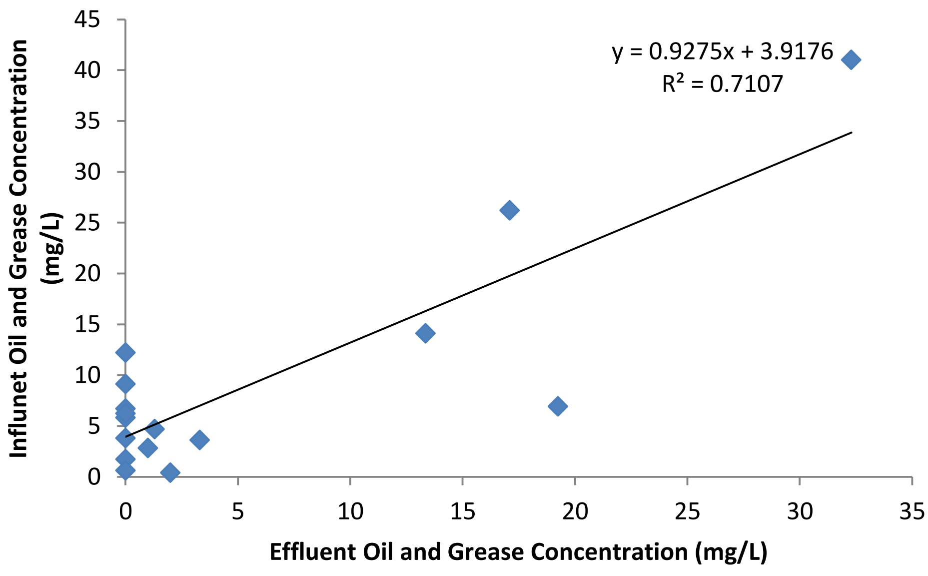

Figure 44: Linear regression model of oil and grease concentration of the unmanaged vegetated strip

Linear regression models of oil and grease mass load of the managed and unmanaged vegetated strips are presented in Figure 45 and Figure 46, respectively. The observed average oil and grease mass load of 3936.9 mg, measured from the Lorton Road runoff averaged over the 16 storm events monitored in this study, was used as the influent mass load for predicting the average effluent mass load of the managed and unmanaged vegetated strips. The linear regression model of the managed vegetated strip predicts an effluent mass load of 568.3 mg compared to the observed average mass load of 568.3 mg. The linear regression model of the unmanaged vegetated strip predicts an effluent mass load of 452.4 mg compared to the observed mass load of 452.4 mg. The linear regression model predicts the managed vegetated strip achieves an average reduction of oil and grease mass load by 85.6 percent. The unmanaged vegetated strip has a predicted average oil and grease mass load removal efficiency of 88.5 percent.

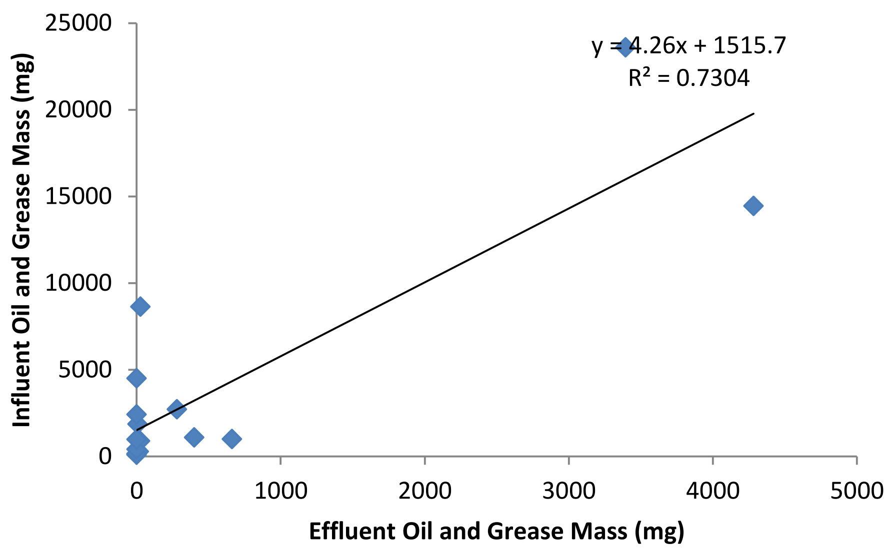

Figure 45: Linear regression model of oil and grease mass load of the managed vegetation strip

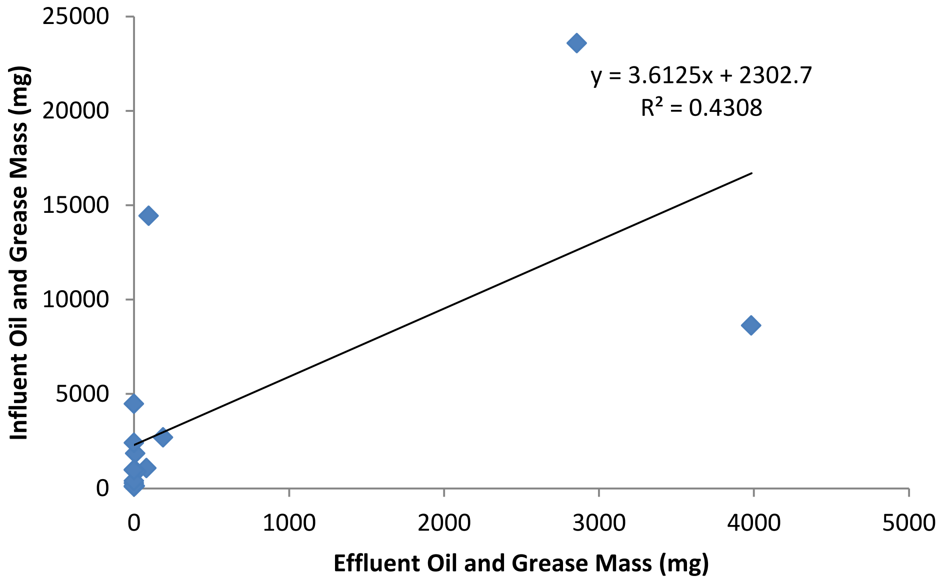

Figure 46: Linear regression model of oil and grease mass load of the unmanaged vegetated strip

Linear regression was performed for both total coliform concentration and total colony forming units per storm event for the managed vegetated strip and unmanaged vegetated strip. The total coliform concentration of 8378.2 colony forming units per 100 mL, measured from the Lorton Road runoff averaged over 11 storm events monitored during this study, was used as the influent concentration for predicting the effluent concentration of the managed vegetated strip and unmanaged vegetated strip. The total coliform linear regression model of the managed vegetated strip is presented in Figure 47. The model of the unmanaged vegetated strip is presented in Figure 48. Linear regression modeling of the managed vegetated strip predicts and average total coliform effluent concentration of 3571.1 colony forming units per 100 mL compared to the observed average of 3570.0 colony forming units per 100 mL. Modeling of the unmanaged vegetated strip predicts a total coliform effluent concentration of 2844.8 colony forming units per 100 mL compared to the observed concentration of 2845.5 colony forming units per 100 mL.

Linear regression modeling of the managed vegetated strip total coliform concentration predicts an average reduction efficiency of 57.4 percent. Modeling of the unmanaged vegetated strip predicts and averaged reduction efficiency of 66.0 percent. Although under average conditions linear regression modeling of the unmanaged vegetated strip predicts a reduction of total coliform concentration, low influent concentrations of total coliform are predicted to result in increased total coliform concentration of the effluent.

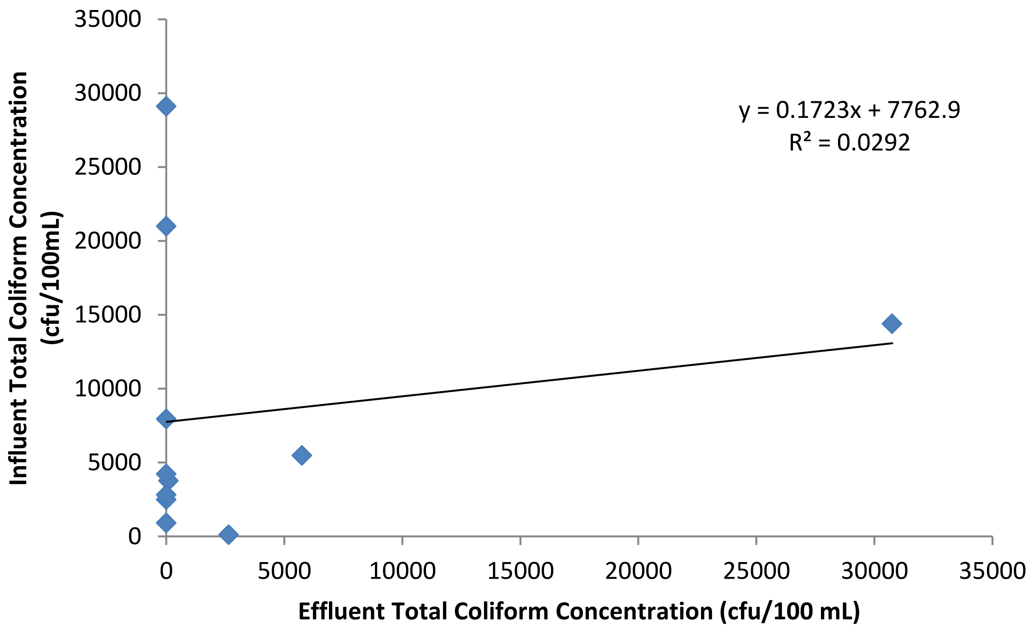

Figure 47: Linear regression model of total coliform concentration of the managed vegetated strip

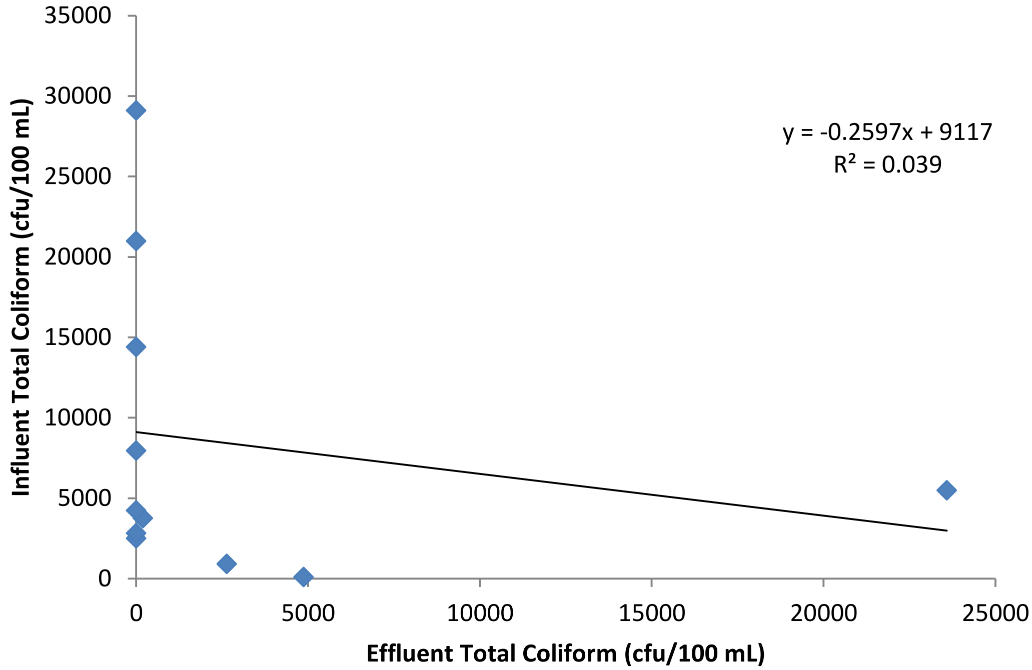

Figure 48: Linear regression model of the total coliform concentration of the unmanaged vegetated strip

Linear regression models for the total coliform colony forming units per event for the managed vegetated strip and unmanaged vegetated strip are presented in Figure 49 and Figure 50, respectively. Colony forming units per event was used as the metric of constituent transport in lieu of mass load due to the mass variability of the colony forming units measured as the total coliform concentration. The average total coliform colony forming units per event value of 13.7 million measured from the Lorton Road runoff, averaged over 11 storm events, was used as the influent of colony forming units to determine the predicted colony forming units of the managed and unmanaged vegetated strips. The linear regression model of the managed vegetated strip predicts an average effluent total coliform colony forming units per event load of 9.41 million colony forming units compared to the observed average of 9.48 colony forming units per event. Linear regression modeling of the unmanaged vegetated strip predicts an average effluent total coliform colony forming units per event of 13.47 million compared to the observed average colony forming units of 13.50 million. The linear regression models predict an average reduction of total coliform colony forming units per event by 31.3 percent for the managed vegetated strip and an average reduction of 1.7 percent for the unmanaged vegetated strip. The unmanaged vegetated strip model predicts that low influent colony forming units will result is increased colony forming units of the effluent resulting in a net export of total coliform during storm events resulting in low total coliform colony forming units in the Lorton Road runoff.

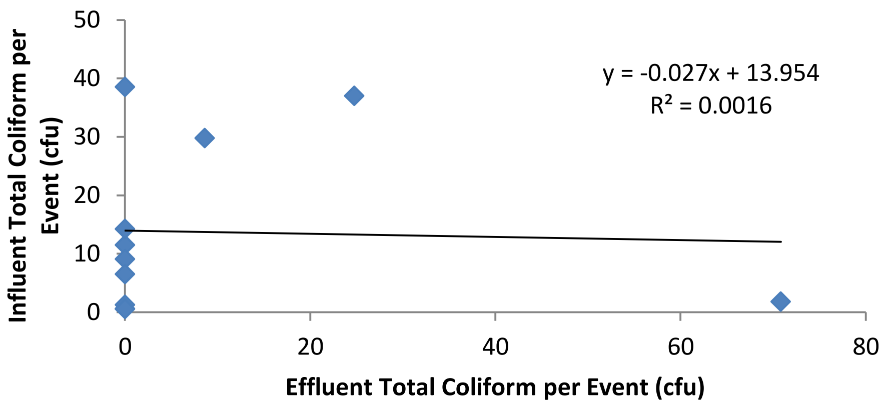

Figure 49: Linear regression model of total coliform per event for the managed vegetated strip

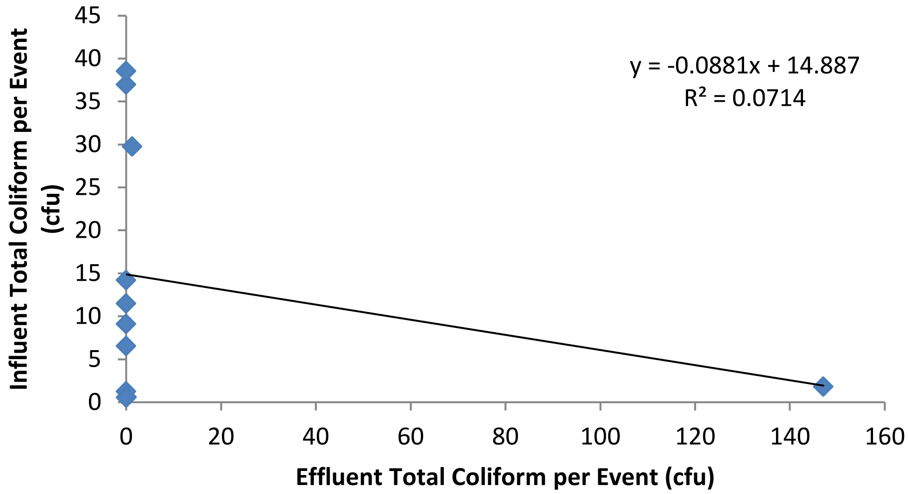

Figure 50: Linear regression model of total coliform per event of the unmanaged vegetated strip

Linear regression modeling of the *E. coli* concentration and colony forming units per event were developed for the managed and unmanaged vegetated strips. The linear regression model of *E. coli* concentration for the managed vegetated strip is presented in Figure 51 while the model for the unmanaged vegetated strip is presented in Figure 52. The linear regression model of the *E. coli* concentration used a measured influent concentration of the Lorton Road runoff of 4.66 colony forming units per 100 mL for predicting effluent concentrations of the managed and unmanaged vegetated strips. The managed vegetated strip linear regression model predicts an *E. coli* effluent concentration of 0.48 colony forming units per 100 mL compared to the observed average concentration of 0.47 colony forming units per 100 mL. The linear regression model of the unmanaged vegetated strip predicts an averaged effluent concentration of 8.79 colony forming units per 100 mL compared to the observed average of 8.90 colony forming units per 100 mL.

The relatively flat slope of the linear regression models of the managed and unmanaged vegetated strip suggests the influent *E. coli* concentration is at or near the reducible concentration achievable by practice of vegetated roadsides. The linear regression model of the managed vegetated strip predicts an average removal efficiency of 89.7 percent. Despite the relatively high removal efficiency of *E. coli* by the managed vegetated strip, the effluent concentration of *E. coli* does not appear to be a meaningful factor in the *E. coli* concentration of the managed vegetated strip effluent and suggests some other factors are responsible such as competition with other micro-organisms. The linear regression model of the unmanaged vegetated strip predicts an increase in the *E. coli* effluent concentration by 88.6 percent.

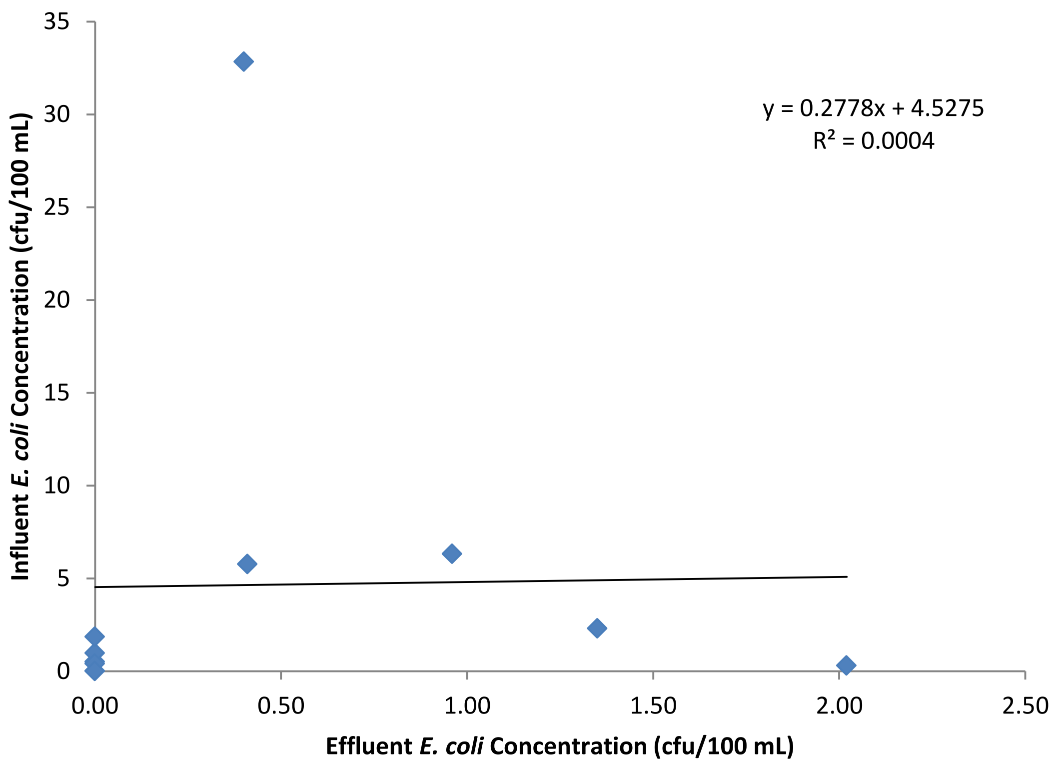

Figure 51: Linear regression model of *E. coli* for the managed vegetated strip

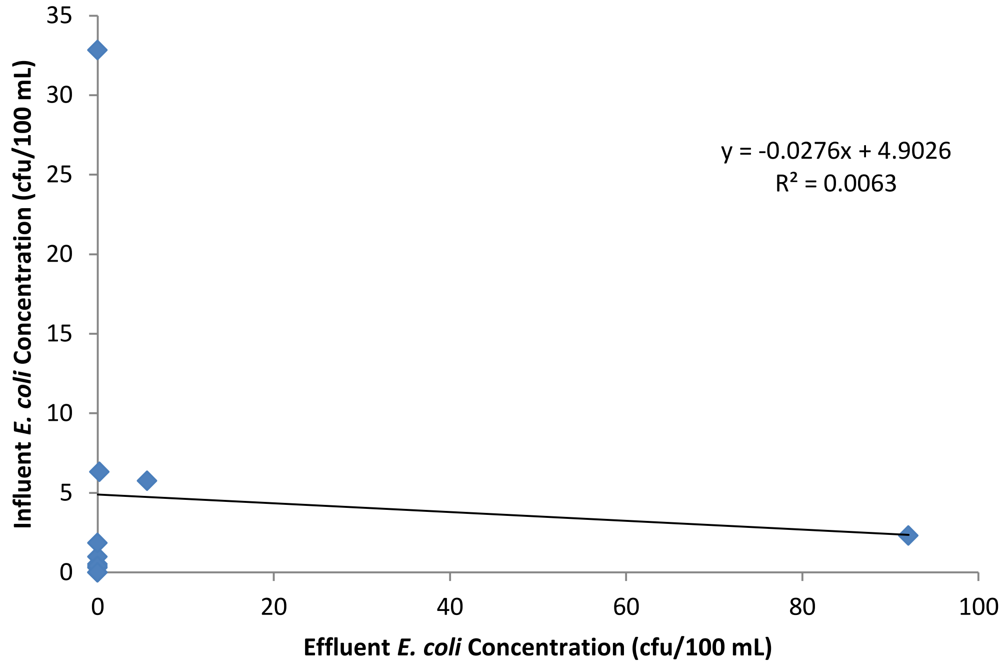

Figure 52: Linear regression model of *E. coli* concentration of the unmanaged vegetated strip

Linear regression modeling developed for *E. coli* colony forming units per storm event for the managed and unmanaged vegetated strips are presented in Figure 53 and Figure 54, respectively. The Lorton Road runoff water quality parameter of 22.39 *E. coli* colony forming units per event, averaged over 11 storm events and used in lieu of mass load, was used as the influent E. coli load for predicting the effluent *E. coli* load of the managed and unmanaged vegetated strips. The managed vegetated strip linear regression model predicts an *E. coli* effluent load of 2.45 colony forming units per event compared to the observed average *E. coli* load of 2.45 colony forming units per event. The unmanaged vegetated strip linear regression model predicts an *E. coli* effluent load of 0.98 colony forming units per event compared to the average observed *E. coli* load of 0.99 colony forming units per event. Linear regression modeling predicts an average reduction of the *E. coli* load by 89.1 percent from the managed vegetated strip while the unmanaged vegetated strip is predicted to achieve an *E. coli* reduction of 95.6 percent.

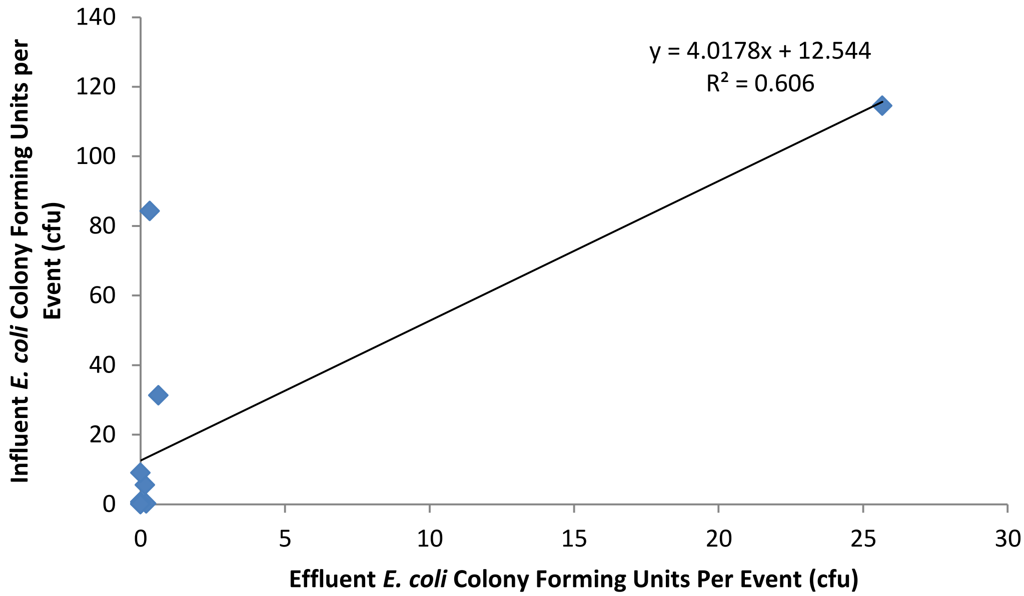

Figure 53: Linear regression model of *E. coli* colony forming units per event of the managed vegetated strip

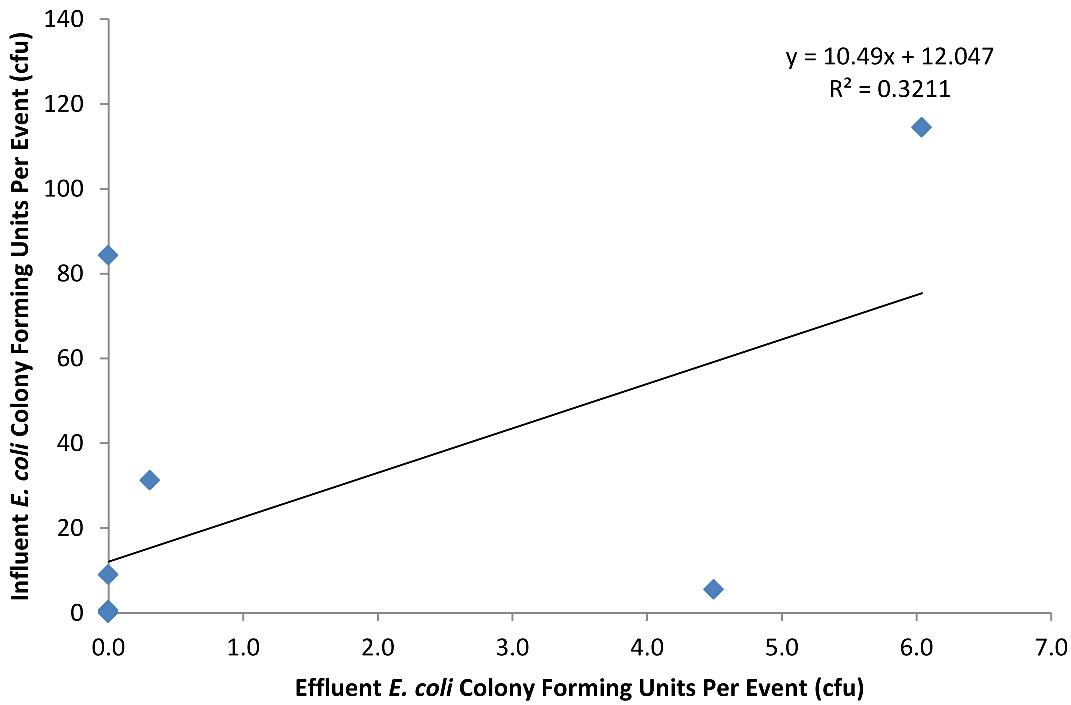

Figure 54: Linear regression model of *E. coli* colony forming units per event of the unmanaged vegetated strip

Linear regression models were developed for cadmium concentration and mass load for the managed and unmanaged vegetated strips. The linear regression model of the cadmium concentration of the managed vegetated strip is presented as Figure 55 while the cadmium concentration model for the unmanaged vegetated strip is presented as Figure 56. The average observed cadmium concentration of 0.88 μg/L measured from the Lorton Road runoff and averaged over the 16 storm events monitored during this study was used as the influent concentration for predicting the average effluent concentration of the managed and unmanaged vegetated strips. The linear regression model of the managed vegetated strip predicts and average effluent cadmium concentration of 0.57 μg/L compared to the observed average effluent concentration of 0.55 μg/L. The unmanaged vegetated strip linear regression model predicts and average cadmium concentration of 0.40 μg/L compared to the observed effluent concentration of 0.39 μg/L. The linear regression model of the managed vegetated strip predicts a cadmium concentration reduction of 35.2 percent. The linear regression model of the unmanaged vegetated strip predicts a cadmium concentration reduction of 54.5 percent. Although the linear regression model of the unmanaged vegetated strip predicts a reduction of cadmium concentration for average storm event conditions, low influent concentrations of cadmium are predicted to result in an increased cadmium effluent concentration.

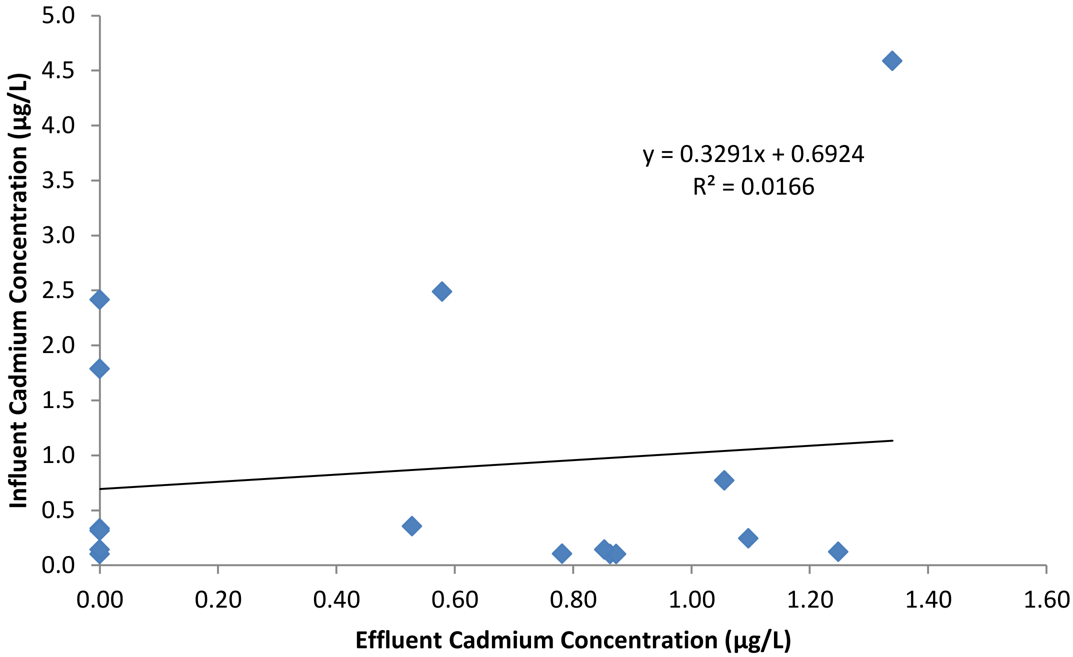

Figure 55: Linear regression model of cadmium concentration of the managed vegetated strip

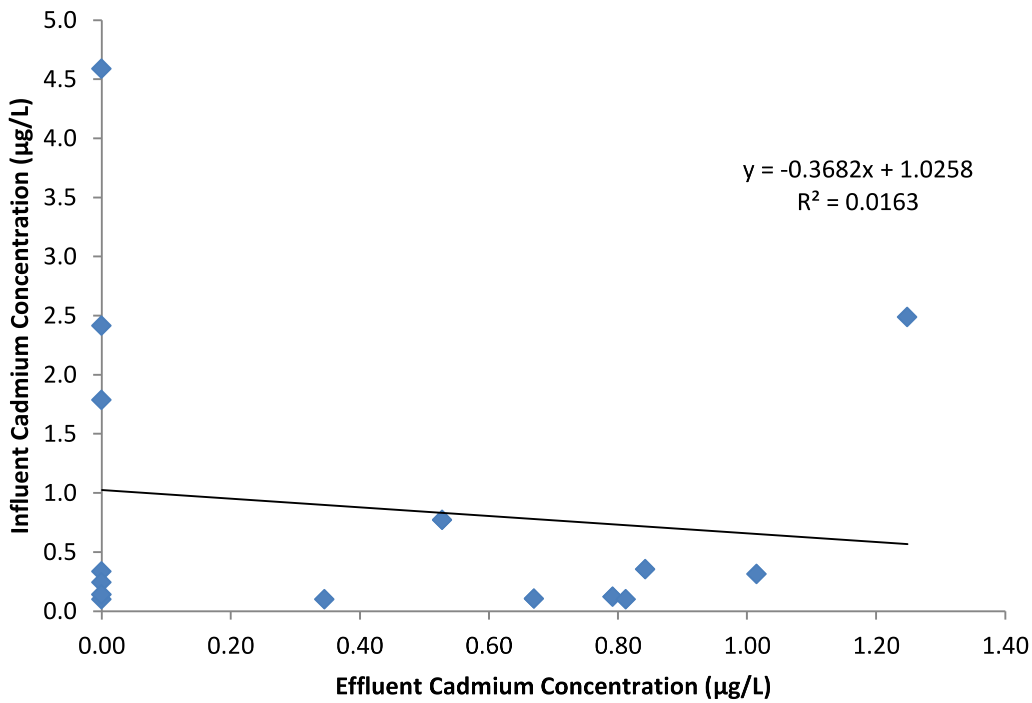

Figure 56: Linear regression model of cadmium concentration of the unmanaged vegetated strip

Linear regression models were developed for the cadmium mass load of the managed and unmanaged vegetated strips and are presented in Figure 57 and Figure 58, respectively. The average influent cadmium mass load of the Lorton Road runoff was used as the influent mass load for predicting effluent cadmium load. The Lorton Road runoff mass load, averaged over 16 storm events monitored during this study, was found to be 407.5 µg. The linear regression model of the managed vegetated strip predicts an effluent cadmium mass load of 138.3 µg per event compared to the observed average cadmium mass load of 138.3 µg per event. The linear regression of the unmanaged vegetated strip predicts an average effluent cadmium mass load of 241.8 µg per event. The linear regression of the managed vegetated strip predicts an average cadmium load reduction of 66.0 percent while the unmanaged vegetated strip is predicted to reduce the cadmium load by 40.7 percent.

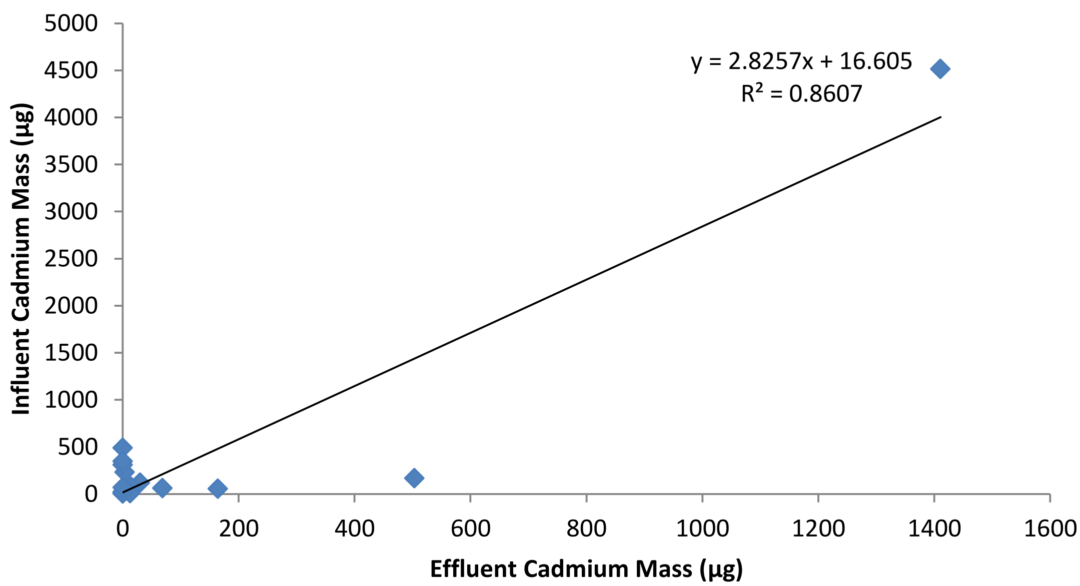

Figure 57: Linear regression model of cadmium mass load of the managed vegetated strip

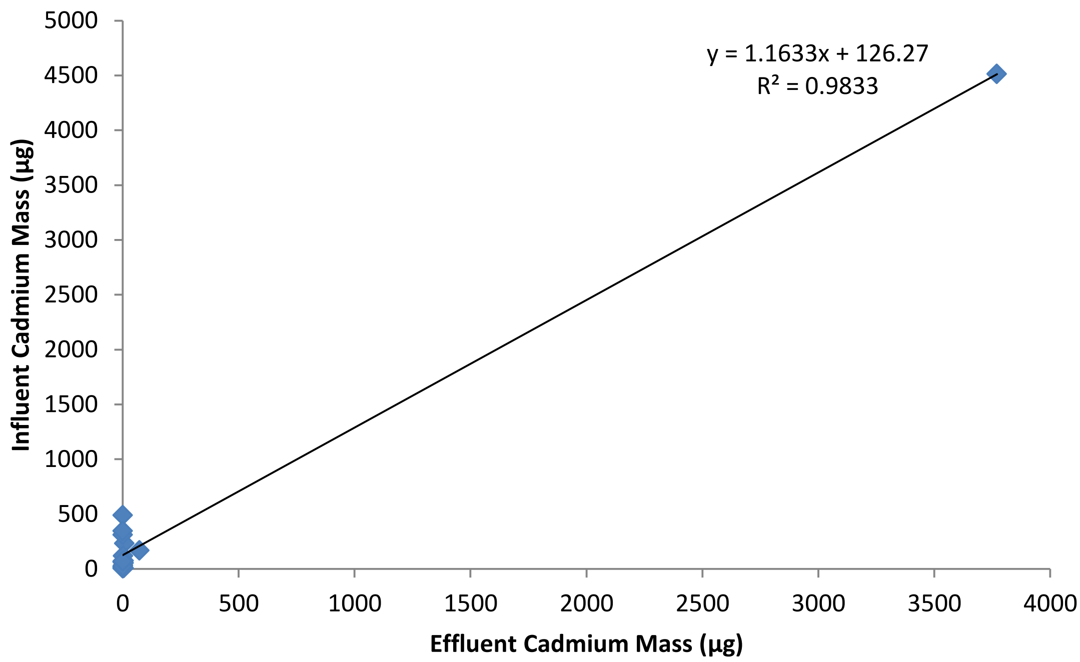

Figure 58: Linear regression model of cadmium mass load of the unmanaged vegetated strip

Linear regression models were developed for chromium concentration and mass load of the managed and unmanaged vegetated strips. The linear regression model of the chromium concentration for the managed vegetated strip is presented in Figure 59 while the model for the unmanaged vegetated strip is presented in Figure 59. The chromium concentration of 9.44 µg/L, determined from the Lorton Road runoff averaged over the 16 storm events monitored during this study, was used for the influent concentration to determine the predicted average chromium concentration of the managed and unmanaged vegetated strips. The linear regression of the managed vegetated strip predicts an average chromium concentration of 5.14 µg/L compared to the observed average concentration of 5.14 µg/L. The linear regression model of the unmanaged vegetated strip predicts an average chromium concentration of 6.09 µg/L compared to the observed average chromium concentration of 6.10 µg/L. Linear regression modeling of the managed vegetated strip predicts an average chromium concentration reduction of 45.6 percent while modeling of the unmanaged vegetated strip predicts a chromium concentration reduction of 35.5 percent.

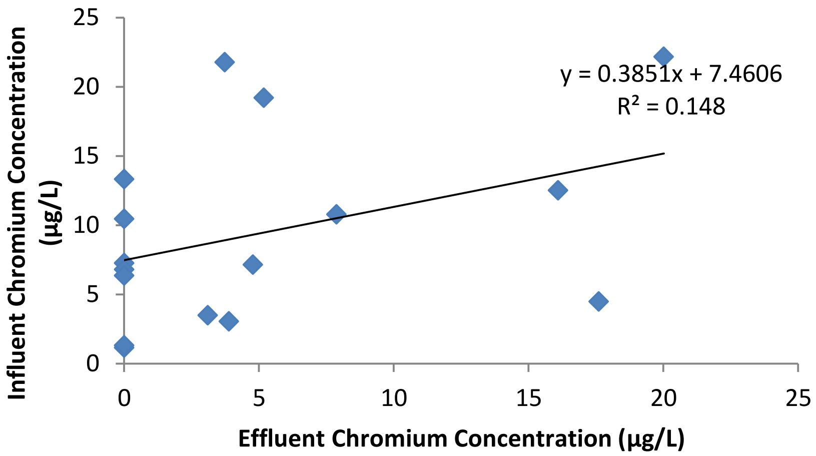

Figure 59: Linear regression model of chromium concentration of the managed vegetated strip

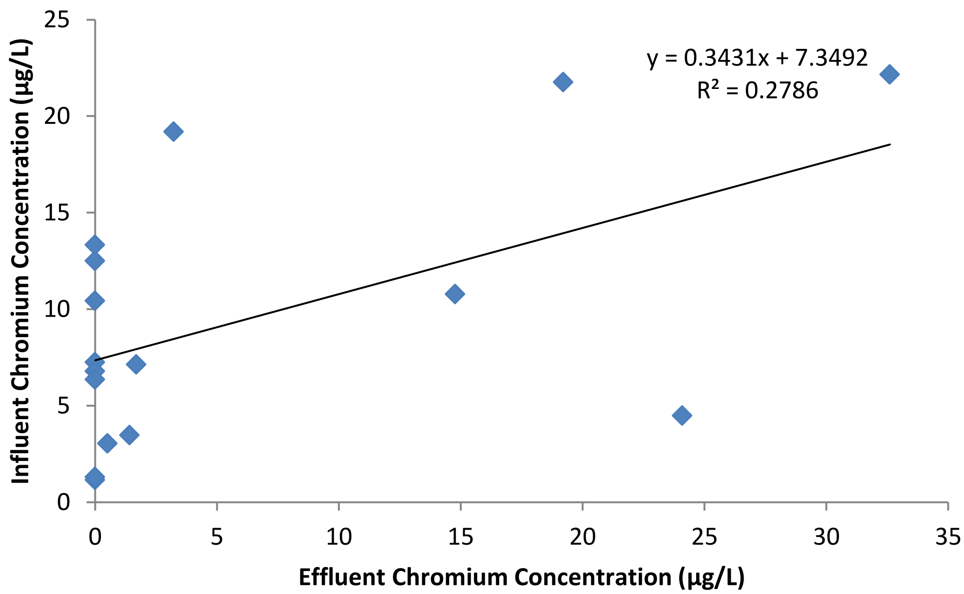

Figure 60: Linear regression model of chromium concentration of the unmanaged vegetated strip

Linear regression modeling performed for the chromium mass load is presented for the managed vegetated strip and unmanaged vegetated strip in Figure 61 and Figure 62, respectively. The chromium mass load of 5052.7 µg, determined from the Lorton Road runoff and averaged over the 16 storm events monitored during this study, was used to predict the chromium mass load of the managed and unmanaged vegetated strip effluent. The linear regression model of the managed vegetated strip predicts an average effluent chromium mass load of 1215.6 µg compared to the observed mass load of 1215.6 µg. The model of the unmanaged vegetated strip predicts an effluent chromium mass load of 660.6 µg compared to the observed average effluent mass load of 660.5 µg. The linear regression models predict an average reduction of chromium mass load by 75.9 percent for the managed vegetated strip and 86.9 percent for the unmanaged vegetated strip.

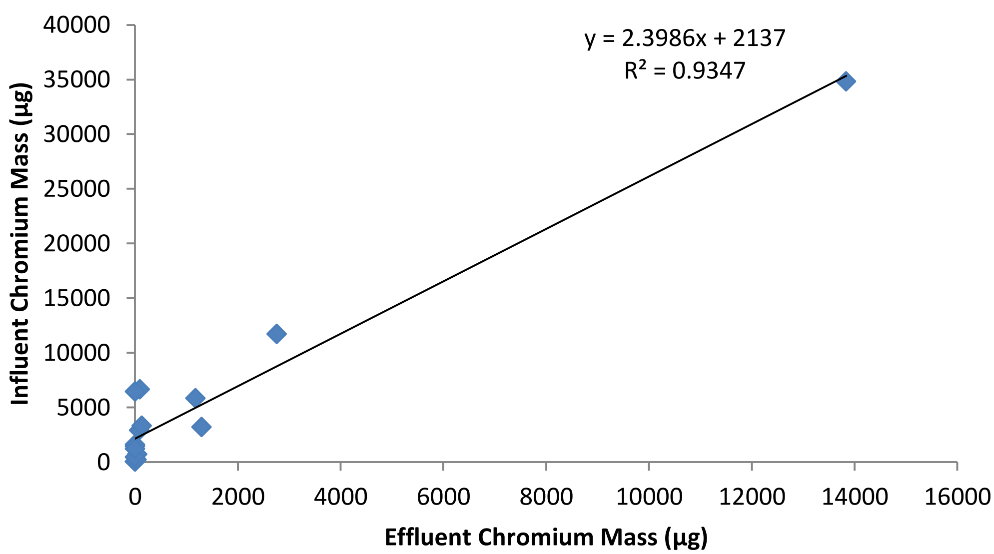

Figure 61: Linear regression model of chromium mass of the managed vegetated strip

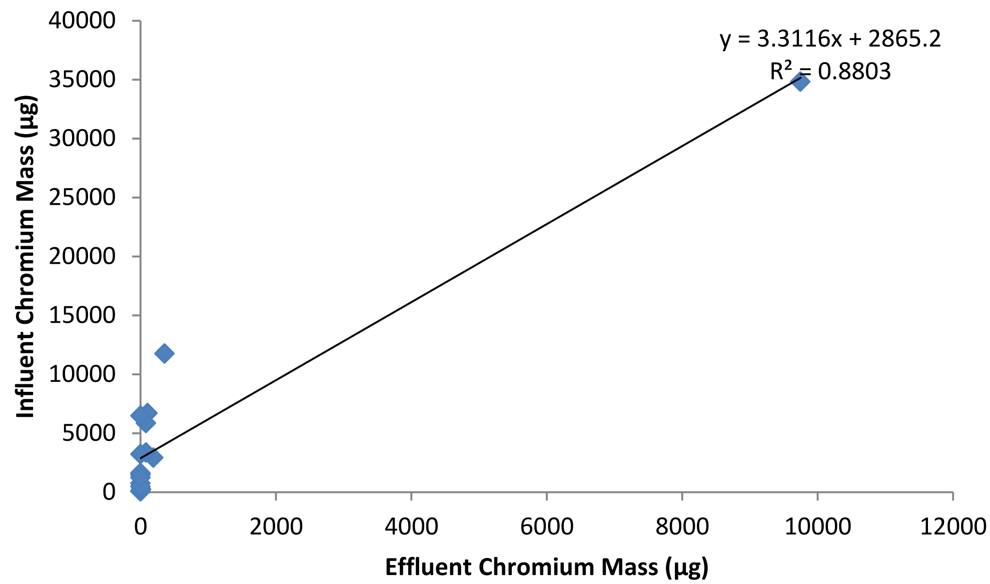

Figure 62: Linear regression model of chromium mass load of the unmanaged vegetated strip

Linear regression models were developed for copper concentration and copper mass load of the managed and unmanaged vegetated strip. The linear regression model of copper concentration of the managed vegetated strip is presented in Figure 63 while the model for the unmanaged vegetated strip is presented in Figure 64. The influent copper concentration of 38.1 µg/L, determined from the water quality of Lorton Road runoff and averaged over the 16 storm events monitored during this study, was used to predict the effluent concentration of the managed and unmanaged vegetated strip.

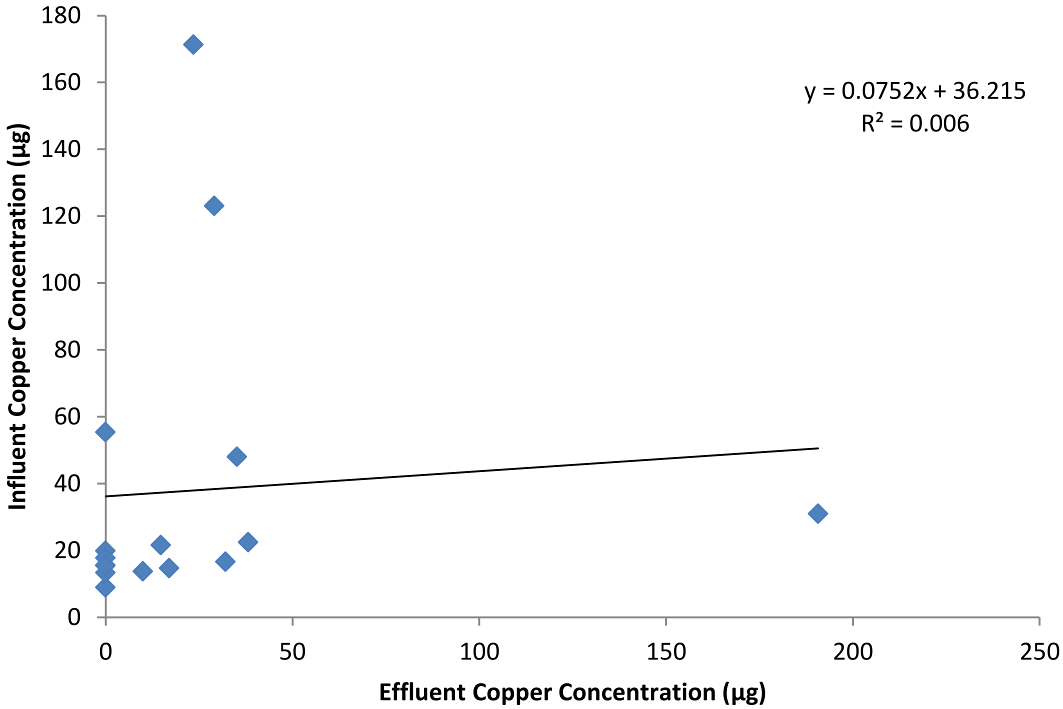

Figure 63: Linear regression of copper concentration of the managed vegetated strip

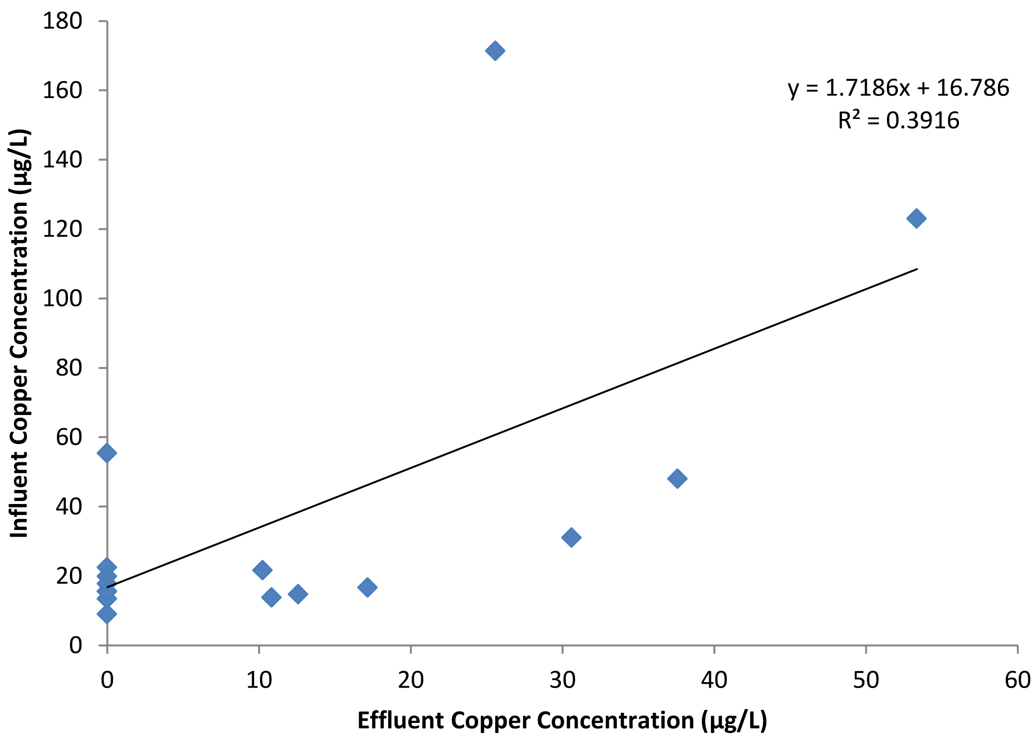

Figure 64: Linear regression of copper concentration of the unmanaged vegetated strip

Linear regression models developed for the copper mass load of the managed vegetated strip and unmanaged vegetated strip are presented in Figure 65 and Figure 66, respectively. The average observed Lorton Road runoff copper mass load of 27174 μg, averaged over the 16 storm events monitored in this study, was used as the influent mass load for predicting the effluent mass load of the managed and unmanaged vegetated strips. The managed vegetated strip linear regression model predicts an effluent copper mass load of 4933 μg compared to the observed mass load of 4933 μg. The unmanaged vegetated strip linear regression model predicts an average copper effluent mass load of 5020 μg compared to the observed average mass load of 5020 μg. The linear regression model predicts a reduction of the average copper mass load of the managed vegetated strip and unmanaged vegetated strip by 81.8 percent and 81.5 percent.

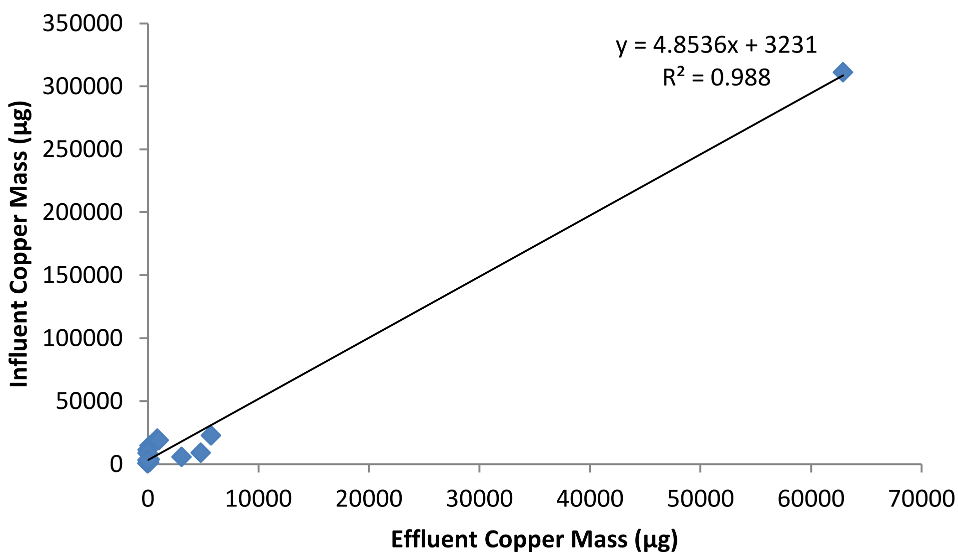

Figure 65: Linear regression model of copper mass of the managed vegetated strip

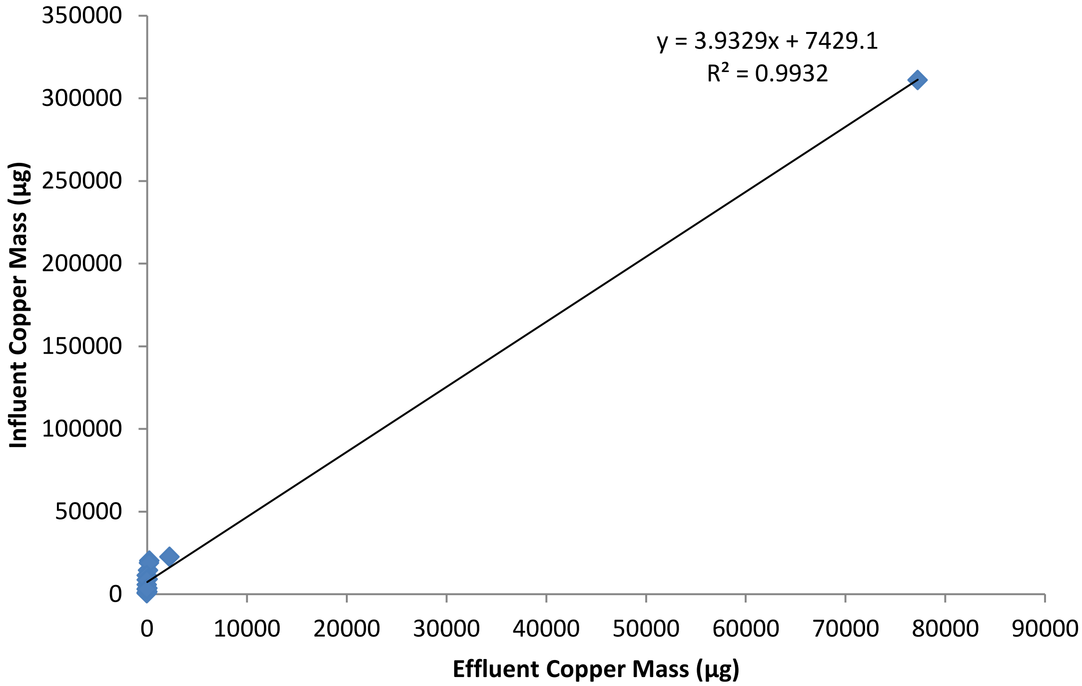

Figure 66: Linear regression model of copper mass of the unmanaged vegetated strip

Linear Regression modeling of lead concentration and lead mass was developed for the managed and unmanaged vegetated strips. The lead concentration linear regression models managed vegetated strip and unmanaged vegetated strip are presented in Figure 67 and Figure 68, respectively. The lead concentration of 7.89 µg/L determined from the Lorton Road runoff water quality averaged over the 16 storm events monitored was used as the influent lead concentration for predicting the effluent concentration of the managed and unmanaged vegetated strips. The linear regression model of the managed vegetated strip predicts an average effluent lead concentration of 5.30 µg/L compared to the observed concentration of 5.28 µg/L. The linear regression model of the unmanaged vegetated strip predicts an average effluent concentration of 6.09 µg/L compared to the observed average concentration of 6.09 µg/L. The managed vegetated strip linear regression model predicts a reduction of lead concentration by 32.8 percent while the unmanaged vegetated strip predicts a reduction of lead concentration by 22.8 percent.

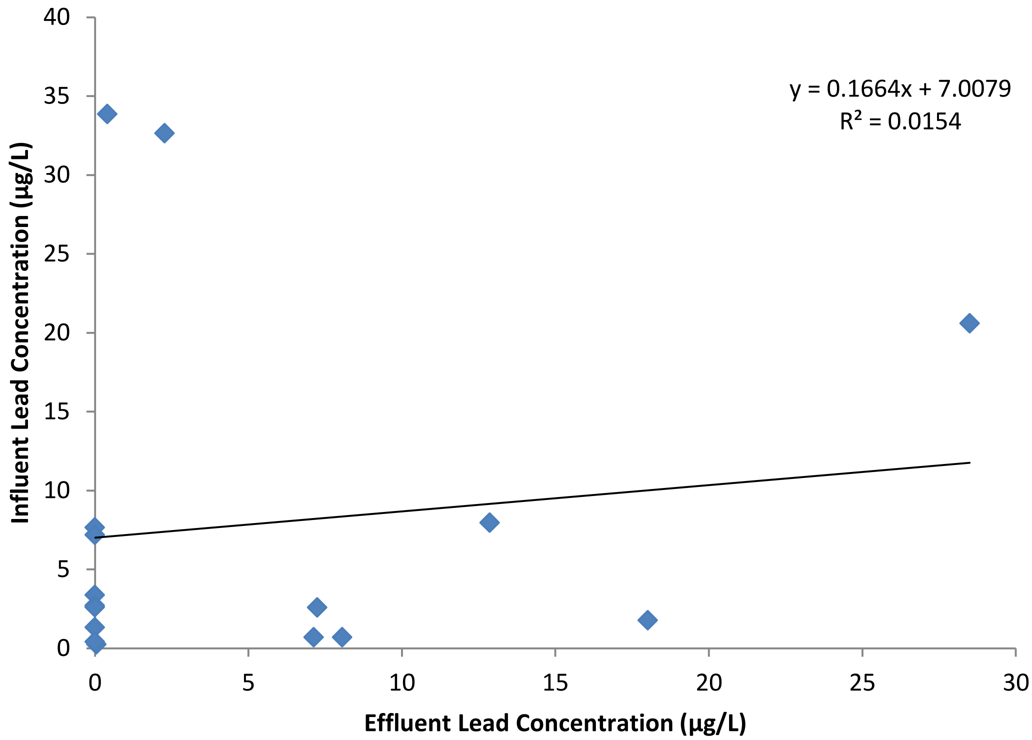

Figure 67: Linear regression model of lead concentration of the managed vegetated strip

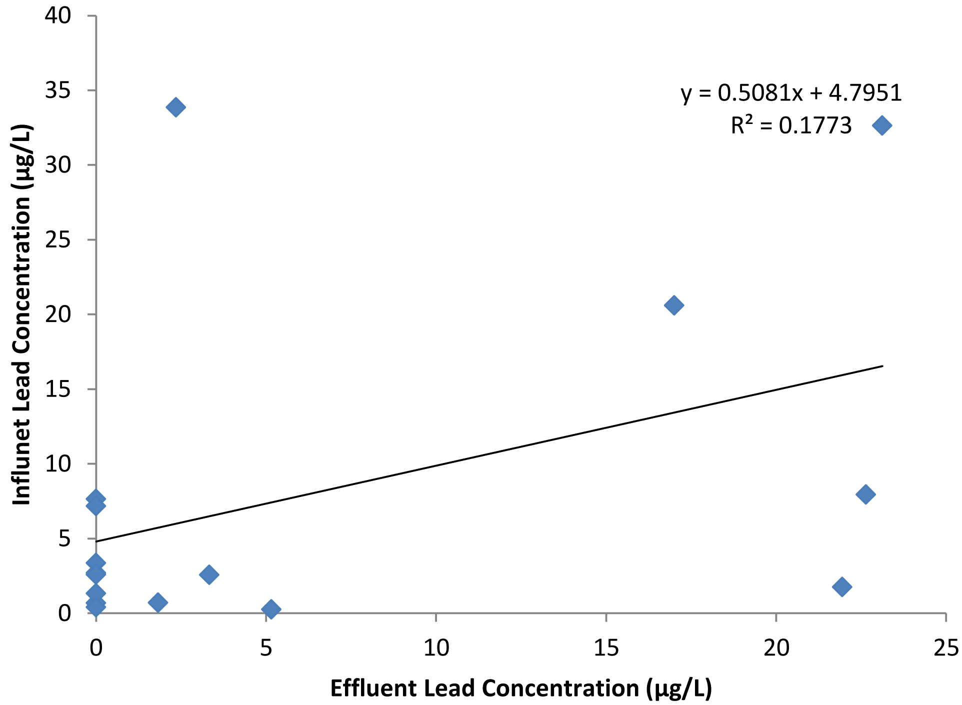

Figure 68: Linear regression model of lead concentration of the unmanaged vegetated strip

Linear regression models developed for lead mass load of the managed and unmanaged vegetated strips are presented in Figure 69 and Figure 70, respectively. The average influent lead mass load of 6771 µg was determined from the Lorton Road runoff water quality averaged over the 16 storm events monitored during this study. The averaged lead influent mass load was used to predict the average effluent mass load from the managed and unmanaged vegetated strips. The linear regression model of the managed vegetated strip lead mass load predicts an average effluent mass load of 1223µg compared to the observed average mass load of 1223 µg. The linear regression model of the unmanaged vegetated strip predicts an average lead mass load of 693 µg compared to the observed average effluent mass load of 693 µg. The linear regression models predict a lead mass load reduction from the managed and unmanaged vegetated strip of 81.9 percent and 89.8 percent, respectively.

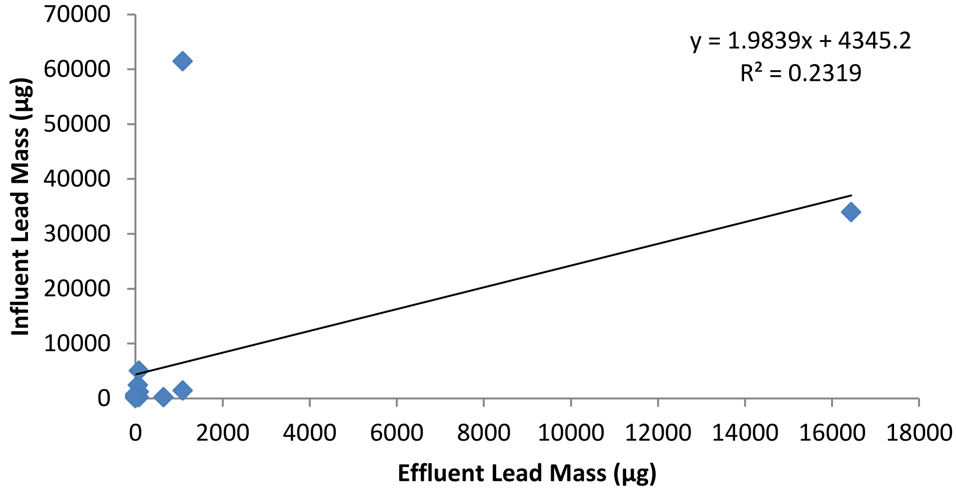

Figure 69: Linear regression model of lead mass load of the managed vegetated strip

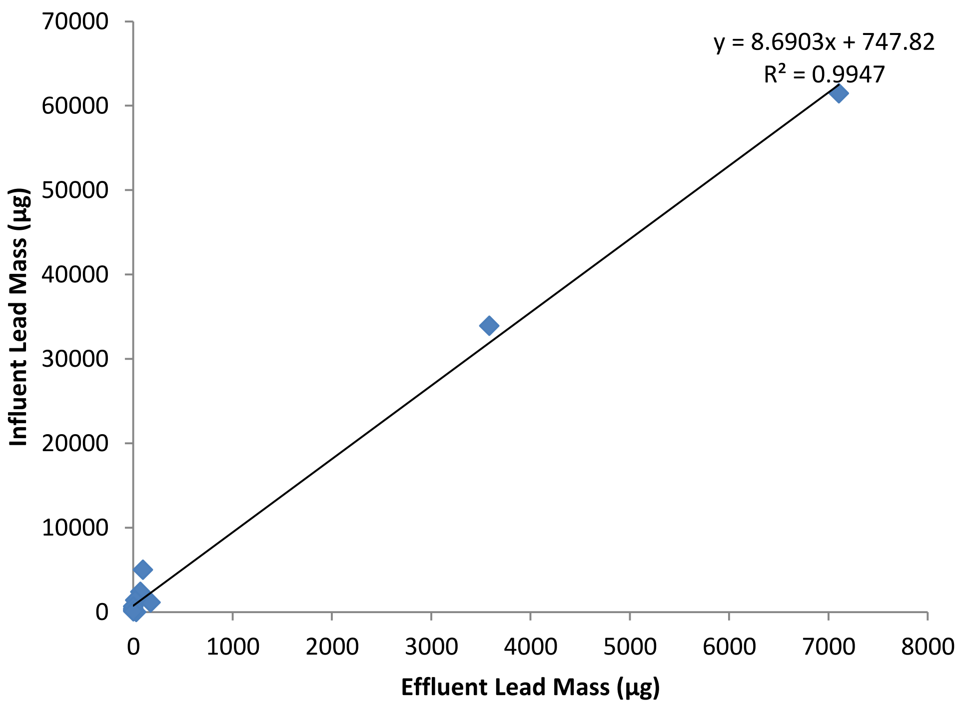

Figure 70: Linear regression model of lead mass load of the unmanaged vegetated strip

Linear regression models were developed for zinc concentration and mass for the managed and unmanaged vegetated strip. Linear regression models are presented in Figure 71 and Figure 72 for the zinc concentration of the managed vegetated strip and unmanaged vegetated strip, respectively. The average influent zinc concentration of 0.37 mg/l, determined from the water quality of the Lorton Road runoff averaged over the 16 storm events monitored in this study, was used to predict the effluent concentration of the managed and unmanaged vegetated strip. The linear regression model of the managed vegetated strip predicts an average effluent zinc concentration of o.47 mg/L compared to the observed average concentration of 0.48 mg/L. The unmanaged vegetated strip linear regression model predicts an average effluent zinc concentration of 0.65 mg/L compared to the observed average concentration of 0.63 mg/L. The linear regression models predict an average increase of zinc concentration for the managed and unmanaged vegetated strips by 29.7 percent and 75.7 percent, respectively.

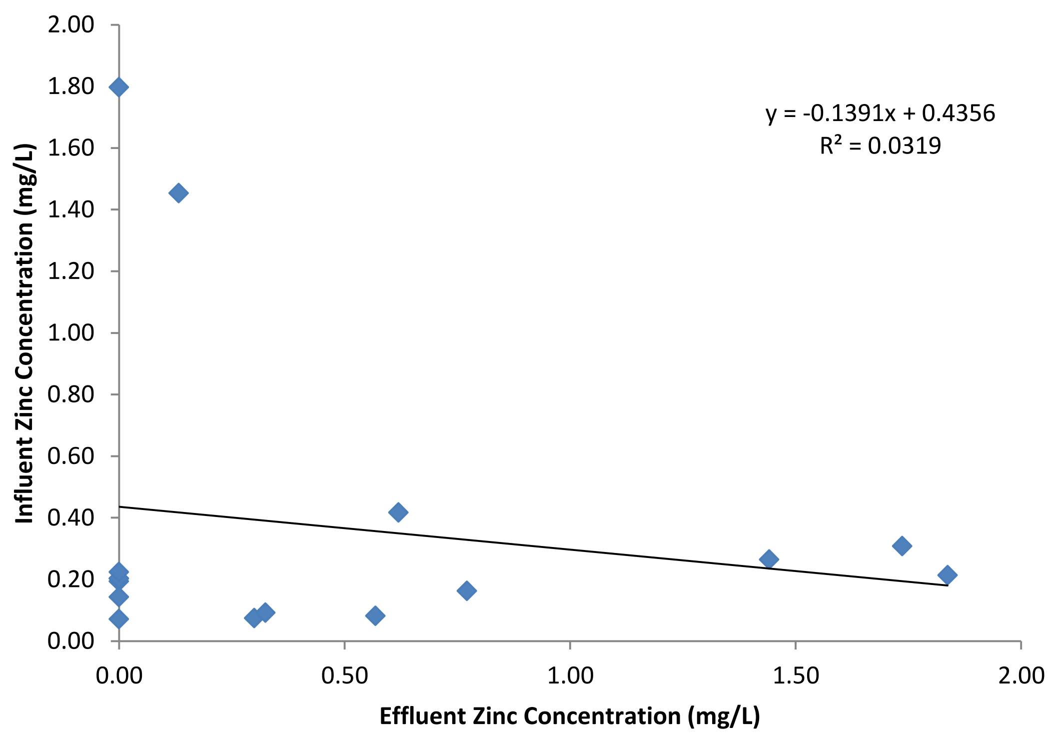

Figure 71: Linear regression model of zinc concentration of the managed vegetated strip

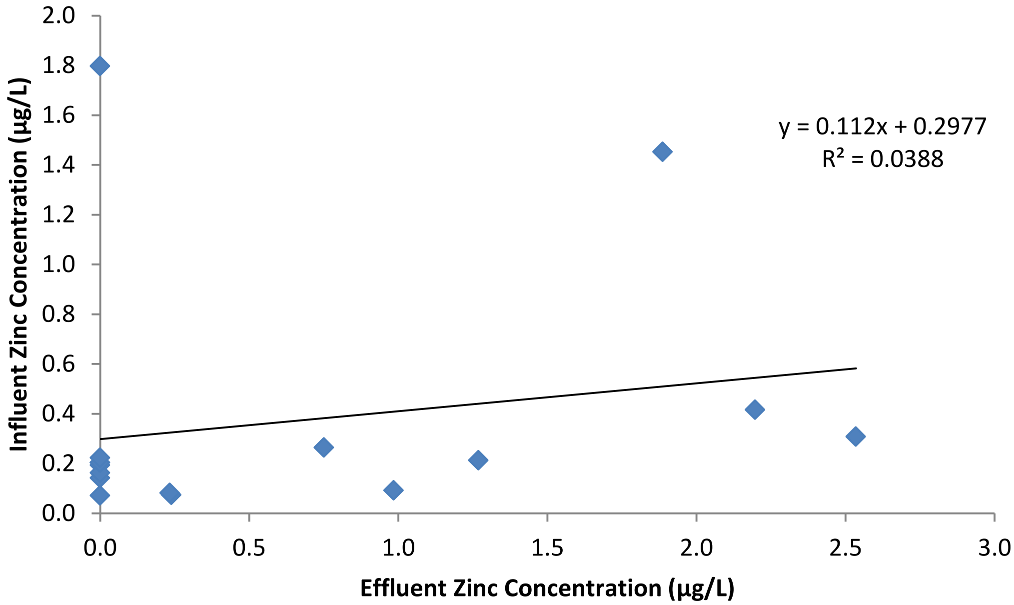

Figure 72: Linear regression model of zinc concentration of the unmanaged vegetated strip

Linear regression models of the zinc mass load are presented in Figure 73 and Figure 74 for the managed vegetated strip and unmanaged vegetated strip, respectively. The influent zinc mass load of 130.6 mg, determined from the Lorton Road runoff water quality averaged over the 16 storm events monitored during this study, was used to predict the effluent zinc mass load of the managed and unmanaged vegetated strips. The managed vegetated strip linear regression model predicts an average effluent mass load of 84.3 mg compared to the observed zinc mass load of 81.6 mg. The unmanaged vegetated strip model predicts an average effluent mass load of 49.6 mg compared to the observed average mass load of 51.1 mg. The linear regression models predict a reduction of the zinc mass by 35.5 percent and 62.0 percent for the managed vegetated strip and unmanaged vegetated strip, respectively.

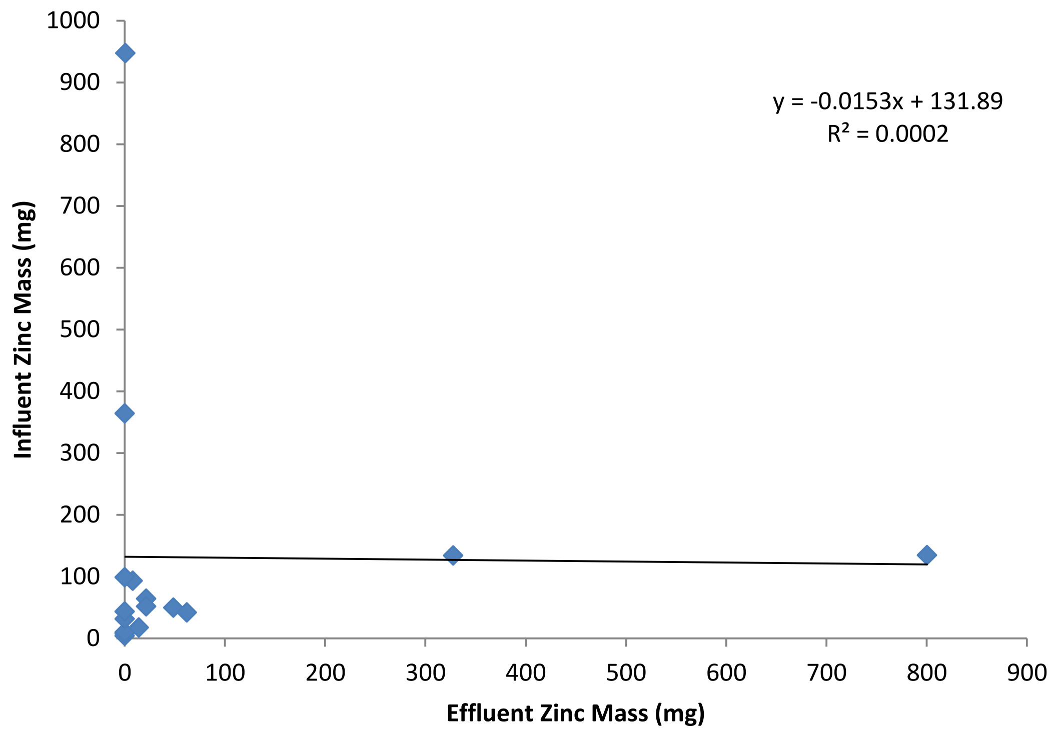

Figure 73: Linear regression model of zinc mass of the managed vegetated strip

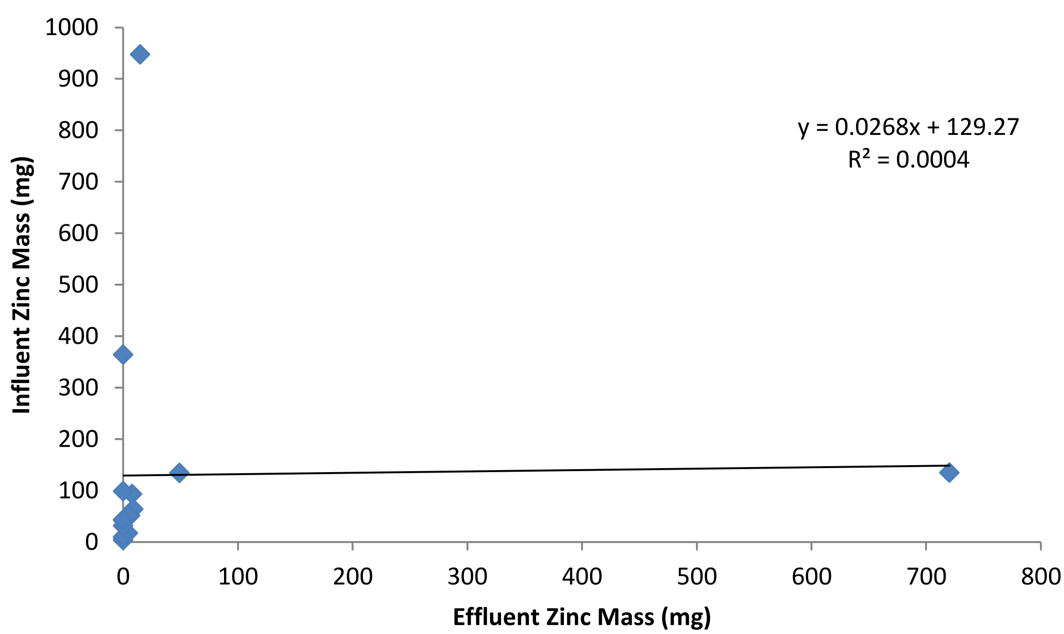

Figure 74: Linear regression model of zinc mass load of the unmanaged vegetated strip

5.0 Future Work

Future work has been proposed as a continuation of research into the mitigation of impacts to receiving waters due to highway stormwater runoff. Future research is intended to close knowledge gaps related to the comparison of LID performance to vegetated roadsides, comparison of performance of various LID practices under similar climate and site conditions, and the long term maintenance requirements and performance of various LID practices.

5.1 Introduction

To mitigate the potential effects of highway runoff on receiving waters, low impact development (LID) stormwater management systems are being employed as a de-centralized, hydraulic and non-point source control alternative to centralized best management practices (BMP). Although LID practices for stormwater management are becoming more common as a stormwater treatment option, a number of knowledge gaps related to the long-term performance and maintenance of LID practices currently exist, particularly in regard to linear transportation systems. The Virginia Department of Environmental Quality (DEQ) has recently passed new measures to improve stormwater quality impacting receiving streams, with a particular interest in reducing nutrients loads of nitrogen and phosphorus and reducing total runoff volume. DEQ's proposed use of the runoff reduction method aims to reduce the volume and rate of flow generated from impervious surfaces while improving runoff quality and limiting pollutant transport which impact receiving waters. Evaluation of LID performance for highway stormwater management is necessary to determine both the short-term and long-term feasibility of LID systems to effectively meet new regulatory guidelines.

The primary objectives of proposed future work are to (1) determine the effectiveness of multiple LID systems for mitigating potential adverse impacts of highway stormwater runoff, and (2) determine the maintenance requirements, procedures, and costs associated with LIDs used in the highway setting. LID performance has been difficult to quantify due to the large variability observed in previous studies. Factors such as rainfall amount, rainfall intensity, and LID influent quality have a significant impact on the performance of LID systems. Studying the performance of multiple LID systems in one area will reduce the impact of watershed variance. The Lorton Road Widening Project provides an ideal opportunity to evaluate and directly compare a variety of LID systems which will receive essentially identical rainfall, climate, daily traffic, and maintenance.

This study will evaluate the performance of a variety of LID systems designed to treat runoff from Lorton Road. A schedule of various study phases and their relationship to Lorton Road construction phases are presented in Figure 75. The study is proposed to begin following the completion of Lorton Road widening and realignment efforts and construction of the associated LID systems in the phase 1 construction area. Four LID systems have been selected for evaluation within the phase 1 construction schedule, located near Furnace Road between Route 123 and Lorton Road. Automated sampling systems used in a related Lorton Road preconstruction study will be relocated to the recently constructed LIDs of the phase 1 construction area, combined with four additional automated sampling systems, to begin this long term evaluation. Approximately 18 months after the LID monitoring begins in the phase one construction area, the remaining two LID systems along Lorton Road will have been constructed. At this time, an additional four to five automated samplers will be installed to begin the evaluation of the two additional LID systems, a type 1 grassy swale and a bioslope located on the southern roadside of Lorton Road. The initial effort of this study will involve the acquisition, installation, and optimization of automated sampling and flow monitoring equipment for LID monitoring as well as characterization of Lorton Road. The study will employ a total of five Sigma 900 automated samplers. Two will be used for Lorton Road runoff sampling, one will be used for sampling of the natural dispersion LID system, and two will be used for sampling of the bioslope. Seven additional AS950 automated samplers are proposed for use in sampling the remaining selected LID systems as well as sampling of outfall #3. It is expected that the installation and optimization of automated stormwater sampling equipment will take approximately two months in order to ensure proper storm characterization is achieved through adequate sampling over the extent of a storm event. A proper sampling procedure will prevent under-sampling so that no one sample represents more than 25% of a storm event as well as preventing over-sampling which results in premature filling of the sample collection bottle, preventing sampling during the tailing end of a storm event. LID systems will also be monitored for signs of erosion, loss of vegetation, flow obstruction, or any other indications that the current maintenance program is insufficient.

The average daily traffic (ADT) data for Lorton Road will be obtained from VDOT, however, if the data are determined to be out of date, current ADT data will be gathered using a pneumatic traffic counter. Currently, the ADT for Lorton Road is estimated to be approximately 8,000 based on previous VDOT estimates (VDOT 2014). Once the optimization of the automated sampling equipment and site characterization is complete, sample collection and analysis will begin. Stormwater samples will be collected from both sheet flow and concentrated flow sources. Sheet flow conditions occur from direct road runoff and dispersive LID systems, such and natural dispersion and bioslopes, and will require the facilitation of flow concentration devices to convert sheet flow to the concentrated flow necessary for flow rate monitoring and for the collection of flow-weighted, automated samples. Concentrated flow, whether concentrated by the stomwater management systems or by sheetflow collectors, will be discharged directly to velocity flumes for flow monitoring and sample collection. The collected samples will be analyzed at the University of Virginia Water Quality Lab to determine the water quality of Lorton Road stormwater runoff as well as the water quality improvement performance of selected LID systems. The hydraulic performance characteristics, such as peak flow rate reduction and flow volume reduction, will be determined for dispersive LID systems by comparing the flow rate data from sheet flow collected directly adjacent to Lorton Road to the sheet flow effluent collected from the dispersive LID systems. Similar hydraulic data will evaluated from concentrated flow LID systems by comparing the hydraulic differences between the concentrated influent and effluent monitoring locations.

The thermal mitigation of selected LID sites will be evaluated by comparing the temperature of samples of the Lorton Road runoff collected from a sampling location, or locations, adjacent to Lorton Road with the temperature of samples collected from the LID effluent sampling locations. The potential beneficial impacts of a more rigorous vegetation management routine will be evaluated during the course of this study. All LID systems will undergo routine VDOT maintenance with respect to mowing and vegetation management during the first year as a control. Beginning in the second year of the study, selected LID systems will undergo a specific maintenance schedule involving monthly mowing and removal of cut vegetation performed by University of Virginia researchers. Previous research of vegetated buffers used for nutrient removal of stormwater runoff of grazed pastures has shown that frequent cutting increases efficiency of nutrient uptake as increased vegetation growth rates are maintained. The removal of cut vegetation prevents re-release of nutrients as cut vegetation decays, decreasing the nutrient load impacting receiving waters due to runoff (Tate et al. 2004).

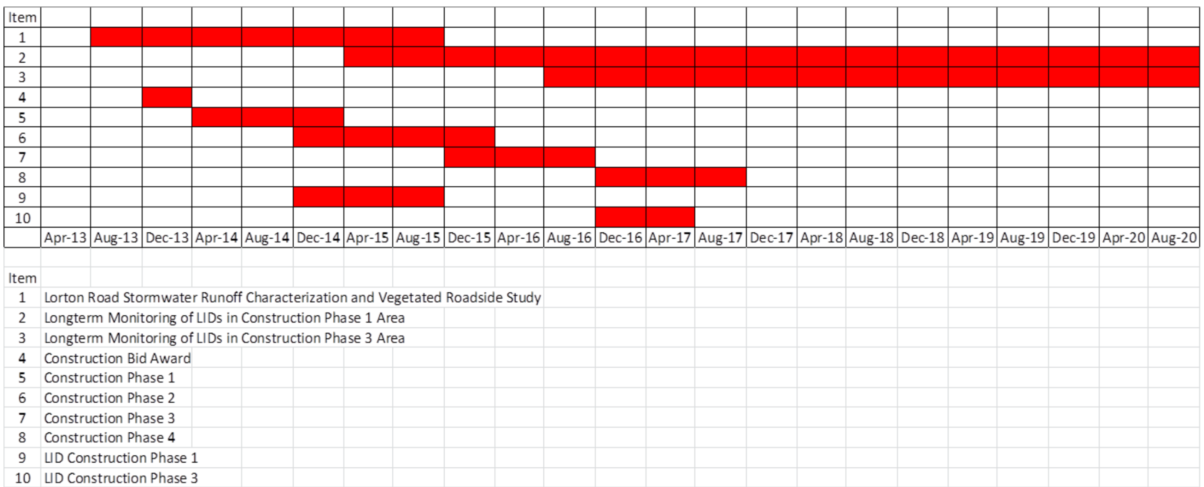

Figure 75: Gantt chart of proposed future work of LID long term performance evaluation

5.2 Proposed Study Sites

Study sites for LID evaluation for the post construction phase of this study where selected according to a number of criteria. Access to the LID systems was evaluated to ensure adequate room was available to install monitoring equipment and that the monitoring equipment location does not pose a threat to driver safety. These criteria invalidated LID systems located in the median of Lorton Road from this study due to the driver safety concerns associated with the permanent automated sampling equipment as well as the safety of monitoring personnel during sample collection. The second criterion for LID site selection was access to the inlet and outlet of each LID system. In order to fully characterize LID performance the influent and effluent of each LID must be fully characterized for each storm event. Therefore, the flume of the flow velocity meter and automated sampler must be integrated into the outfall of each inlet and outlet. In addition, LID systems with only one influent flow were chosen to reduce the quantity of automated samplers required to characterize an individual LID. LID systems with an underdrain were further examined to ensure the underdrain system's outfall would be located in an area sampling equipment could be installed. Finally, LID systems were selected according to the expected influent water quality. Due to the impact of influent quality on LID removal efficiency, LID systems which receive runoff directly from Lorton Road were given priority.

Many of the LID systems for the Lorton Road stormwater management design are installed in series to create what is commonly referred to as a "treatment train." The concern associated with selecting LID systems receiving runoff which has been pre-treated by upstream LIDs is that the influent water quality would likely contain low concentrations of pollutants, possibly near the limit of achievable water quality effluent for a given LID. The removal efficiency of LID systems receiving pre-treated runoff is expected to be significantly lower than those which receive untreated runoff. The impact of influent water quality on removal efficiency has historically produced a large degree of variation in removal efficiency, even among LID systems of similar design. In order to minimize bias associated with influent water quality, LID systems receiving untreated, direct road runoff were chosen to maintain similar influent quality to each LID system for a given storm event. This will provide an unprecedented opportunity for comparison of various LID designs receiving similar water quality influent under field conditions. A summary of LID sites proposed for this study are listed in Table 13.

Table 16: Summary of proposed LIDs selected for long term evaluation

LID	Type	Drainage Area (acres)	Impervious Drainage Area (acres)	Footprint ft or sqft	Retention Volume ft^3	Construction Phase
LID 5-1	Bioretention Filter	36.41	4.07	9,283	15,781	1
LID 5-2	Natural Dispersion	36.41	4.07	382×40	526	1
LID 2-1	Type 3 Swale	49.76	1.38	738×8	11,365	1
LID 3-2A	Type 2 Swale	18.69	5.53	763×5	279	1
LID 4-1A	Type 1 Swale	6.71	1.89	278×5	76	3
LID 4-5	Bioslope	0.49	0.12	250×10	625	3

A plan view of the Lorton Road Widening Project, provided by ATCS, is shown in Figure 76 found below. Areas marked in blue are proposed LID locations selected for this study. Four LID systems, LID 5-1, LID 5-2, LID 2-1, and LID 3-2A are located within the construction schedule phase 1 area which is scheduled to be complete summer 2014. These four LID systems are expected to be the first LID systems to be completed for the Lorton Road Widening Project, and the first to be studied during the post construction study. Two LID systems, LID 4-1A and LID 4-5, are located in the construction schedule phase 3 area which is scheduled to be complete summer 2015.

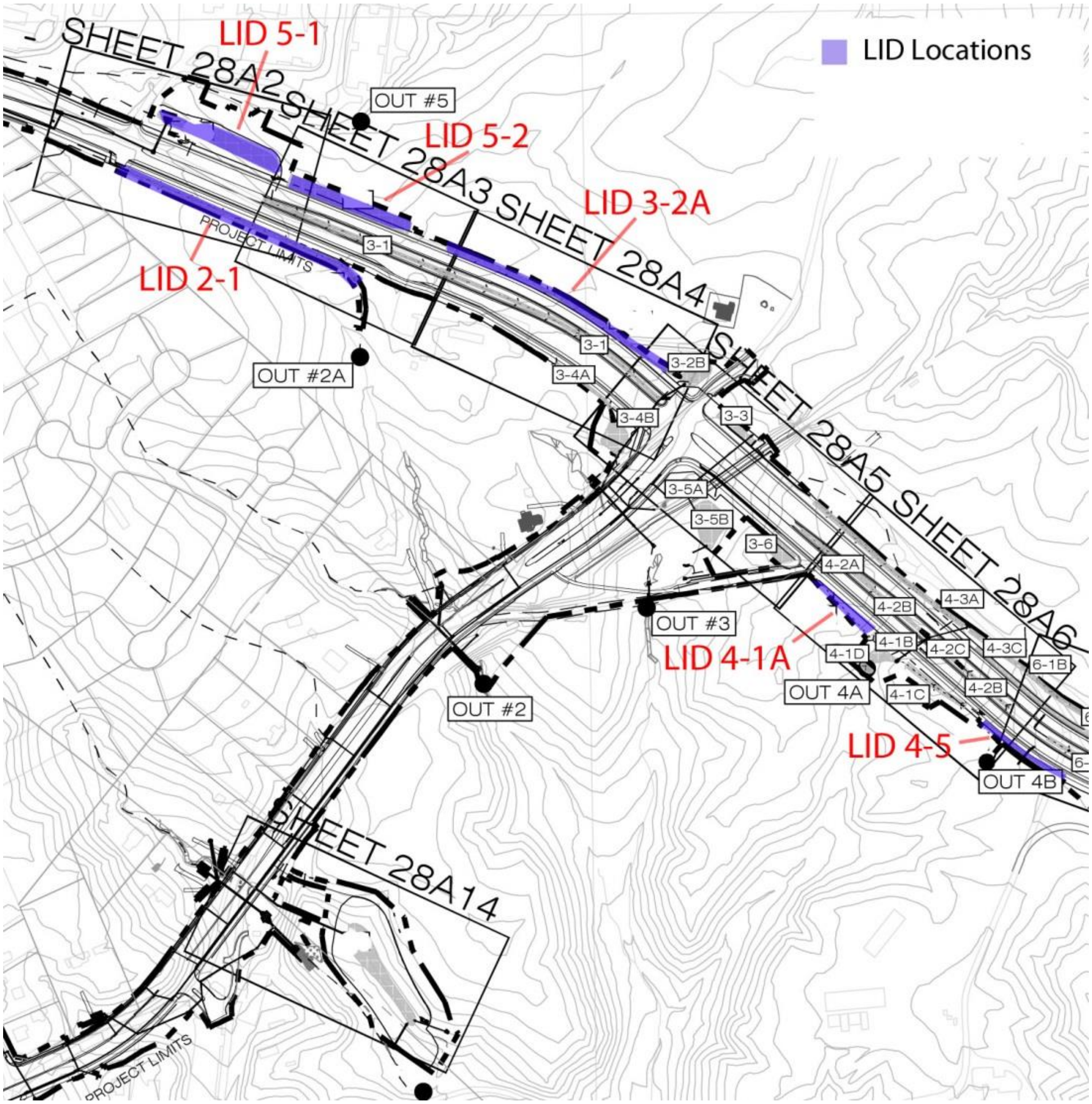

Figure 76: Overview of proposed LID study site locations along post-construction Lorton Road, Source: ATCS Lorton Road Improvements Low Impact Development Sheets

The bioretention filter LID 5-1 and the influent and effluent sampling locations for LID 5-1 are shown in Figure 77, provided by ATCS. The LID systems are highlighted in blue and sampling locations are marked in red. The bioretention filter LID 5-1 is located on the north side of Furnace Road, on the western side of the project site. LID 5-1 receives concentrated influent into a forebay before flowing into the engineered soil media filter area of the bioretention filter. Runoff which has infiltrated into the engineered soil media is collected and conveyed from the system by an underdrain. The underdrain daylights north of the bioretention system and is the location of the effluent sampling equipment. During storm events producing high volume runoff, excessive runoff volume will bypass the system via the overflow spillway located on the north side of the forebay.

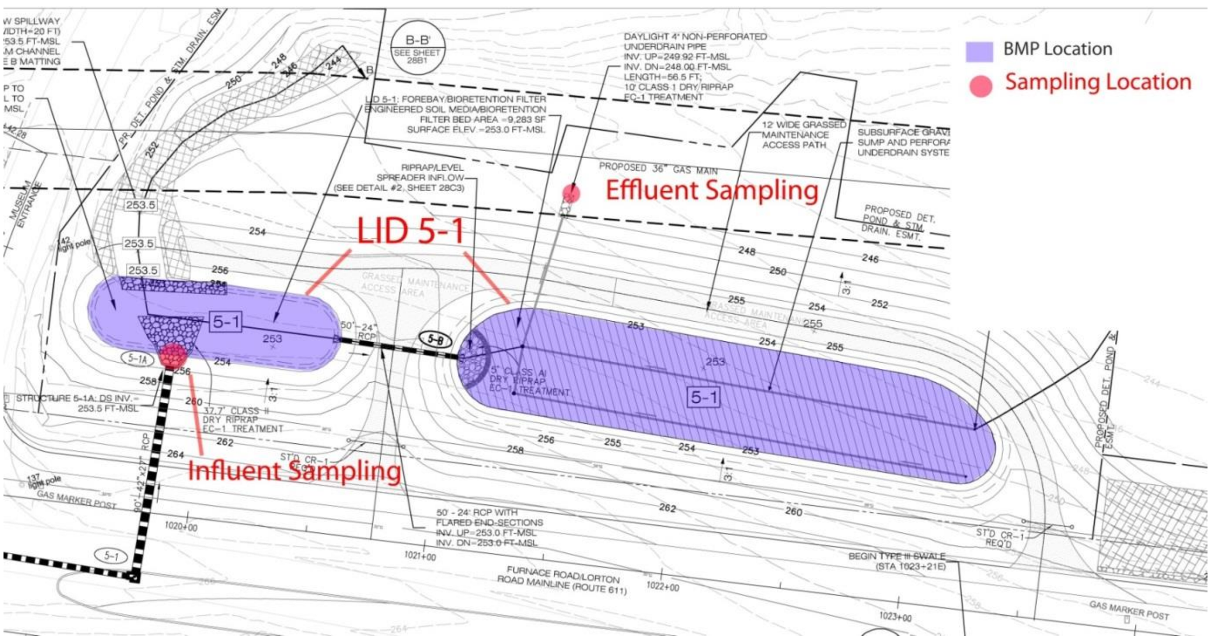

Figure 77: Monitoring locations for site LID 5-1, Source: ATCS Lorton Road Improvements Low Impact Development Sheets

The type 3 swale LID 2-1, along with influent and effluent sampling locations, may be found in Figures 78 and 79. The LID system 2-1 is located on the south side of Furnace Road on the western portion of the project site. The type 3 swale receives concentrated influent from the west end as well as sheet flow directly from the road surface. The location of LID 2-1 is marked in blue while the concentrated influent sampling location is marked as a red circle in Figure 78 and the effluent sampling location is marked as a red circle in Figure 79, both provided by ATCS. Concentrated influent will be sampled immediately prior to the influent outfall to the rip rap flow dispersion device. Runoff which has infiltrated the engineered soil media of LID 2-1 is collected and conveyed via the underdrain which runs parallel to the flow path of LID 2-1. Treated effluent is conveyed through the underdrain and outfalls at the daylighted location of the underdrain. The underdrain outfall is the effluent sampling location for LID 2-1 and is marked as a red circle. Runoff which is not infiltrated and is instead conveyed by the surface of LID 2-1 will continue to be conveyed to the location of the underdrain outfall and will be sampled by the same effluent sampling and flow monitoring flume as the underdrain effluent. This will allow for all effluent from LID 2-1 to be monitored and analyzed for full performance and hydraulic characterization of LID 2-1.

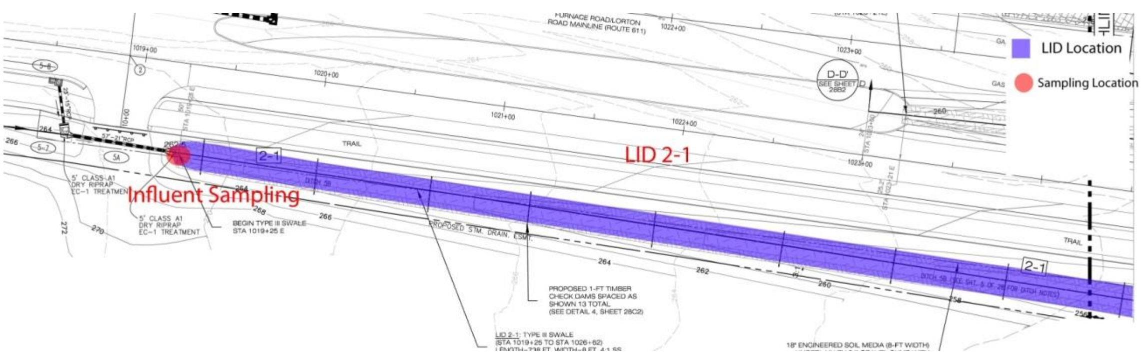

Figure 78 Influent monitoring location for type 3 swale LID 2-1, Source: ATCS Lorton Road Improvements Low Impact Development Sheets

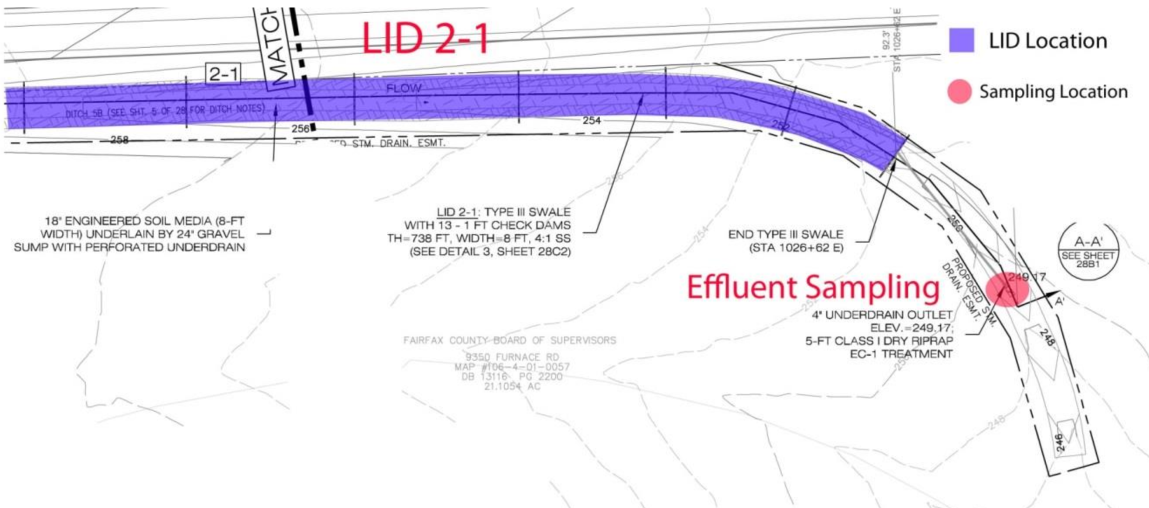

Figure 79 Effluent monitoring location for type 3 swale LID 2-1, Source: ATCS Lorton Road Improvements Low Impact Development Sheets

The natural dispersion LID 5-2 as well as the sheetflow sampling location and effluent sampling location for LID 5-2 can be found in Figure 80, provided by ATCS. Locations of the LID systems area highlighted in blue and sampling locations are marked in red. LID 5-2 is located on the north side of Furnace Road on the western portion of the project area. LID 5-2 receives sheet flow directly from Furnace Road, as opposed to concentrated influent. Therefore, influent samples must be taken from a PVC sheet flow concentration trough which will collect and convey sheet flow into the flow monitoring and automated sampling flume. The location of the sheet flow influent sampling for LID 5-2 is marked as a red line adjacent to the southern portion of LID 5-2, nearest to Furnace Road. This sampling location will also serve as the sampling location to the type 2 swale LID 3-2A, shown in Figure 81. The effluent of natural dispersion LID 5-2 is also overland sheet flow and will similarly require a sheet flow collection trough in order to collect and concentration the sheet flow and convey the runoff to the effluent flow meter and automated sampling flume. The location of the effluent sampling sheet flow collection trough is marked as a red line on the north side of LID 5-2.

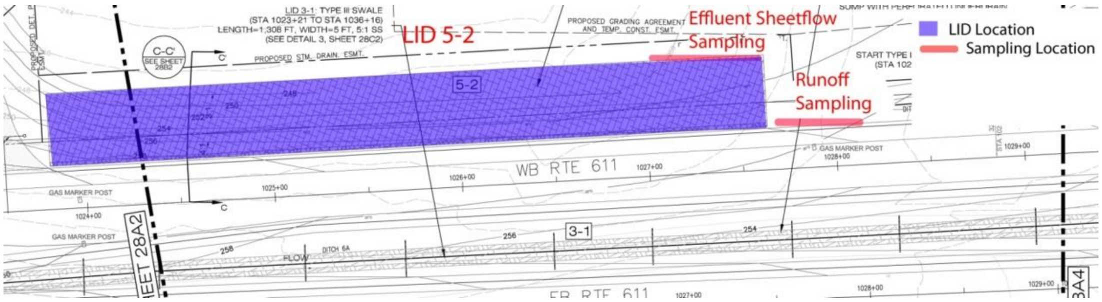

Figure 80 Monitoring locations for natural dispersion site LID 5-2, Source: ATCS Lorton Road Improvements Low Impact Development Sheets

Type 2 Swale LID 3-2A can be found in Figure 81, provided by ATCS. LID 3-2A is highlighted in blue along the north side of Furnace Road and the effluent sampling location is marked as a red circle at the eastern end of LID 3-2A. LID 3-2A receives direct overland sheet flow from Furnace Road and outfalls concentrated effluent into bioretention filter LID 3-2B. Influent flow monitoring and sampling for LID 3-2A will be combined with the sheet flow influent sampling used for the adjacent natural dispersion LID 5-2. Effluent flow monitoring and sampling for LID 3-2A is located at the outfall of LID 3-2A immediately prior to the flow dispersion riprap located at bioretention filter LID 3-2B.

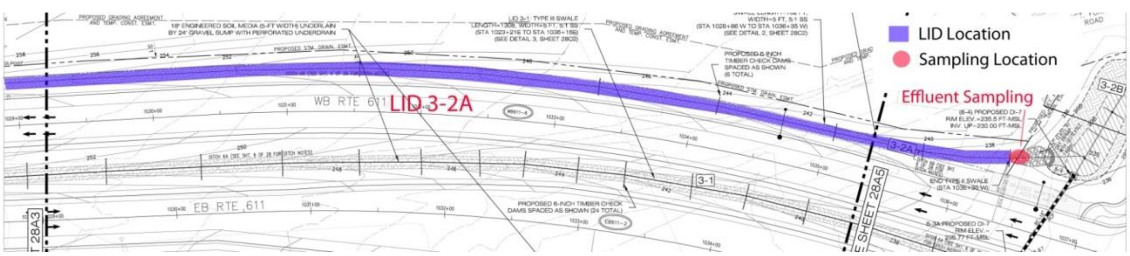

Figure 81 Monitoring locations for type 2 swale site LID 3-2A, Source: ATCS Lorton Road Improvements Low Impact Development Sheets

Type 1 swale LID 4-1A and its effluent sampling location can be found in Figure 82, provided by ATCS. The LID location is highlighted in blue and sampling locations are marked in red.

LID 4-1A is located on the south side of Lorton Road, in the central area of the Project site. LID 4-1A is a type 1 grassy swale which receives overland sheet flow from Lorton Road and conveys and discharges concentrated runoff into bioretention filter 4-1B. Influent sampling for LID 4-1A will require concentration on conveyance of overland sheet flow in the vicinity of LID 4-1A to a flow monitoring and sampling flume and will be used to also represent water quality and flow conditions for the nearby bioslope LID 4-5, which can be found in Figure 17. Effluent flow monitoring and sampling of concentrated effluent will be located at the outfall of LID 4-1A prior to the flow dispersion riprap of LID 4-1B.

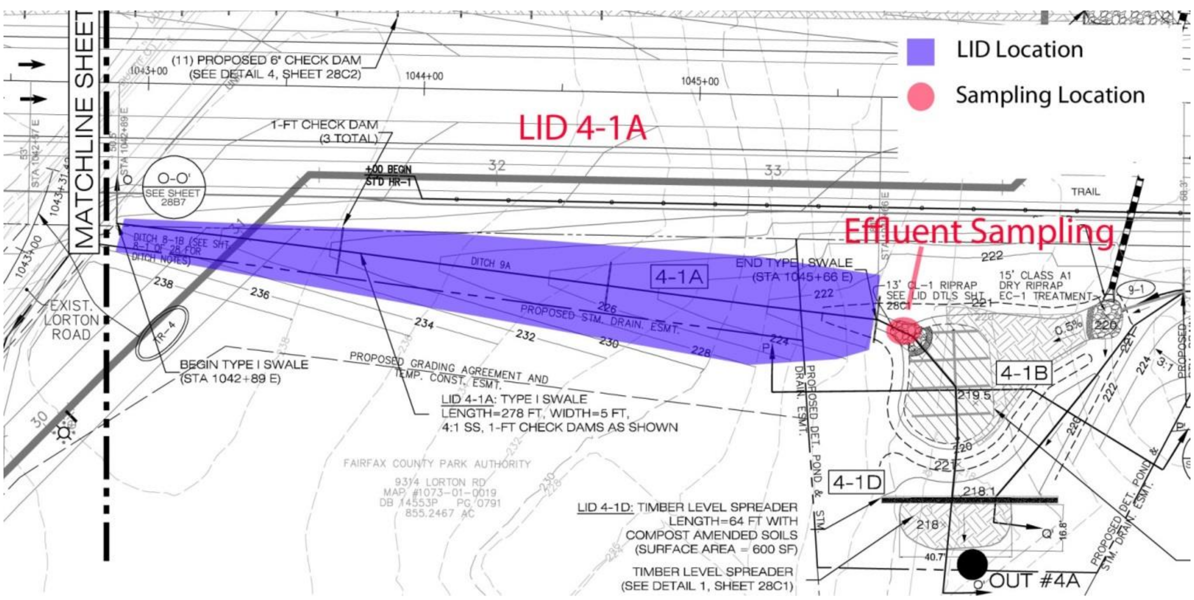

Figure 82 Monitoring location for type 1 swale LID 4-1A, Source: ATCS Lorton Road Improvements Low Impact Development Sheets

Bioslope LID 4-5, as well as the runoff collection sampling used to represent the influent of LID 4-5 and LID 4-1A and the effluent sampling location of LID 4-5 may be found in Figure 83. LID 4-5, highlighted in blue, is located on the south side of Lorton Road near the center of the project site. Bioslope 4-5 receives overland sheet flow from Lorton Road and discharges both sheet flow and concentrated effluent. Influent conditions will be represented by a sheet flow monitoring and sampling system located in the vicinity of both LID 4-1A and LID 4-5 and used to represent the influent conditions of both LID systems. Effluent monitoring and sampling will require concentration of sheet flow at the southern, downslope side of bioslope LID 4-5 and conveyance of concentrated sheet flow to the LID 4-5 underdrain outfall located to the south of the bioslope. Runoff infiltrated into the engineered soil media of the bioslope is collected in a gravel sump located at the base of the slope. The gravel sump contains the perforated underdrain collection system which conveys treated runoff to the underdrain outfall. The effluent sampling flume for LID 4-5 will be located at the underdrain outfall marked in red on Figure 83. The sampling flume will receive the concentrated effluent from the sheet flow collector as well as the concentrated effluent from the underdrain system.

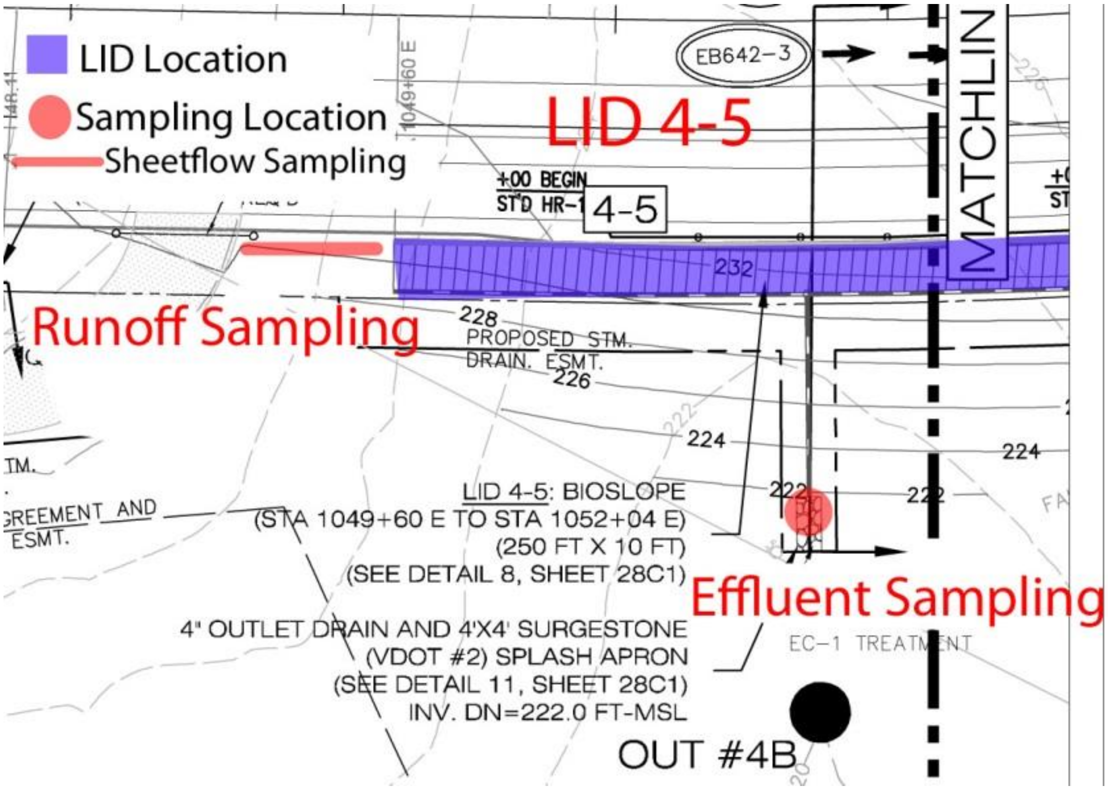

Figure 83 Monitoring locations for bioslope LID 4-5, Source: ATCS Lorton Road Improvements Low Impact Development Sheets

6.0 CONCLUSION

The vegetated roadsides evaluated in this study were found to be comparable to engineered LID systems used for linear transportation (Barrett et al. 1997, Barrett et al. 1998, Conlon and Journey 2008, Line and Hunt 2009, Maurer 2009, Mitchell et al. 2010, NCHRP 2006, Storey et al. 2009, Yu et al. 1993, Yu and Kaighn 1995, Walsh et al. 1997). The mean reduction of total flow volume by 80.7 and 87.3 for the managed vegetated strip and unmanaged vegetated strip, respectively, is credited as the most substantial influence to mitigation of constituent mass migration as infiltration prevents constituents from migrating to and impacting receiving streams. The results of the Sign test show that the mass loading for each constituent is statistically higher for the Lorton Road runoff relative to both the managed and unmanaged vegetated strips. The Sign test also shows that peak flow velocity and total flow volume from the managed and unmanaged vegetated strips are significantly reduced from those of the Lorton Road runoff. Managed vegetation was found to be less effective than unmanaged vegetation due to the reduction flow friction, preferential infiltration pathways, and solids filtration and sedimentation.

Sign test analysis comparing the managed vegetated strip to the unmanaged vegetated strip showed significant differences for only 5 of the 14 parameters monitored. However, the large constituent mass release of the 5/01/14 storm event may suggest that vegetation management could reduce large, infrequent releases of constituent mass during large storm events and/or early spring storm events. For example, the total nitrogen mass of the managed vegetated strip effluent for the May 1st storm event was responsible for 85.9 percent of the total nitrogen mass of the managed vegetated strip effluent measured throughout the entire study and 94.5 percent of the unmanaged effluent total nitrogen mass measured throughout the study. The Lorton Road runoff total nitrogen mass loading of the May 1st storm event was responsible for 60 percent of the total mass of total nitrogen migrated from the road surface during the course of this study. One extensive annual vegetation management session may help to reduce the large, infrequent mass releases. However, a study spanning multiple years would be required to determine the impact of ongoing vegetation management.

Averaged over the five storm events, the managed vegetated roadside strip reduced runoff temperature by 3.3 percent. The unmanaged vegetated roadside strip reduced runoff temperature by 3.0 percent. However, infiltration in the vegetated strips of flow volume which could potentially migrate heat from the road surface to receiving waters reduced the thermal load potentially impacting receiving waters. The managed vegetated strip reduced the thermal load of the effluent by 83.0 percent compared to the Lorton Road runoff. The unmanaged vegetated strip reduced the thermal load of the effluent by 98.2 percent. The results of the thermal mitigation evaluation show a reduction in runoff temperature and reduction of thermal load. The results of this study suggest that the use of vegetated roadsides in lieu of curbs and gutters, assuming curb and gutters perform no water quality improvement or reduce water quantity, will statistically and substantially reduce constituent migration and impacts to receiving streams.

The results of this study may help VDOT and other state transportation departments, transportation planners, and water quality regulators in low impact development planning going forward into the future. In particular, if vegetated roadsides are found to be comparable to the LID practices currently being installed at Lorton Road, the use of vegetated roadsides as an LID practice should be considered. In addition, vegetated roadsides were also found to require minimal maintenance to maintain optimal performance relative to the requirements of engineering LID systems.

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Appendix A

Additional Figures and Tables

Table A 1 Total flow volume and peak flow rate of the managed vegetated strip, unmanaged vegetated strip, and Lorton Road runoff for each storm event

	Site 1		Site 2		Site 3	
Date	Total Flow Volume (gpm)	Peak Flow Rate (L/s)	Total Flow Volume (gpm)	Peak Flow Rate (L/s)	Total Flow Volume (gpm)	Peak Flow Rate (L/s)
5/1/2014	2673.23	3.52	1815.02	2.21	3020.01	2.71
5/29/2014	4.58	0.07	652.27	3.77	7.95	0.07
6/11/2014	4.62	0.07	301.40	2.11	3.14	0.03
6/12/2014	34.86	0.45	153.52	1.75	4.16	0.05
8/12/2014	576.83	9.01	1647.04	10.57	210.94	2.16
8/22/2014	0.19	0.01	50.79	0.97	0.45	0.01
9/12/2014	8.06	0.13	39.44	0.97	1.10	0.03
9/25/2014	0.23	0.01	202.65	1.78	0.15	0.00
10/4/2014	11.73	0.31	241.48	4.07	4.88	0.13
10/8/2014	9.77	0.26	64.95	1.15	5.72	0.07
10/12/2014	1.02	0.00	67.64	0.36	0.00	0.00
10/16/2014	149.66	0.89	542.58	2.97	5.49	0.06
10/22/2014	80.51	0.16	256.85	0.64	3.86	0.01
11/6/2014	0.64	0.02	154.47	1.56	0.57	0.01
11/17/2014	0.34	0.01	485.01	1.91	0.00	0.00
11/24/2014	1.14	0.02	194.36	0.77	2.65	0.01

Table A 2 Total suspended solids concentration and mass for the managed vegetated strip, unmanaged vegetated strip, and Lorton Road runoff for each storm event

	Site 1		Site 2		Site 3	
Date	Total Suspended Solids Concentration (mg/L)	Total Suspended Solids Mass (g)	Total Suspended Solids Concentration (mg/L)	Total Suspended Solids Mass (g)	Total Suspended Solids Concentration (mg/L)	Total Suspended Solids Mass (g)
5/1/2014	289.00	772.56	13616.00	24713.33	326.00	984.52
5/29/2014	0.00	0.00	1206.00	786.64	0.00	0.00
6/11/2014	0.00	0.00	2332.00	702.86	0.00	0.00
6/12/2014	297.00	10.35	8639.00	1326.26	1864.00	7.76
8/12/2014	619.00	357.06	257.00	423.29	451.00	95.13
8/22/2014	0.00	0.00	86.00	4.37	0.00	0.00
9/12/2014	0.00	0.00	50.00	1.97	0.00	0.00
9/25/2014	0.00	0.00	725.00	146.92	0.00	0.00
10/4/2014	235.00	2.76	54.00	13.04	384.00	1.87
10/8/2014	181.00	1.77	157.00	10.20	145.00	0.83
10/12/2014	0.00	0.00	117.00	7.91	0.00	0.00
10/16/2014	286.00	42.80	547.00	296.79	531.00	2.91
10/22/2014	175.00	14.09	208.00	53.42	0.00	0.00
11/6/2014	0.00	0.00	293.00	45.26	0.00	0.00
11/17/2014	0.00	0.00	819.00	397.22	0.00	0.00
11/24/2014	0.00	0.00	819.00	159.18	0.00	0.00

Table A 3 Nitrates concentration and mass for the managed vegetated strip, the unmanaged vegetated strip, and the Lorton Road runoff for each storm event

	Site 1		Site 2		Site 3	
Date	Nitrates Concentration (mg/L)	Nitrates Mass (mg)	Nitrates Concentration (mg/L)	Nitrates Mass (mg)	Nitrates Concentration (mg/L)	Nitrates Mass (mg)
5/1/2014	0.00	0.00	0.25	452.61	0.00	0.00
5/29/2014	0.00	0.00	0.40	261.73	0.00	0.00
6/11/2014	0.00	0.00	1.07	323.15	0.00	0.00
6/12/2014	0.16	5.41	1.29	197.63	1.35	5.62
8/12/2014	0.63	365.12	2.17	3579.71	0.12	25.90
8/22/2014	0.00	0.00	0.38	19.10	0.00	0.00
9/12/2014	0.00	0.00	0.17	6.84	0.00	0.00
9/25/2014	0.00	0.00	0.12	24.88	0.00	0.00
10/4/2014	0.20	2.29	0.49	118.30	0.00	0.00
10/8/2014	0.05	0.48	1.73	112.39	0.67	3.81
10/12/2014	0.00	0.00	0.38	25.43	0.00	0.00
10/16/2014	1.06	158.28	0.63	341.34	1.60	8.80
10/22/2014	0.94	75.53	1.07	275.38	0.00	0.00
11/6/2014	0.00	0.00	0.79	122.60	0.00	0.00
11/17/2014	0.00	0.00	0.31	151.64	0.00	0.00
11/24/2014	0.00	0.00	0.35	68.15	0.00	0.00

Table A 4 Total nitrogen concentration and mass for the managed vegetated strip, the unmanaged vegetated strip, and the Lorton Road runoff for each storm event

Date	Total Nitrogen Concentration (mg/L)	Total Nitrogen Mass (mg)	Total Nitrogen Concentration (mg/L)	Total Nitrogen Mass (mg)	Total Nitrogen Concentration (mg/L)	Total Nitrogen Mass (mg)
5/1/2014	8.39	22419.51	5.43	9862.82	5.43	16410.75
5/29/2014	5.98	27.37	1.88	1227.14	9.72	77.25
6/11/2014	0.00	0.00	1.78	535.44	9.09	28.56
6/12/2014	9.33	325.25	0.73	112.30	18.50	77.01
8/12/2014	5.03	2902.63	1.15	1893.28	3.55	749.46
8/22/2014	0.00	0.00	1.67	84.93	0.00	0.00
9/12/2014	0.00	0.00	2.93	115.40	0.00	0.00
9/25/2014	0.00	0.00	4.08	825.90	0.00	0.00
10/4/2014	2.10	24.60	2.72	656.11	1.57	7.65
10/8/2014	2.73	26.62	2.51	162.90	1.05	5.97
10/12/2014	3.04	3.11	2.82	190.84	0.00	0.00
10/16/2014	1.36	203.96	0.10	56.70	1.36	7.46
10/22/2014	2.10	168.80	1.15	295.25	0.00	0.00
11/6/2014	0.00	0.00	1.46	225.98	0.00	0.00
11/17/2014	0.00	0.00	0.52	253.42	0.00	0.00
11/24/2014	0.00	0.00	0.00	0.00	0.00	0.00

Table A 5 Total phosphate concentration and mass for the managed vegetated strip, the unmanaged vegetated strip, and the Lorton Road runoff for each storm event

	Site 1		Site 2		Site 3	
Date	Total Phosphate Concentration (mg/L)	Total Phosphate Mass (mg)	Total Phosphate Concentration (mg/L)	Total Phosphate Mass (mg)	Total Phosphate Concentration (mg/L)	Total Phosphate Mass (mg)
5/1/2014	1.49	3979.46	0.64	1161.61	2.12	6402.43
5/29/2014	3.07	14.07	2.93	1911.15	0.00	0.00
6/11/2014	0.00	0.00	0.83	250.16	0.00	0.00
6/12/2014	1.46	50.80	1.24	190.36	0.00	0.00
8/12/2014	1.68	967.54	0.51	839.99	0.26	54.84
8/22/2014	0.00	0.00	0.19	9.65	0.00	0.00
9/12/2014	0.00	0.00	1.46	57.58	0.00	0.00
9/25/2014	0.00	0.00	0.66	133.75	0.00	0.00
10/4/2014	3.60	42.19	2.61	630.27	2.91	14.21
10/8/2014	3.28	32.04	1.35	87.68	2.90	16.57
10/12/2014	0.03	0.03	0.61	41.26	0.00	0.00
10/16/2014	0.70	105.12	0.60	325.55	1.94	10.65
10/22/2014	0.30	24.48	0.99	254.28	0.00	0.00
11/6/2014	0.00	0.00	1.68	259.50	0.00	0.00
11/17/2014	0.00	0.00	0.08	38.80	0.00	0.00
11/24/2014	0.00	0.00	0.07	13.61	0.00	0.00

Table A 6 Chemical oxygen demand per liter of runoff and total chemical oxygen demand per storm event for the managed vegetated strip, the unmanaged vegetated strip, and the Lorton Road runoff for each storm event

	Site 1		Site 2		Site 3	
Date	Chemical Oxygen Demand (mg/L)	Total Chemical Oxygen Demand Per Event (mg)	Chemical Oxygen Demand (mg/L)	Total Chemical Oxygen Demand Per Event (mg)	Chemical Oxygen Demand (mg/L)	Total Chemical Oxygen Demand Per Event (mg)
5/1/2014	107.89	288.43	189.72	344.35	170.63	170.63
5/29/2014	0.00	0.00	Not Analyzed	Not Analyzed	0.00	0.00
6/11/2014	0.00	0.00	94.12	28.37	243.77	243.77
6/12/2014	254.36	8.87	139.72	21.45	350.06	350.06
8/12/2014	178.88	103.18	59.32	97.70	163.77	163.77
8/22/2014	0.00	0.00	63.72	3.24	0.00	0.00
9/12/2014	0.00	0.00	68.92	2.72	0.00	0.00
9/25/2014	0.00	0.00	176.12	35.69	0.00	0.00
10/4/2014	247.17	2.90	105.32	25.43	179.77	179.77
10/8/2014	172.89	1.69	82.12	5.33	89.49	89.49
10/12/2014	115.38	0.12	54.92	3.71	0.00	0.00
10/16/2014	242.37	36.27	52.92	28.71	254.06	254.06
10/22/2014	241.18	19.42	69.32	17.80	0.00	0.00
11/6/2014	0.00	0.00	73.72	11.39	0.00	0.00
11/17/2014	0.00	0.00	60.52	29.35	0.00	0.00
11/24/2014	0.00	0.00	78.92	15.34	0.00	0.00

Table A 7 Oil and grease concentration and mass for the managed vegetated strip, the unmanaged vegetated strip, and the Lorton Road runoff for each storm event

	Site 1		Site 2		Site 3	
Date	Oil and Grease Concentration (mg/L)	Oil and Grease Mass (mg)	Oil and Grease Concentration (mg/L)	Oil and Grease Mass (mg)	Oil and Grease Concentration (mg/L)	Oil and Grease Mass (mg)
5/1/2014	0.01	27.13	4.75	8621.71	1.32	3984.91
5/29/2014	1.52	6.97	2.84	1853.75	1.02	8.07
6/11/2014	0.00	0.00	0.42	126.59	2.03	6.38
6/12/2014	11.47	399.83	7.00	1075.17	19.53	81.31
8/12/2014	5.89	3395.82	14.31	23571.65	13.55	2858.26
8/22/2014	0.00	0.00	1.73	87.65	0.00	0.00
9/12/2014	1.83	14.73	6.80	268.21	0.00	0.00
9/25/2014	0.00	0.00	0.61	123.41	0.00	0.00
10/4/2014	2.03	23.82	3.65	882.38	3.35	16.35
10/8/2014	28.62	279.51	41.62	2702.92	32.78	187.37
10/12/2014	0.00	0.00	5.89	398.18	0.00	0.00
10/16/2014	28.62	4283.69	26.59	14428.82	17.36	95.26
10/22/2014	8.22	661.89	3.86	990.67	0.00	0.00
11/6/2014	0.00	0.00	6.29	972.05	0.00	0.00
11/17/2014	0.00	0.00	9.24	4479.79	0.00	0.00
11/24/2014	0.00	0.00	12.38	2406.76	0.00	0.00

Table A 8 Total Coliform concentration and Total Coliform per event for the managed vegetated strip, the unmanaged vegetated strip, and the Lorton Road runoff for each storm event

	Site 1		Site 2		Site 3	
Date	Total Coliform (cfu/100mL)	Total Coliform (Million cfu/event)	Total Coliform (cfu/100mL)	Total Coliform (Million cfu/event)	Total Coliform (cfu/100mL)	Total Coliform (Million cfu/event)
5/1/2014	2650.00	70.84	100.00	1.82	4870.00	147.07
5/29/2014	Not Analyzed	Not Analyzed	Not Analyzed	Not Analyzed	Not Analyzed	Not Analyzed
6/11/2014	Not Analyzed	Not Analyzed	Not Analyzed	Not Analyzed	Not Analyzed	Not Analyzed
6/12/2014	Not Analyzed	Not Analyzed	Not Analyzed	Not Analyzed	Not Analyzed	Not Analyzed
8/12/2014	Not Analyzed	Not Analyzed	Not Analyzed	Not Analyzed	Not Analyzed	Not Analyzed
8/22/2014	0.00	0.00	2490.00	1.26	0.00	0.00
9/12/2014	0.00	0.00	29090.00	11.47	0.00	0.00
9/25/2014	Not Analyzed	Not Analyzed	Not Analyzed	Not Analyzed	Not Analyzed	Not Analyzed
10/4/2014	100.00	0.01	3760.00	9.08	200.00	0.01
10/8/2014	0.00	0.00	900.00	0.58	2640.00	0.15
10/12/2014	0.00	0.00	20980.00	14.19	0.00	0.00
10/16/2014	5760.00	8.62	5480.00	29.73	23590.00	1.29
10/22/2014	30760.00	24.76	14390.00	36.96	0.00	0.00
11/6/2014	0.00	0.00	4220.00	6.52	0.00	0.00
11/17/2014	0.00	0.00	7940.00	38.51	0.00	0.00
11/24/2014	0.00	0.00	2810.00	0.55	0.00	0.00

Table A 9 Cadmium concentration and mass for the managed vegetated strip, the unmanaged vegetated strip, and the Lorton Road runoff for each storm event

	Site 1		Site 2		Site 3	
Date	Cadmium Concentration (µg/L)	Cadmium Mass (µg)	Cadmium Concentration (µg/L)	Cadmium Mass (µg)	Cadmium Concentration (µg/L)	Cadmium Mass (µg)
5/1/2014	0.53	1410.93	2.49	4513.50	2.49	4513.50
5/29/2014	0.78	3.58	0.36	231.72	0.36	231.72
6/11/2014	1.06	4.87	0.11	31.65	0.11	31.65
6/12/2014	0.86	30.08	0.77	118.27	0.77	118.27
8/12/2014	0.87	503.52	0.10	167.17	0.10	167.17
8/22/2014	0.00	0.00	0.10	5.16	0.10	5.16
9/12/2014	0.00	0.00	0.33	13.21	0.33	13.21
9/25/2014	0.00	0.00	2.42	489.54	2.42	489.54
10/4/2014	1.25	14.65	0.31	75.98	0.31	75.98
10/8/2014	1.34	13.08	0.12	7.91	0.12	7.91
10/12/2014	0.00	0.00	4.59	310.31	4.59	310.31
10/16/2014	1.10	164.06	0.10	55.07	0.10	55.07
10/22/2014	0.85	68.64	0.24	62.57	0.24	62.57
11/6/2014	0.00	0.00	0.14	21.95	0.14	21.95
11/17/2014	0.00	0.00	0.14	68.92	0.14	68.92
11/24/2014	0.00	0.00	1.79	347.20	1.79	347.20

Table A 10 Chromium concentration and mass for the managed vegetated strip, the unmanaged vegetated strip, and the Lorton Road runoff for each storm event

	Site 1		Site 2		Site 3	
Date	Chromium Concentration (µg/L)	Chromium Mass (µg)	Chromium Concentration (µg/L)	Chromium Mass (µg)	Chromium Concentration (µg/L)	Chromium Mass (µg)
5/1/2014	5.18	13837.99	19.18	34818.46	3.23	9747.70
5/29/2014	17.60	80.61	4.48	2919.65	24.09	191.45
6/11/2014	20.02	92.43	22.14	6674.34	32.61	102.45
6/12/2014	3.73	129.85	21.76	3340.83	19.21	80.00
8/12/2014	4.78	2757.64	7.13	11735.67	1.68	355.41
8/22/2014	0.00	0.00	1.15	58.26	0.00	0.00
9/12/2014	0.00	0.00	1.30	51.24	0.00	0.00
9/25/2014	0.00	0.00	7.25	1468.62	0.00	0.00
10/4/2014	3.89	45.61	3.03	732.86	0.51	2.48
10/8/2014	3.10	30.23	3.47	225.46	1.41	8.06
10/12/2014	0.00	0.00	6.79	459.29	0.00	0.00
10/16/2014	7.88	1178.77	10.77	5843.12	14.78	81.11
10/22/2014	16.10	1295.99	12.49	3209.25	0.00	0.00
11/6/2014	0.00	0.00	10.43	1611.73	0.00	0.00
11/17/2014	0.00	0.00	13.32	6458.78	0.00	0.00
11/24/2014	0.00	0.00	6.35	1234.94	0.00	0.00

Table A 11 Copper concentration and mass for the managed vegetated strip, the unmanaged vegetated strip, and the Lorton Road runoff for each storm event

	Site 1		Site 2		Site 3	
Date	Copper Concentration (µg/L)	Copper Mass (µg)	Copper Concentration (µg/L)	Copper Mass (µg)	Copper Concentration (µg/L)	Copper Mass (µg)
5/1/2014	23.54	62922.13	171.33	310971.19	25.58	77245.91
5/29/2014	190.72	873.46	31.00	20219.10	30.61	243.32
6/11/2014	35.19	162.50	47.99	14462.66	37.59	118.08
6/12/2014	29.08	1013.72	123.02	18885.67	53.36	222.16
8/12/2014	9.95	5737.77	13.74	22635.47	10.83	2284.47
8/22/2014	0.00	0.00	8.96	455.24	0.00	0.00
9/12/2014	0.00	0.00	15.50	611.28	0.00	0.00
9/25/2014	0.00	0.00	55.39	11224.43	0.00	0.00
10/4/2014	16.98	199.25	14.72	3554.03	12.59	61.45
10/8/2014	14.77	144.22	21.62	1404.20	10.25	58.59
10/12/2014	0.00	0.00	13.38	904.84	0.00	0.00
10/16/2014	32.07	4800.16	16.62	9015.26	17.16	94.20
10/22/2014	38.20	3075.74	22.46	5769.35	0.00	0.00
11/6/2014	0.00	0.00	19.89	3072.94	0.00	0.00
11/17/2014	0.00	0.00	17.71	8590.37	0.00	0.00
11/24/2014	0.00	0.00	15.48	3008.45	0.00	0.00

Table A 12 Lead concentration and mass for the managed vegetated strip, the unmanaged vegetated strip, and the Lorton Road runoff for each storm event

	Site 1		Site 2		Site 3	
Date	Lead Concentration (µg/L)	Lead Mass (µg)	Lead Concentration (µg/L)	Lead Mass (µg)	Lead Concentration (µg/L)	Lead Mass (µg)
5/1/2014	0.41	1088.05	33.86	61457.34	2.35	7105.40
5/29/2014	18.02	82.51	1.76	1148.00	21.94	174.42
6/11/2014	12.86	59.38	7.94	2394.41	22.63	71.11
6/12/2014	2.28	79.33	32.64	5011.25	23.12	96.27
8/12/2014	28.50	16440.46	20.59	33919.77	17.00	3586.21
8/22/2014	0.00	0.00	7.64	388.22	0.00	0.00
9/12/2014	0.00	0.00	7.18	283.02	0.00	0.00
9/25/2014	0.00	0.00	3.37	682.89	0.00	0.00
10/4/2014	7.13	83.60	0.70	169.12	1.83	8.92
10/8/2014	0.05	0.50	0.24	15.82	5.16	29.47
10/12/2014	0.00	0.00	2.69	181.93	0.00	0.00
10/16/2014	7.25	1084.59	2.57	1393.32	3.33	18.27
10/22/2014	8.06	648.81	0.69	177.28	0.00	0.00
11/6/2014	0.00	0.00	2.59	399.80	0.00	0.00
11/17/2014	0.00	0.00	1.32	639.97	0.00	0.00
11/24/2014	0.00	0.00	0.41	78.91	0.00	0.00

Table A 13 Zinc concentration and mass for the managed vegetated strip, the unmanaged vegetated strip, and the Lorton Road runoff for each storm event

	Site 1		Site 2		Site 3	
Date	Zinc Concentration (µg/L)	Zinc Mass (µg)	Zinc Concentration (µg/L)	Zinc Mass (µg)	Zinc Concentration (µg/L)	Zinc Mass (µg)
5/1/2014	0.41	1088.05	33.86	61457.34	2.35	7105.40
5/29/2014	18.02	82.51	1.76	1148.00	21.94	174.42
6/11/2014	12.86	59.38	7.94	2394.41	22.63	71.11
6/12/2014	2.28	79.33	32.64	5011.25	23.12	96.27
8/12/2014	28.50	16440.46	20.59	33919.77	17.00	3586.21
8/22/2014	0.00	0.00	7.64	388.22	0.00	0.00
9/12/2014	0.00	0.00	7.18	283.02	0.00	0.00
9/25/2014	0.00	0.00	3.37	682.89	0.00	0.00
10/4/2014	7.13	83.60	0.70	169.12	1.83	8.92
10/8/2014	0.05	0.50	0.24	15.82	5.16	29.47
10/12/2014	0.00	0.00	2.69	181.93	0.00	0.00
10/16/2014	7.25	1084.59	2.57	1393.32	3.33	18.27
10/22/2014	8.06	648.81	0.69	177.28	0.00	0.00
11/6/2014	0.00	0.00	2.59	399.80	0.00	0.00
11/17/2014	0.00	0.00	1.32	639.97	0.00	0.00
11/24/2014	0.00	0.00	0.41	78.91	0.00	0.00

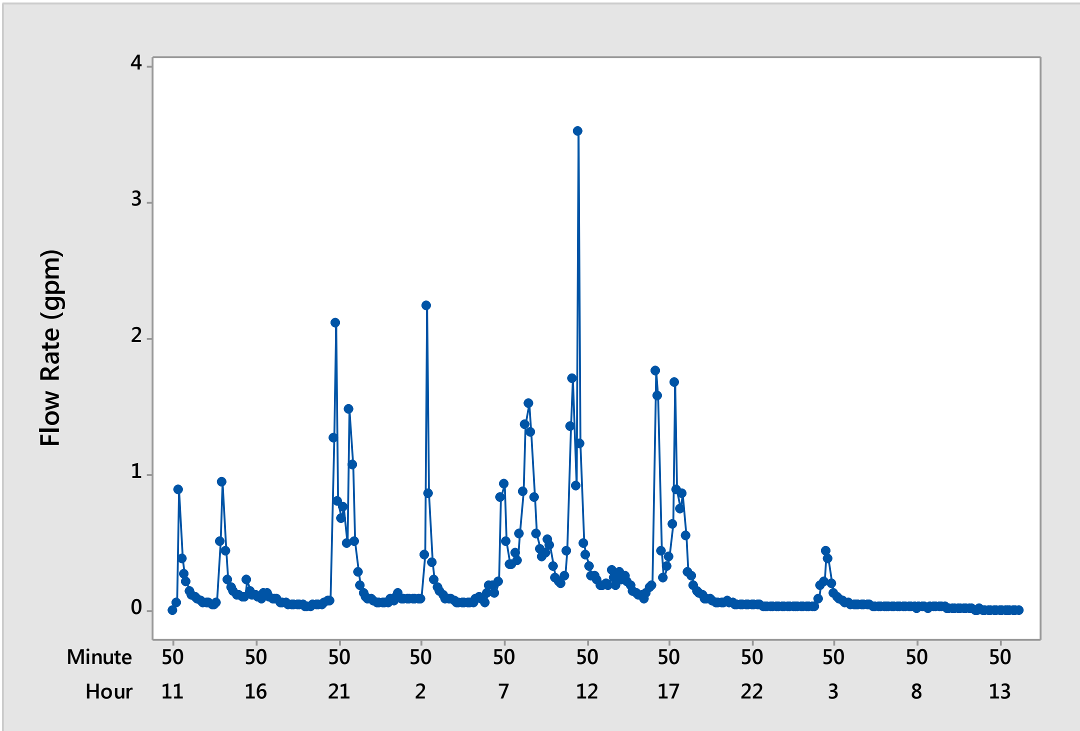

Figure A 1: Hydrograph of flowrate for the managed vegetated strip for the 5/01/14 storm event

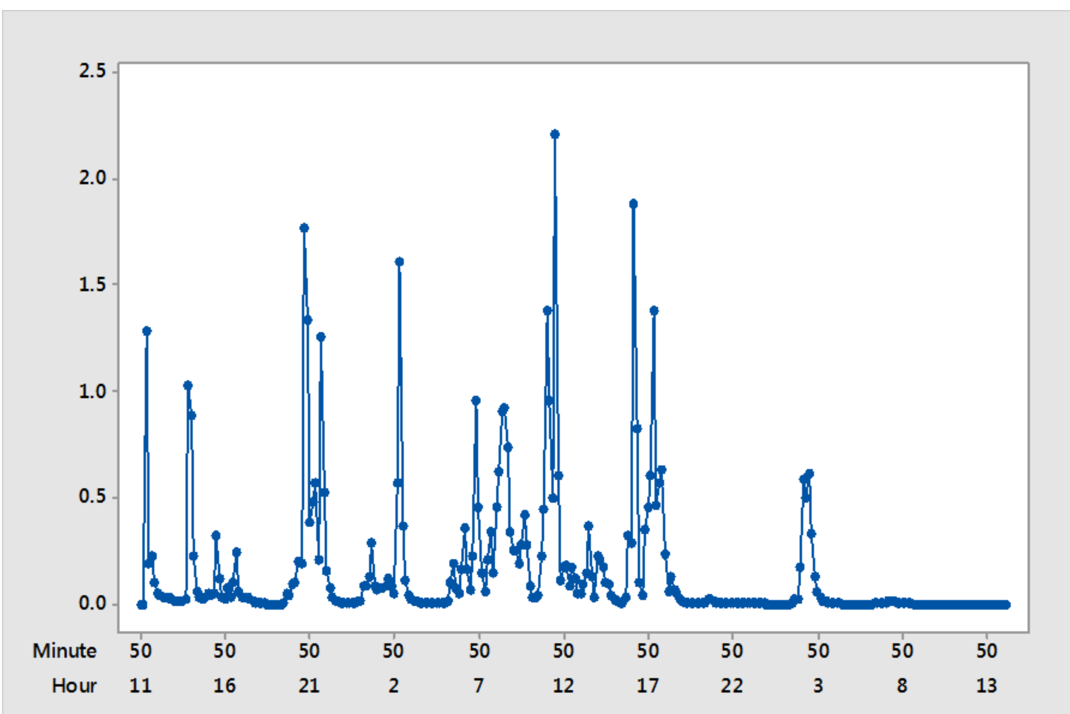

Figure A 2: Hydrograph of flow rate for the Lorton Road runoff for the 5/01/14 storm event

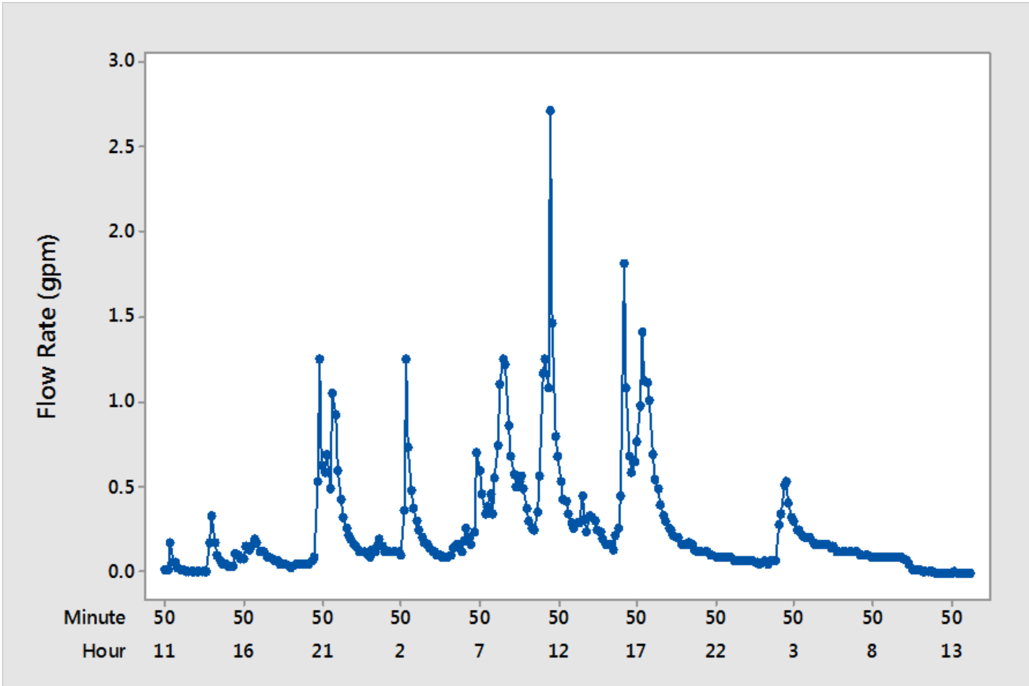

Figure A 3 Hydrograph of the flow rate for the unmanaged vegetated strip for the 5/01/14 storm event

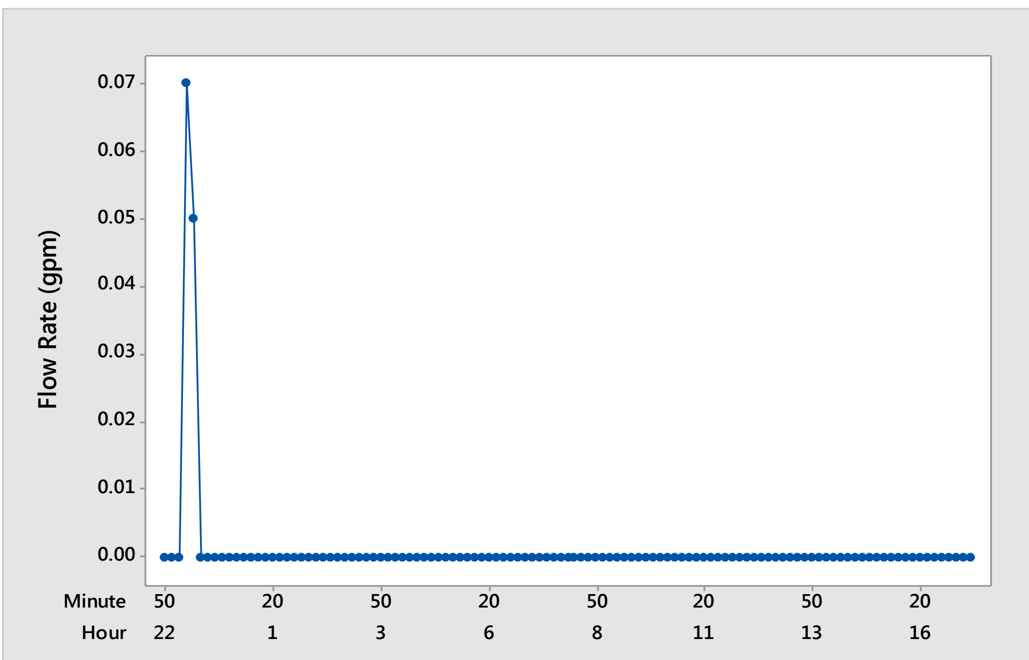

Figure A 4 Hydrograph of the flow rate for the managed vegetated strip for the 5/29/14 storm event

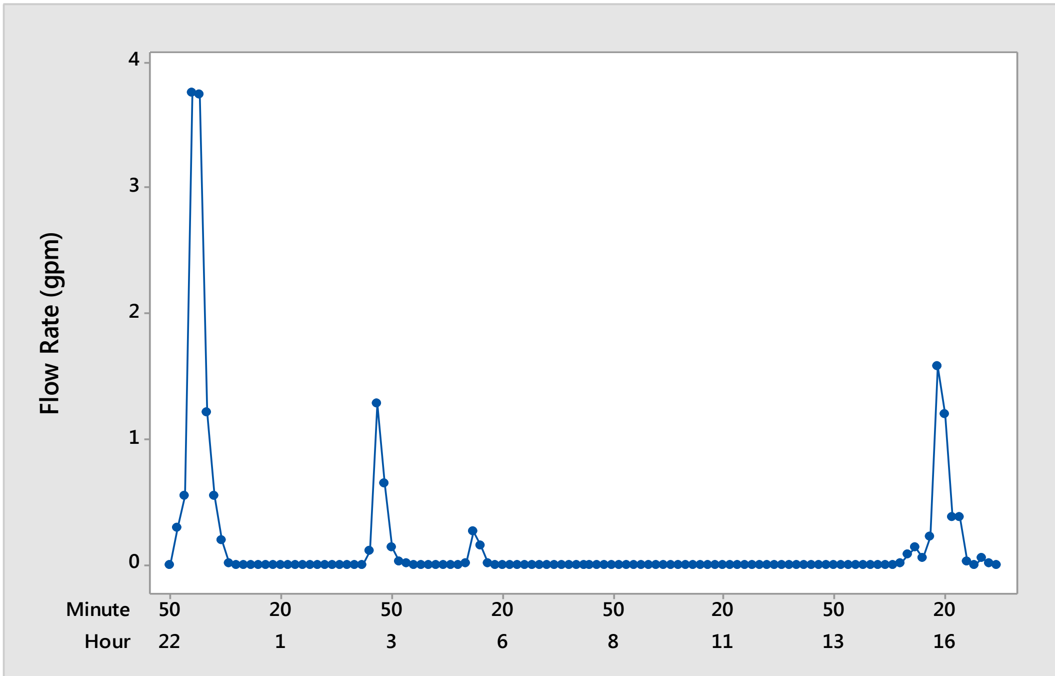

Figure A 5 Hydrograph of the flow rate for the Lorton Road runoff for the 5/29/14 storm event

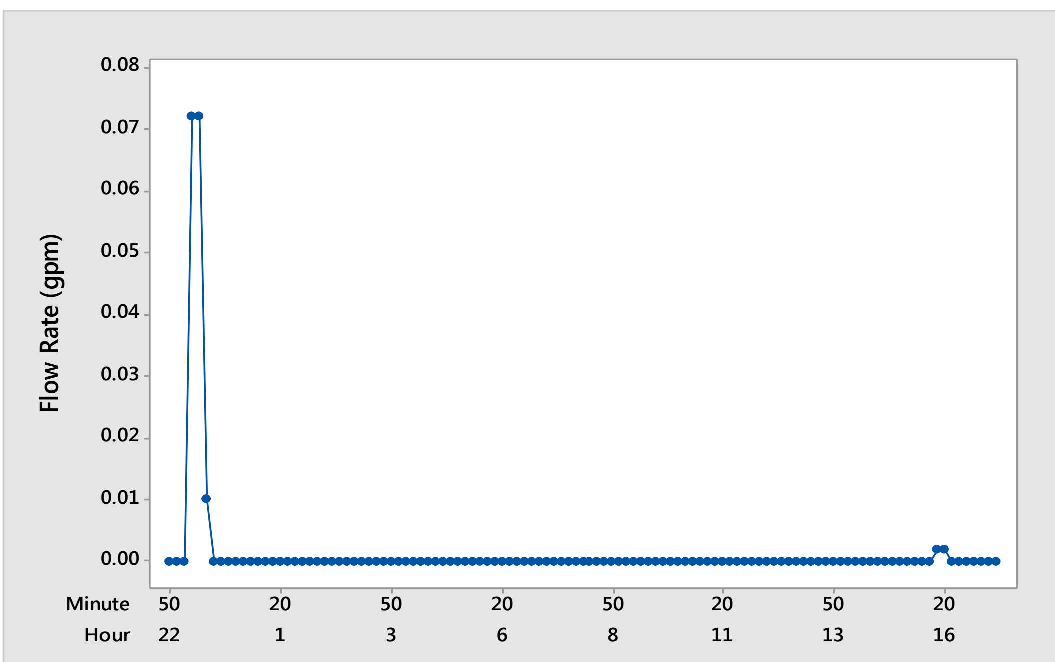

Figure A 6 Hydrograph of the flow rate of the unmanaged vegetated strip for the 5/29/14 storm event

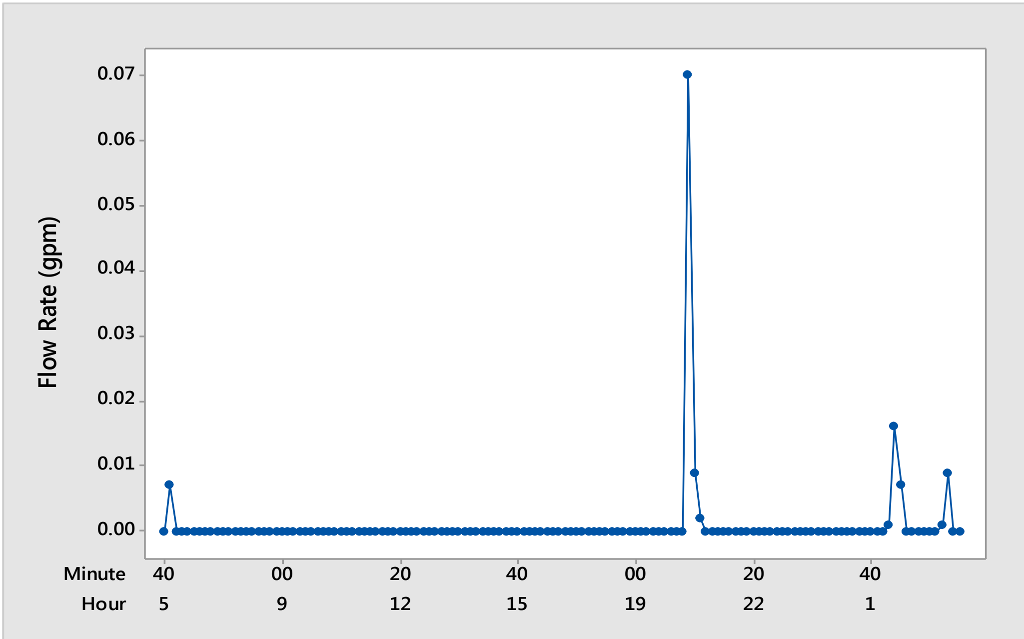

Figure A 7 Hydrograph of the flow rate for the managed vegetated strip for the 6/11/14 storm event

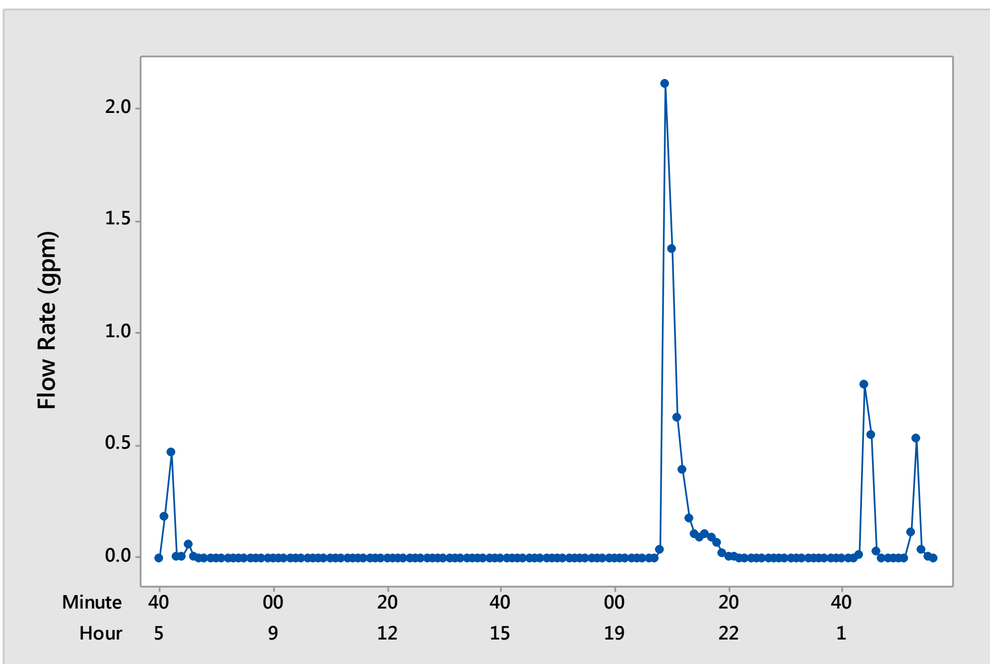

Figure A 8 Hydrograph of flow rate for the Lorton Road runoff for the 6/11/14 storm event

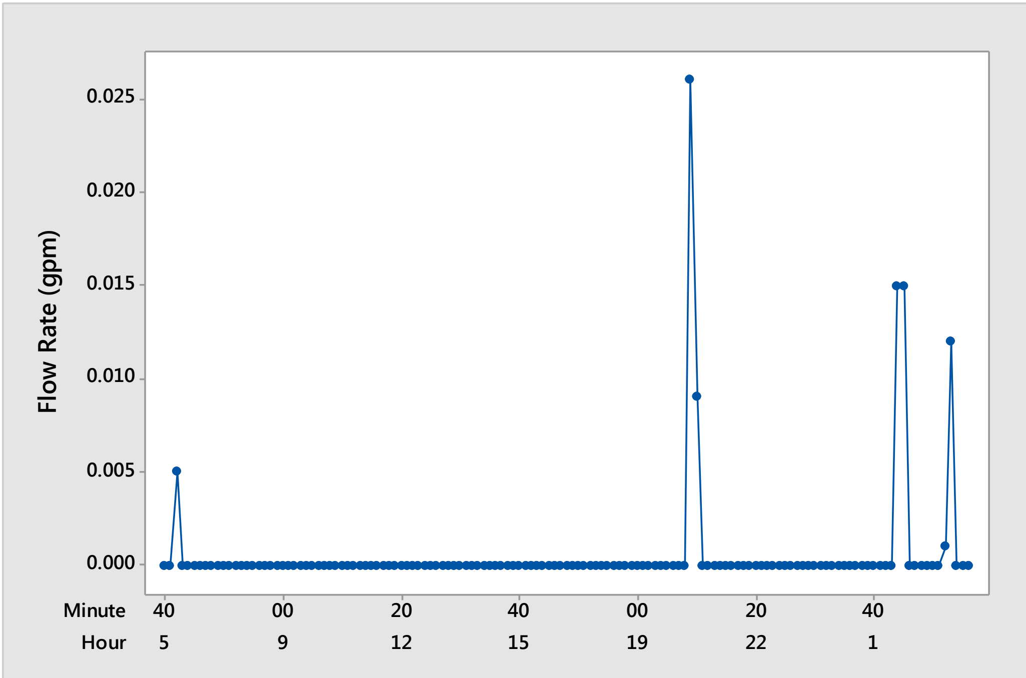

Figure A 9 Hydrograph of the flow rate for the unmanaged vegetated strip for the 6/11/14 storm event

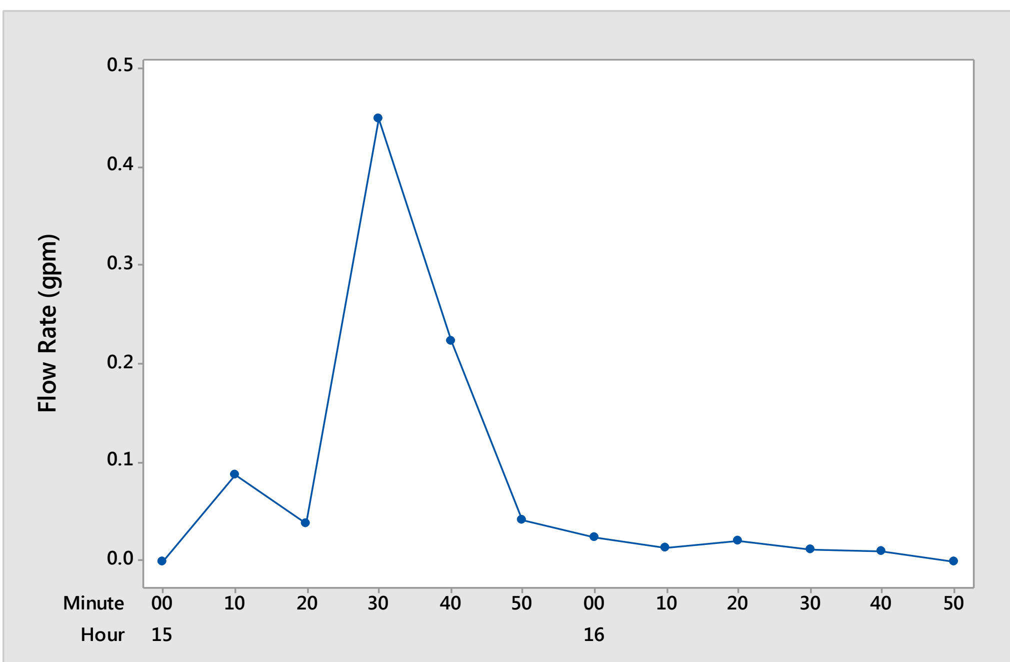

Figure A 10 Hydrograph of the flow rate for the managed vegetated strip for the 6/12/14 storm event

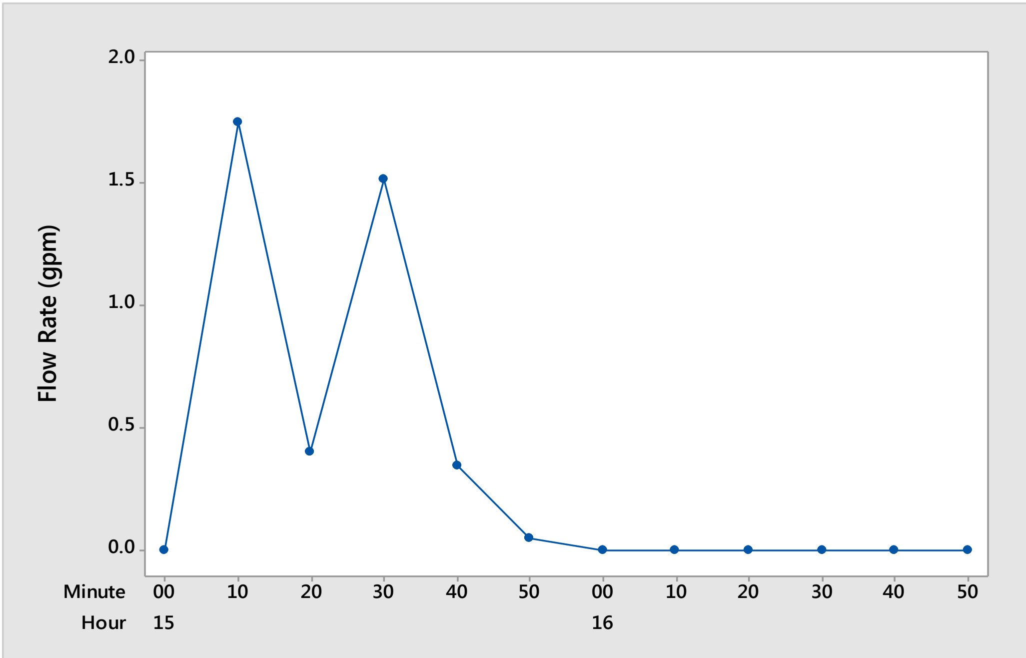

Figure A 11 Hydrograph of the flow rate for the Lorton Road runoff for the 6/12/14 storm event

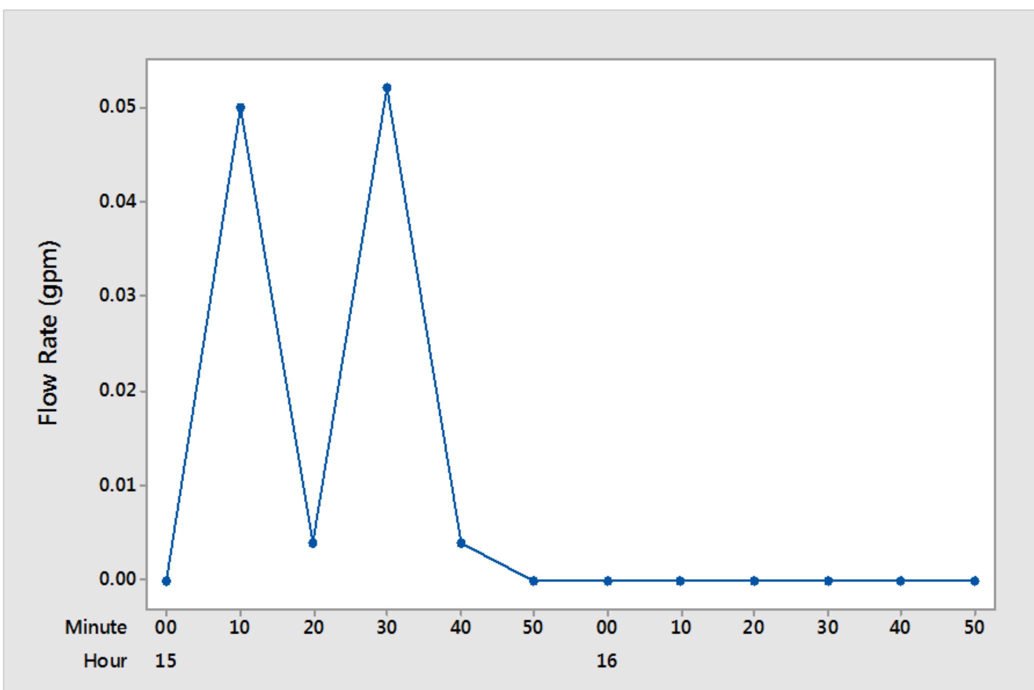

Figure A 12 Hydrograph of the flow rate for the unmanaged vegetated strip for the 6/12/14 storm event

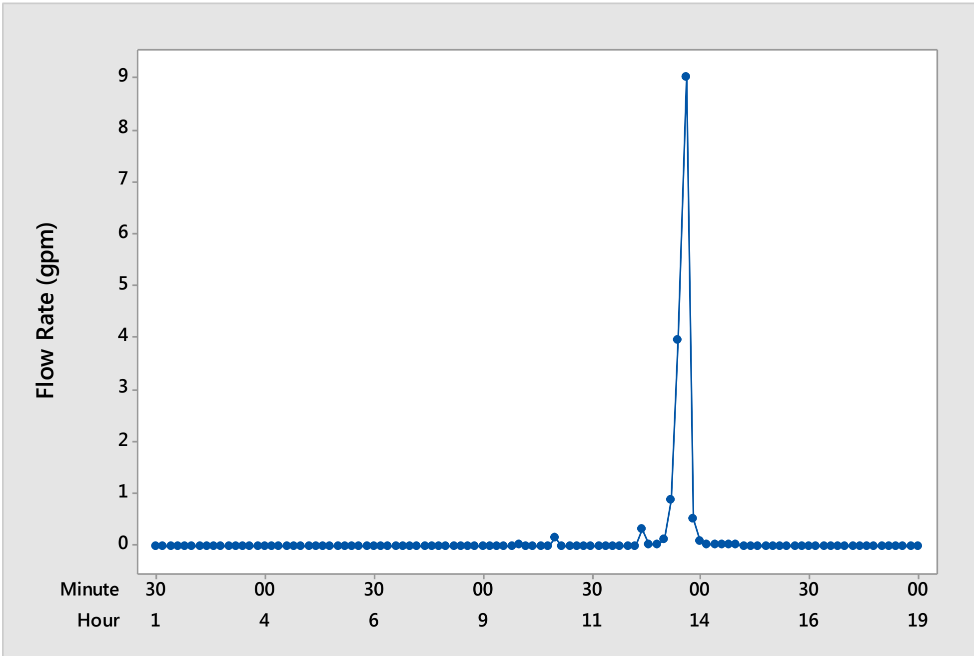

Figure A 13 Hydrograph of the flow rate for the managed vegetated strip for the 8/12/14 storm event

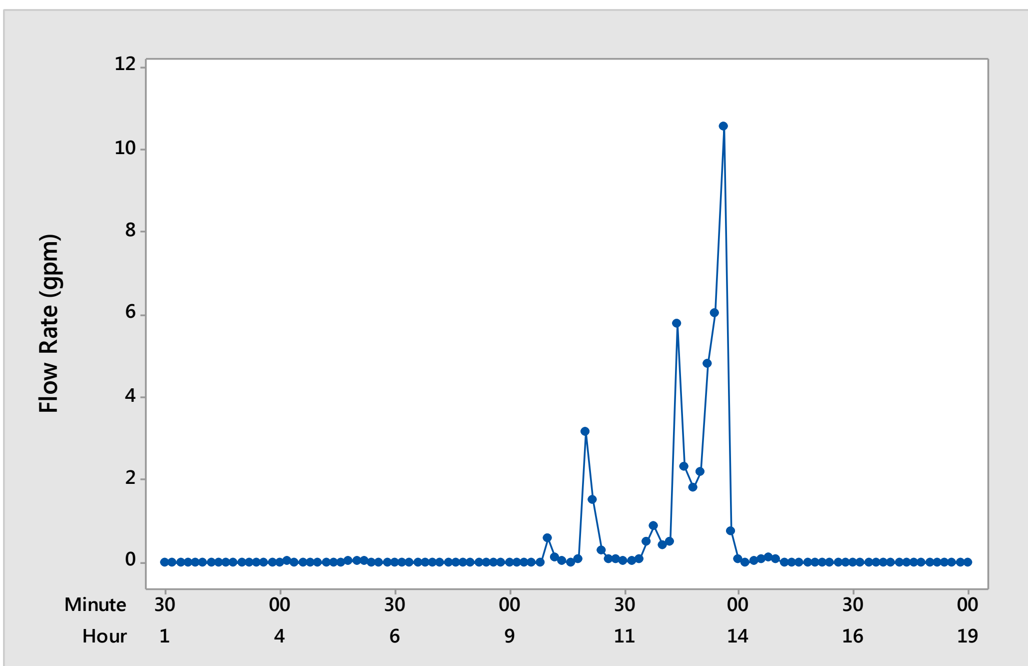

Figure A 14 Hydrograph of the flow rate for the Lorton Road runoff for the 8/12/14 storm event

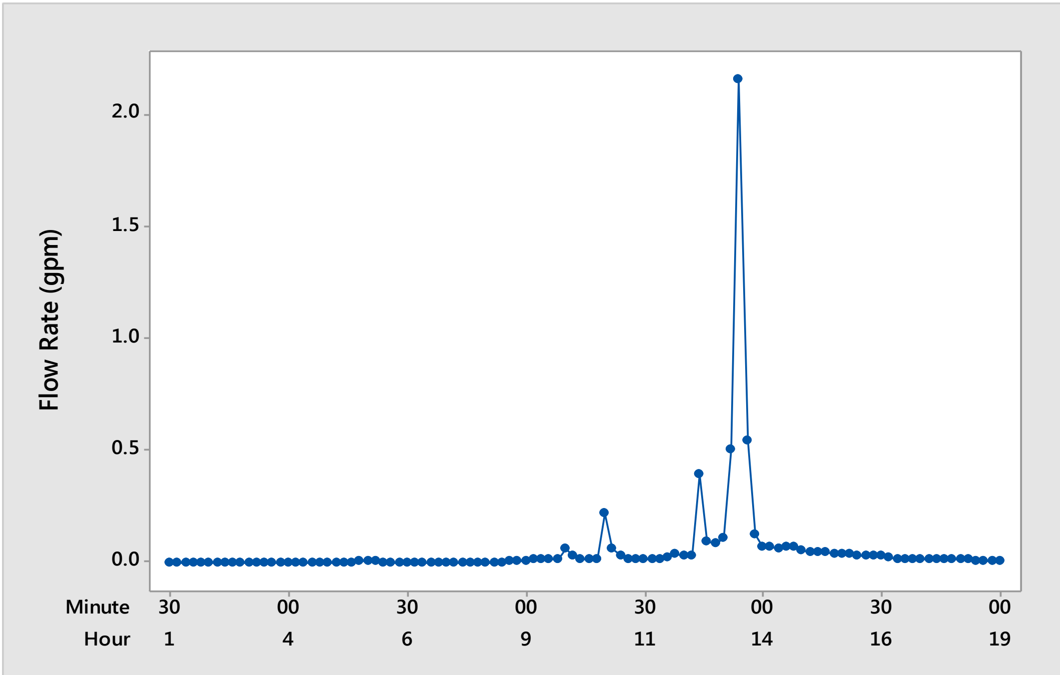

Figure A 15 Hydrograph of the flow rate for the unmanaged vegetated strip for the 8/12/14 storm event

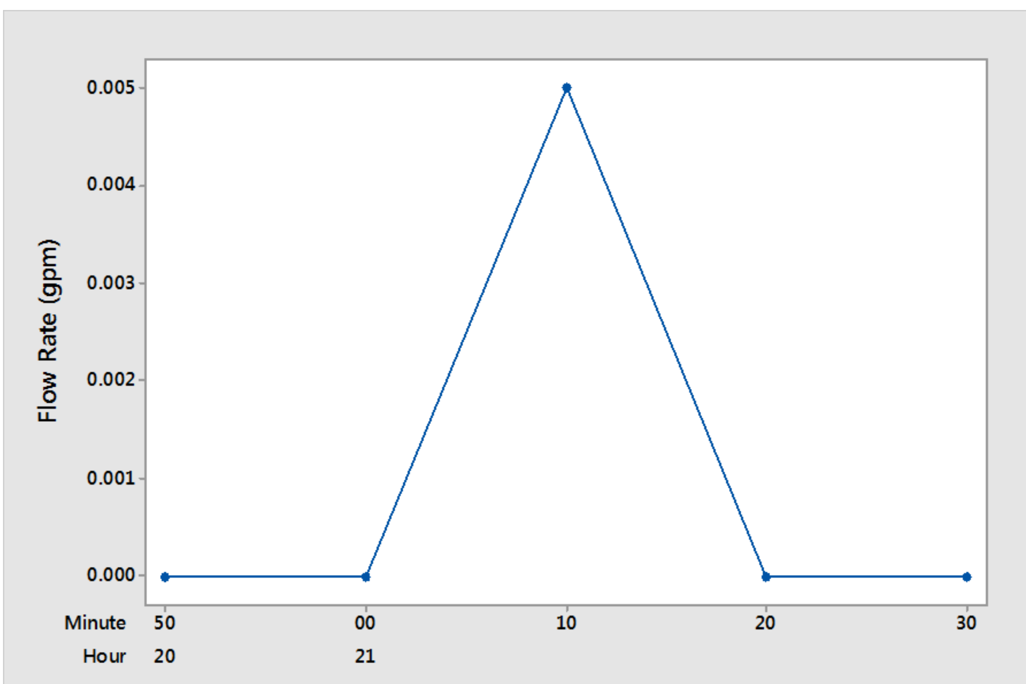

Figure A 16 Hydrograph of the flow rate for the managed vegetated strip for the 8/22/14 storm event

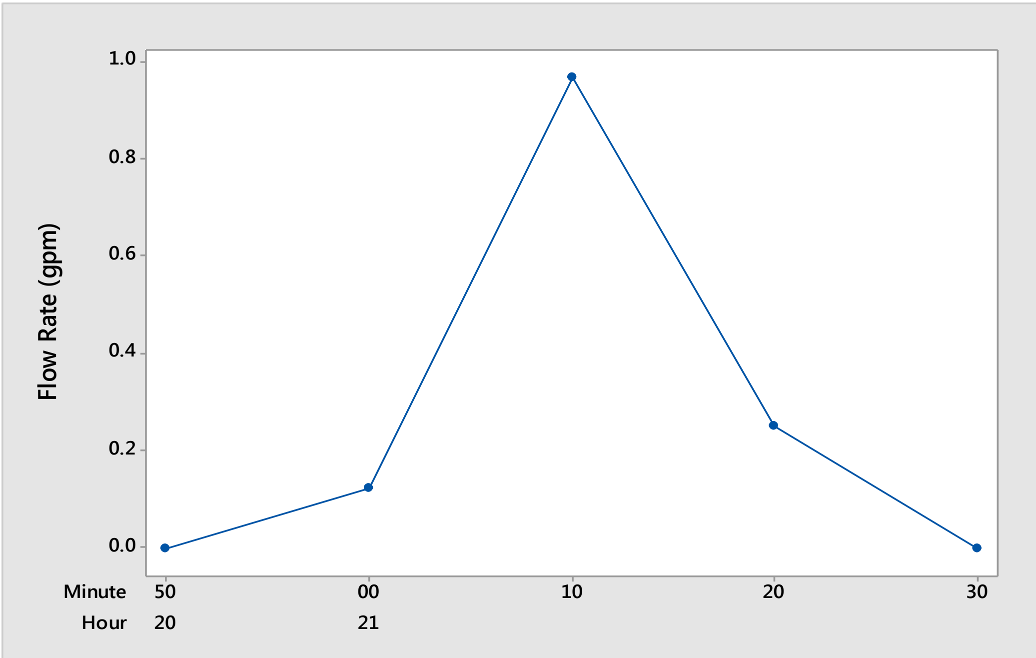

Figure A 17 Hydrograph of the flow rate for the Lorton Road runoff for the 8/22/14 storm event

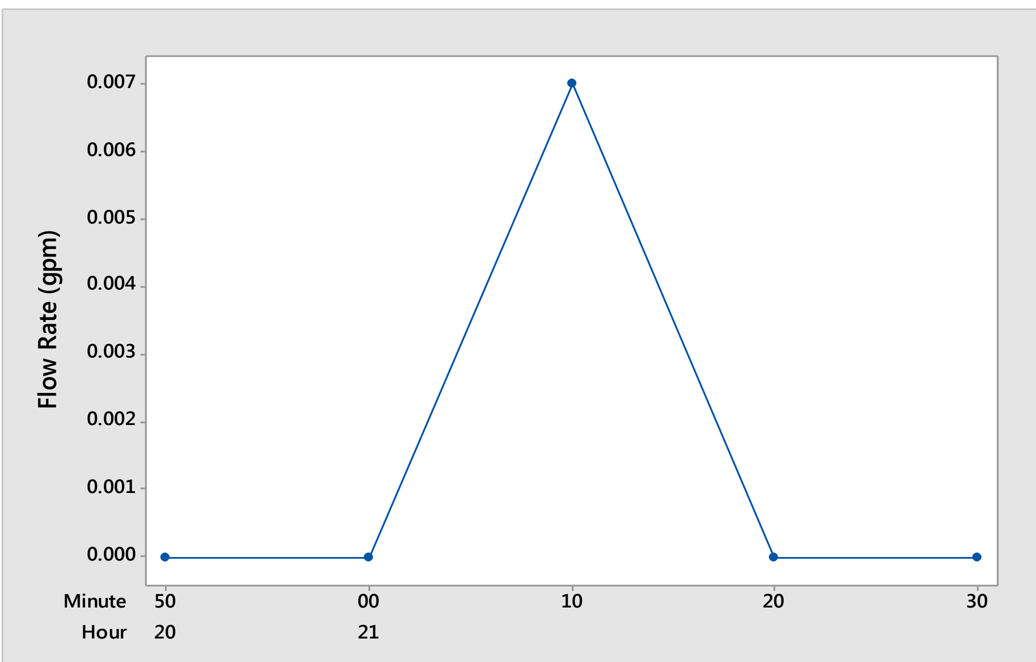

Figure A 18 Hydrograph of the flow rate for the unmanaged vegetated strip for the 8/22/14 storm event

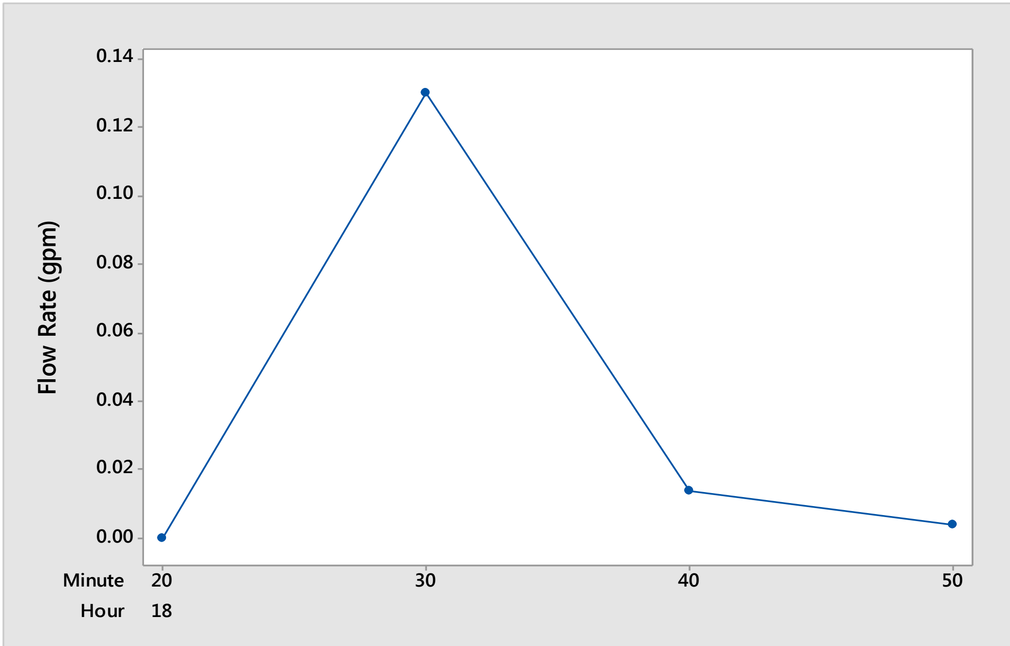

Figure A 19 Hydrograph of the flow rate for the managed vegetated strip for the 9/12/14 storm event

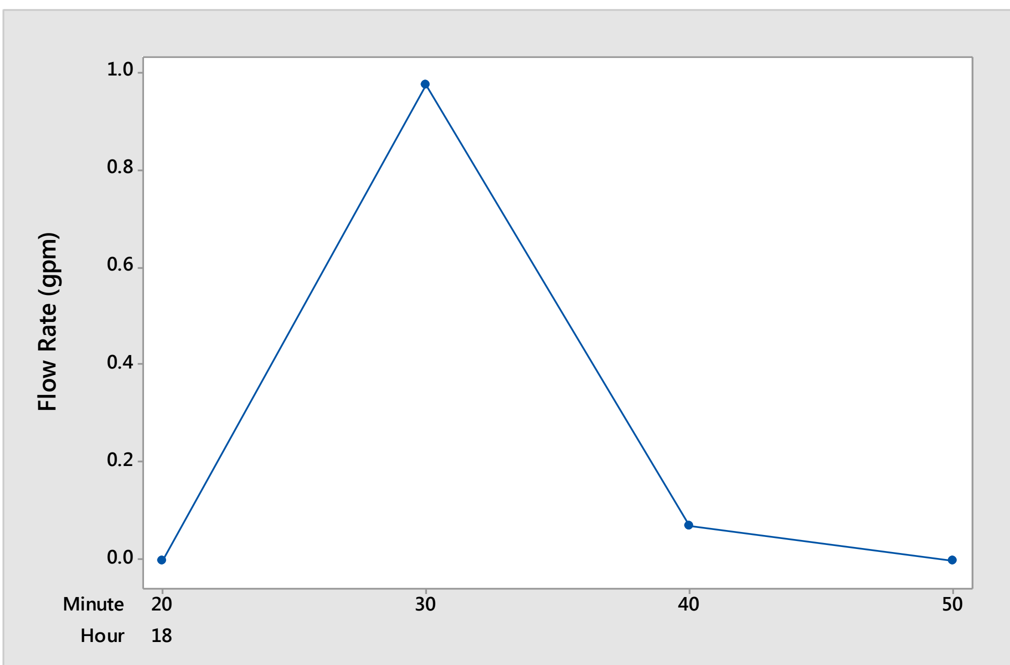

Figure A 20 Hydrograph of the flow rate for the Lorton Road runoff for the 9/12/14 storm event

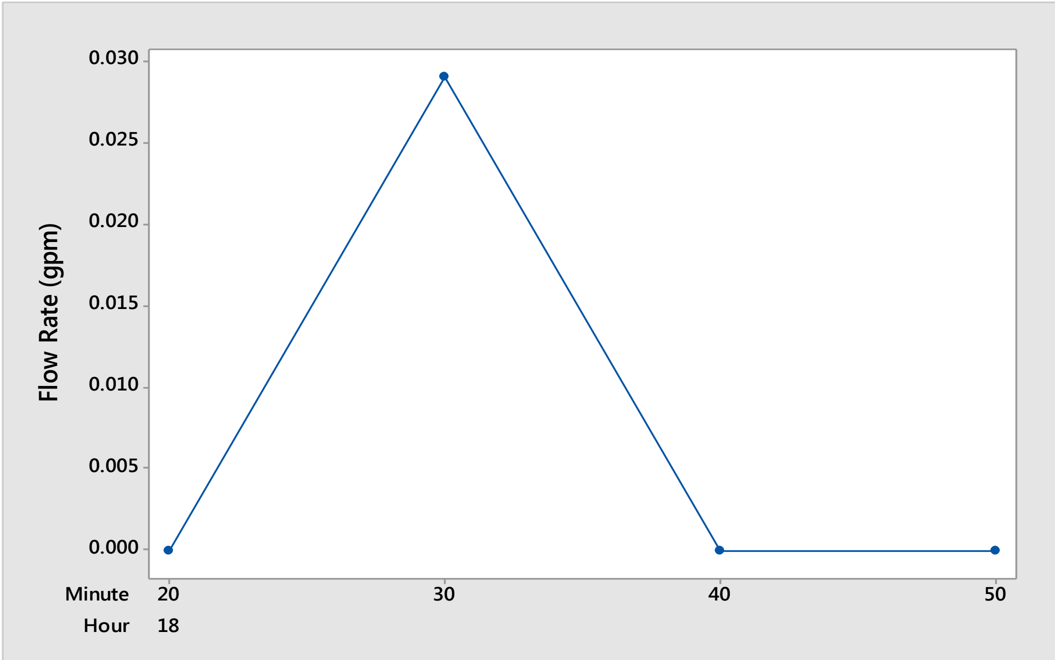

Figure A 21 Hydrograph of the flow rate for the unmanaged vegetated strip for the 9/12/14 storm event

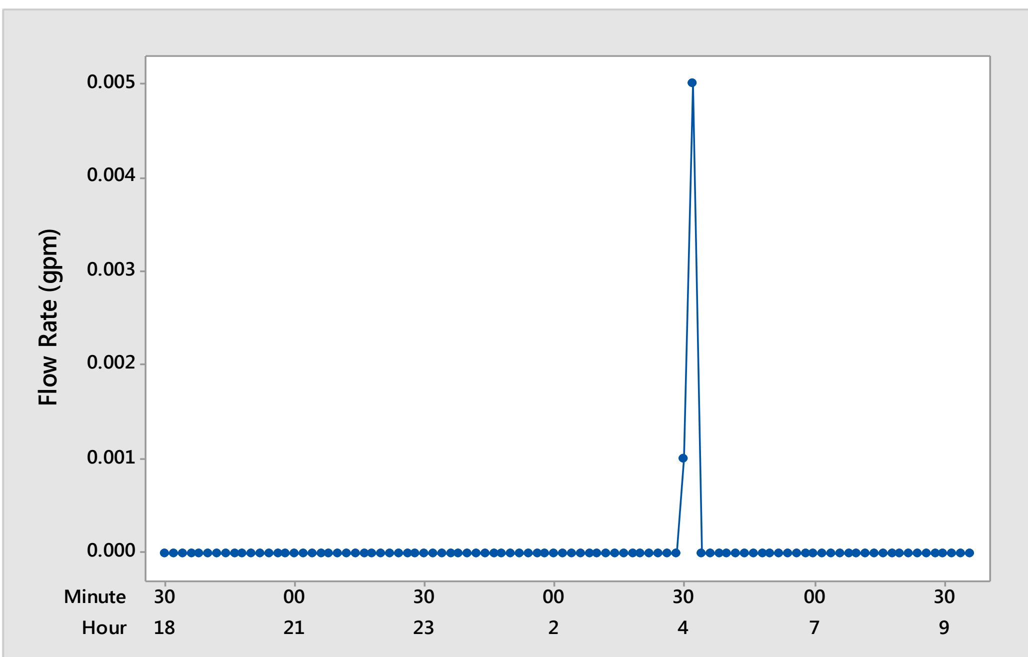

Figure A 22 Hydrograph of the flow rate for the managed vegetated strip for the 9/25/14 storm event

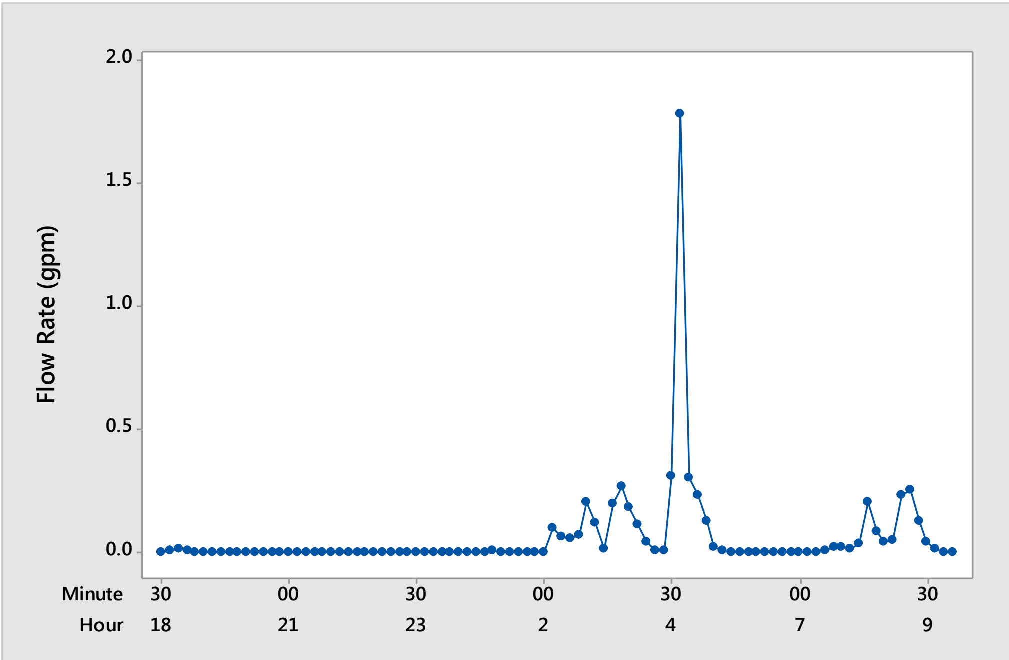

Figure A 23 Hydrograph of the flow rate for the Lorton Road runoff for the 9/25/14 storm event

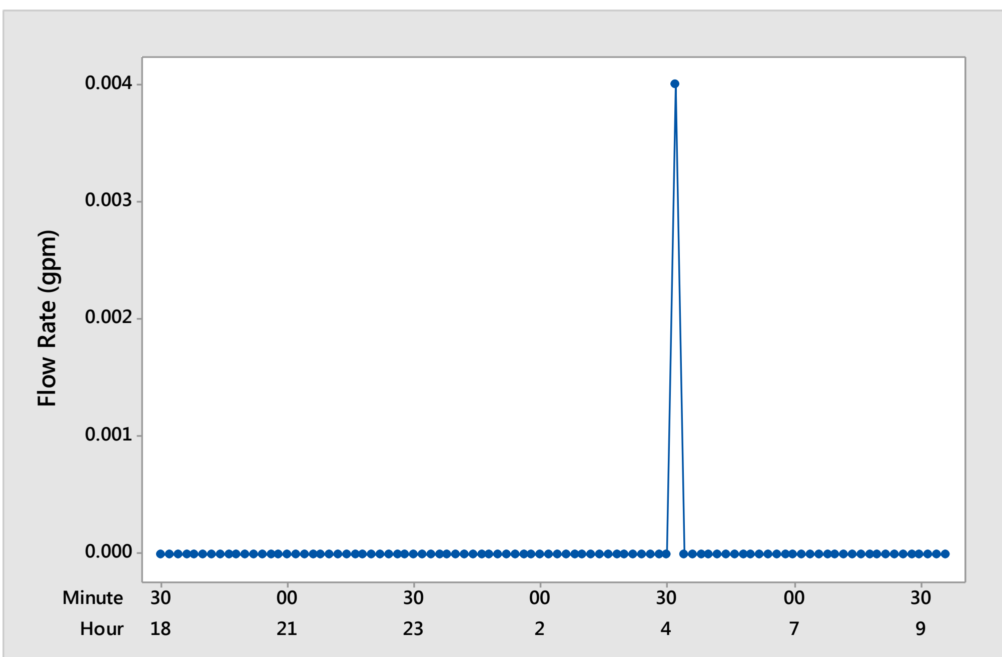

Figure A 24 Hydrograph of the flow rate for the unmanaged vegetated strip for the 9/25/14 storm event

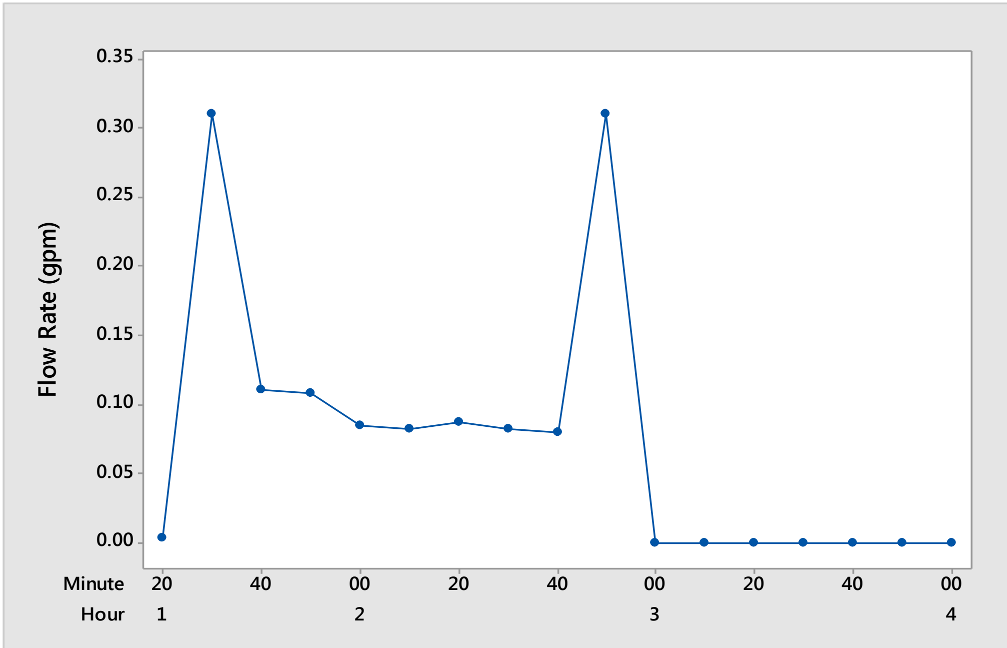

Figure A 25 Hydrograph of the flow rate for the managed vegetated strip for the 10/04/14 storm event. A malfunction with the depth sensor prevented the logged flow rate from returning to zero.

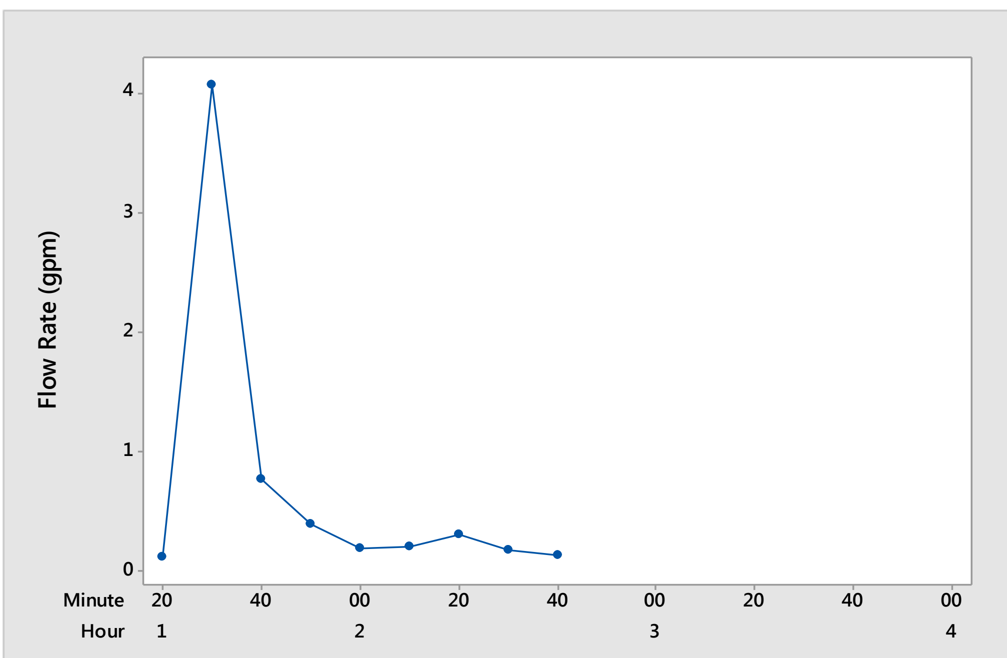

Figure A 26 Hydrograph of the flow rate for the Lorton Road runoff for the 10/04/14 storm event. A malfunction with the depth sensor prevented the logged flow rate from returning to zero.

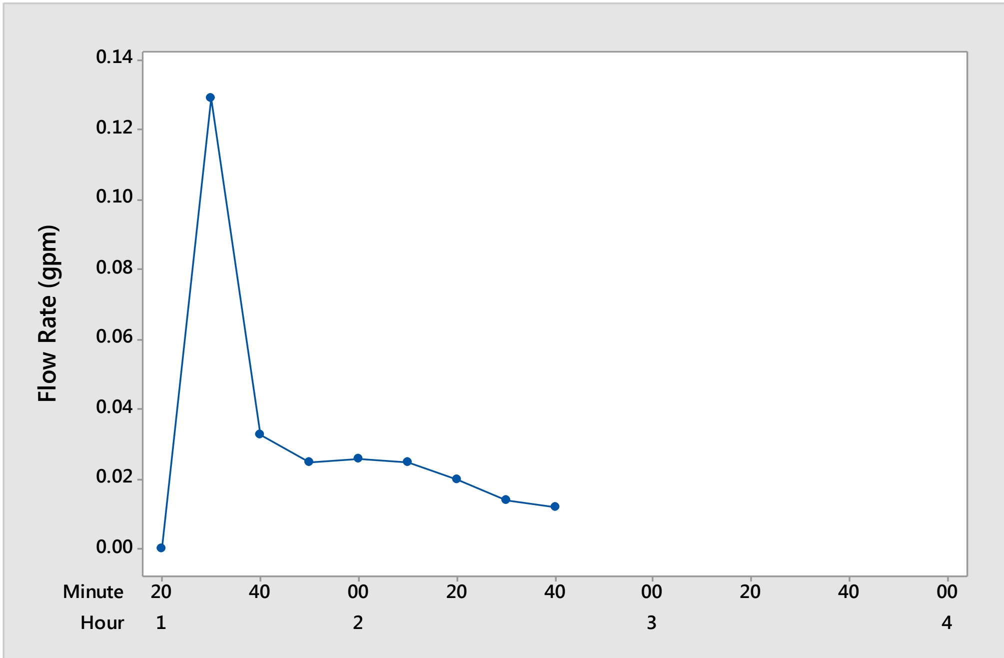

Figure A 27 Hydrograph of the flow rate for the unmanaged vegetated strip for the 10/04/14 storm event. A malfunction with the depth sensor prevented the logged flow rate from returning to zero.

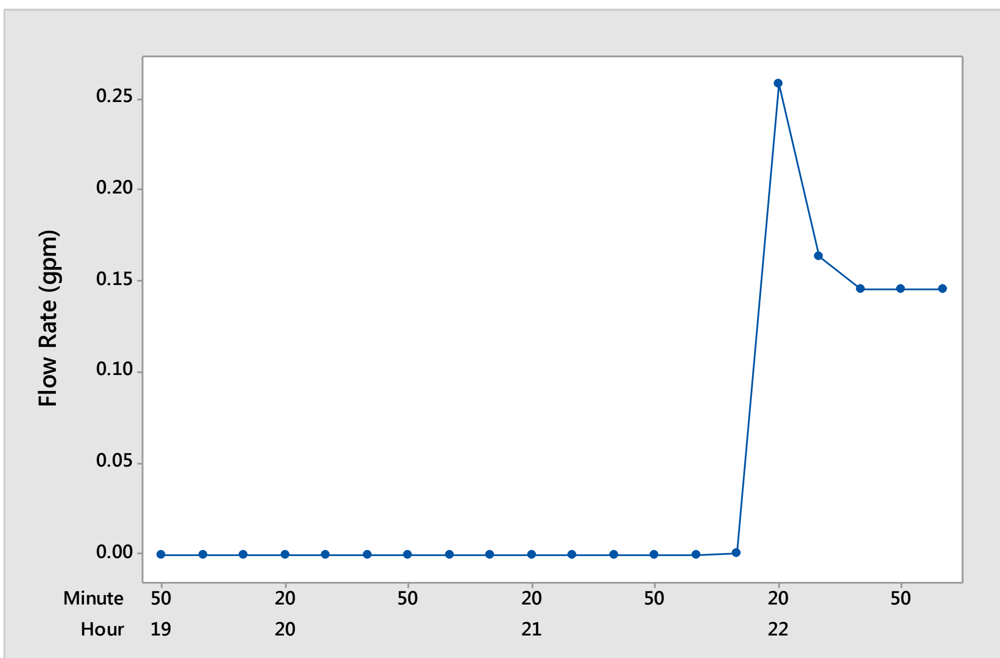

Figure A 28 Hydrograph of the flow rate for the managed vegetated strip for the 10/08/14 storm event. A malfunction with the depth sensor prevented the logged flow rate from returning to zero.

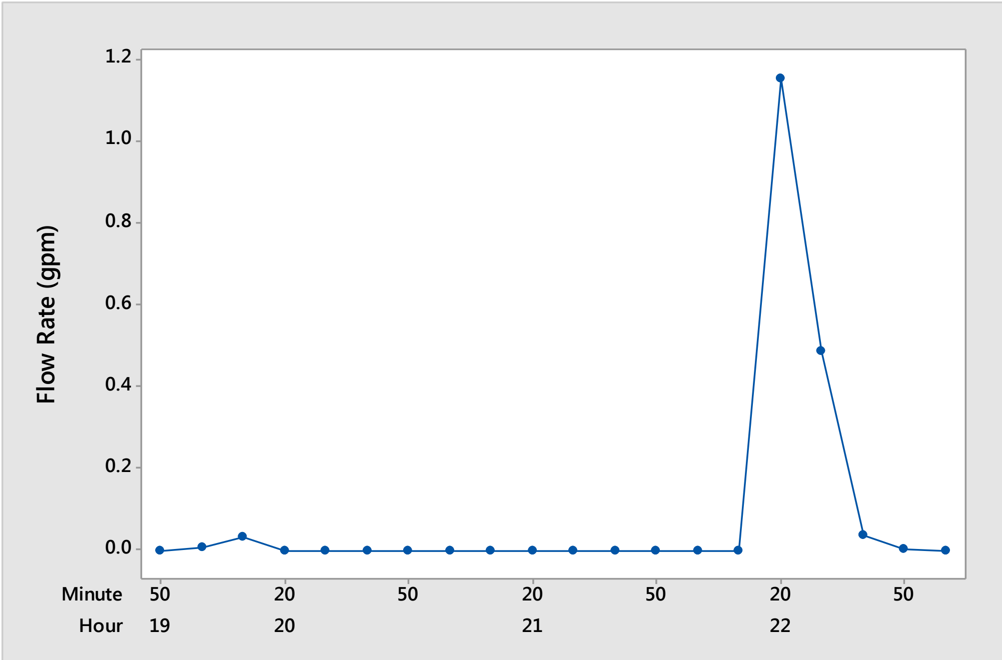

Figure A 29 Hydrograph of the flow rate for the Lorton Road runoff for the 10/08/14 storm event. A malfunction with the depth sensor prevented the logged flow rate from returning to zero.

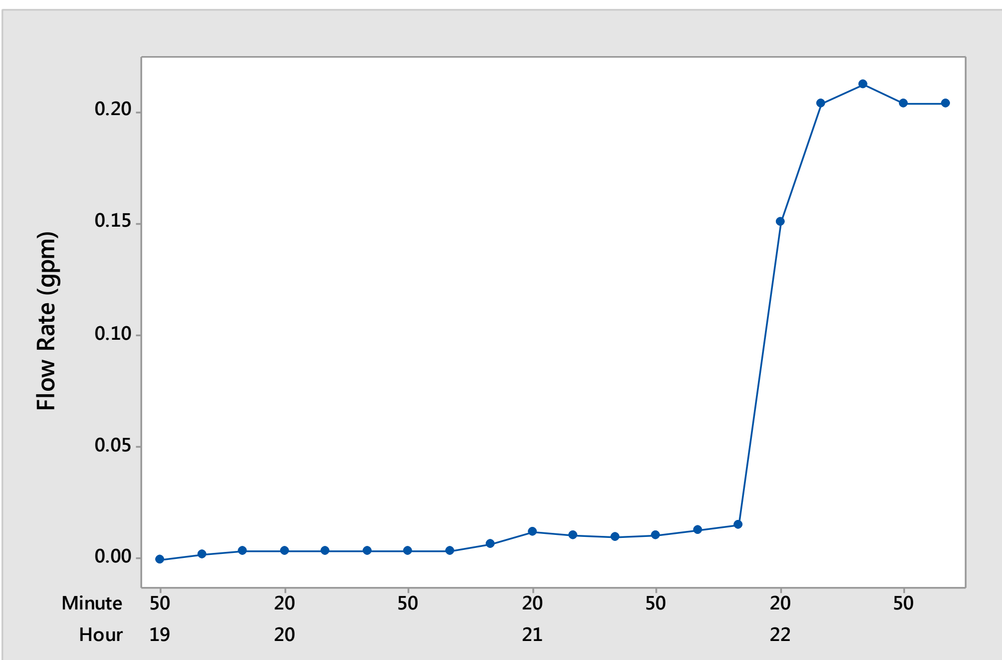

Figure A 30 Hydrograph of the flow rate for the unmanaged vegetated strip for the 10/08/14 storm event. A malfunction with the depth sensor prevented the logged flow rate from returning to zero.

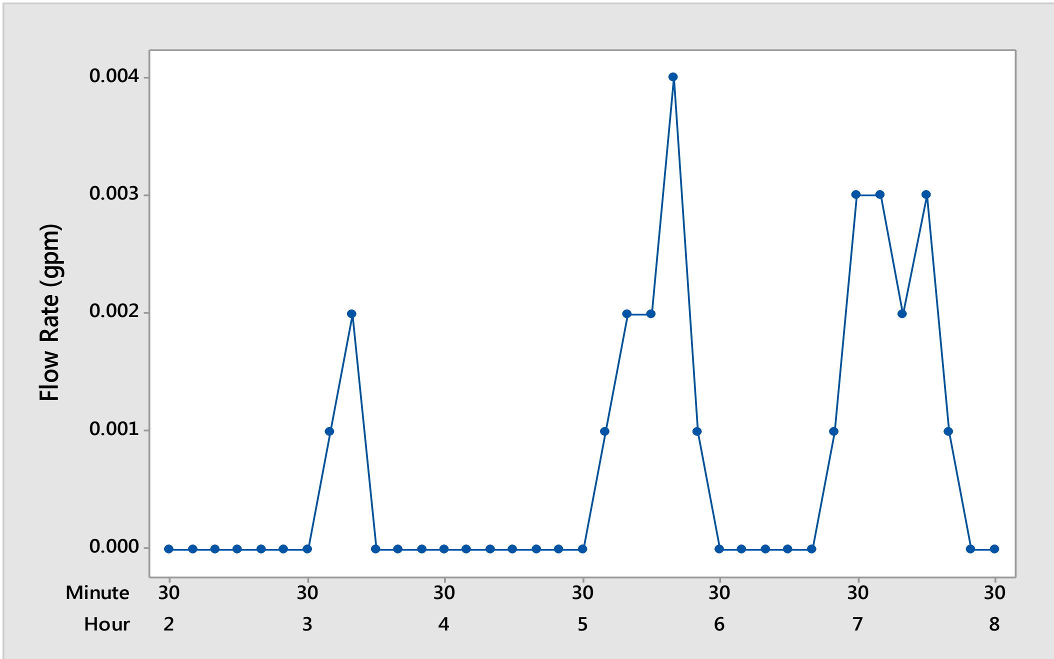

Figure A 31 Hydrograph of the flow rate for the managed vegetated strip for the 10/12/14 storm event

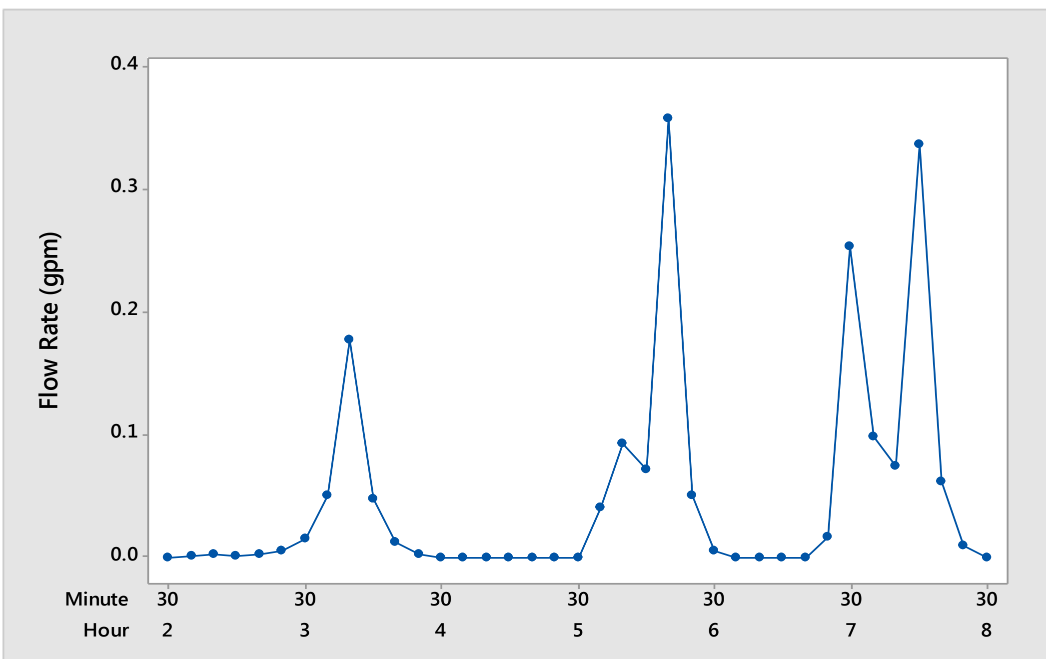

Figure A 32 Hydrograph of the flow rate for the Lorton Road runoff for the 10/12/14 storm event

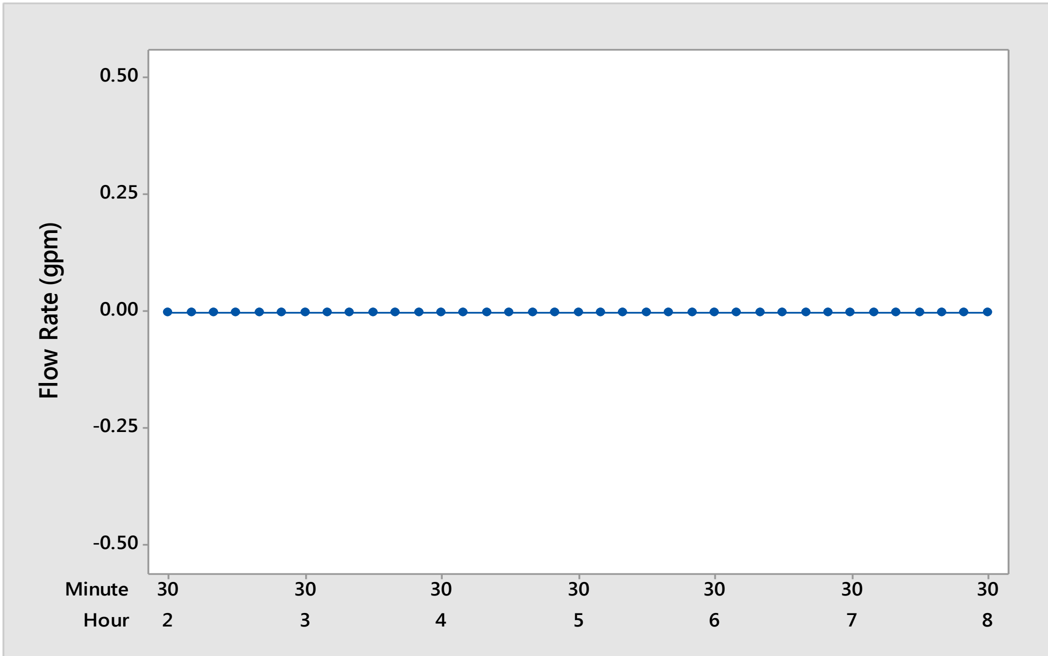

Figure A 33 Hydrograph of the flow rate for the unmanaged vegetated strip for the 10/12/14 storm event

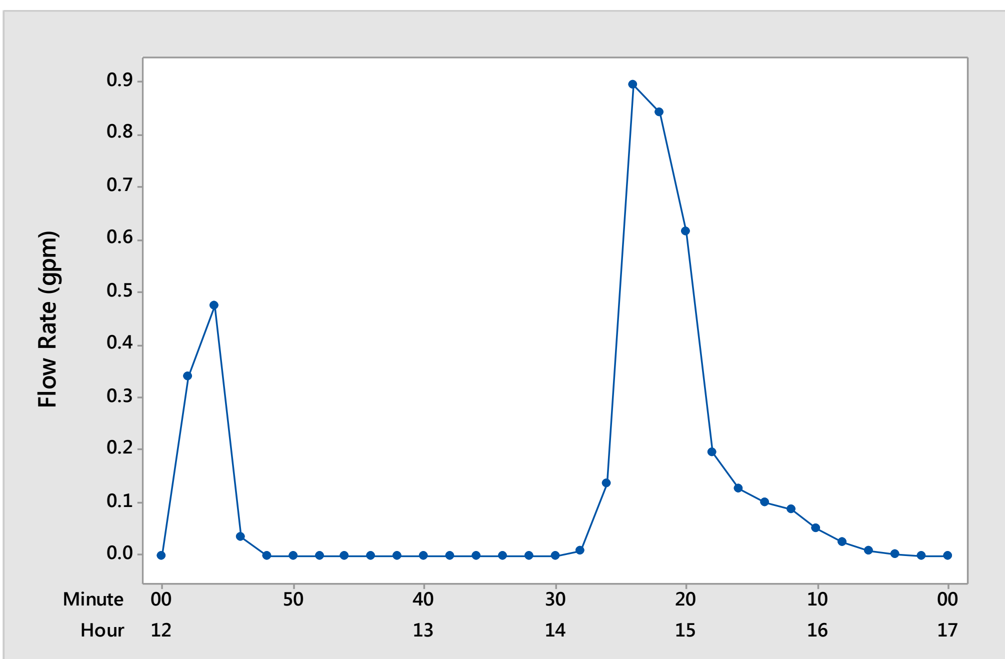

Figure A 34 Hydrograph of the flow rate for the managed vegetated strip for the 10/16/14 storm event

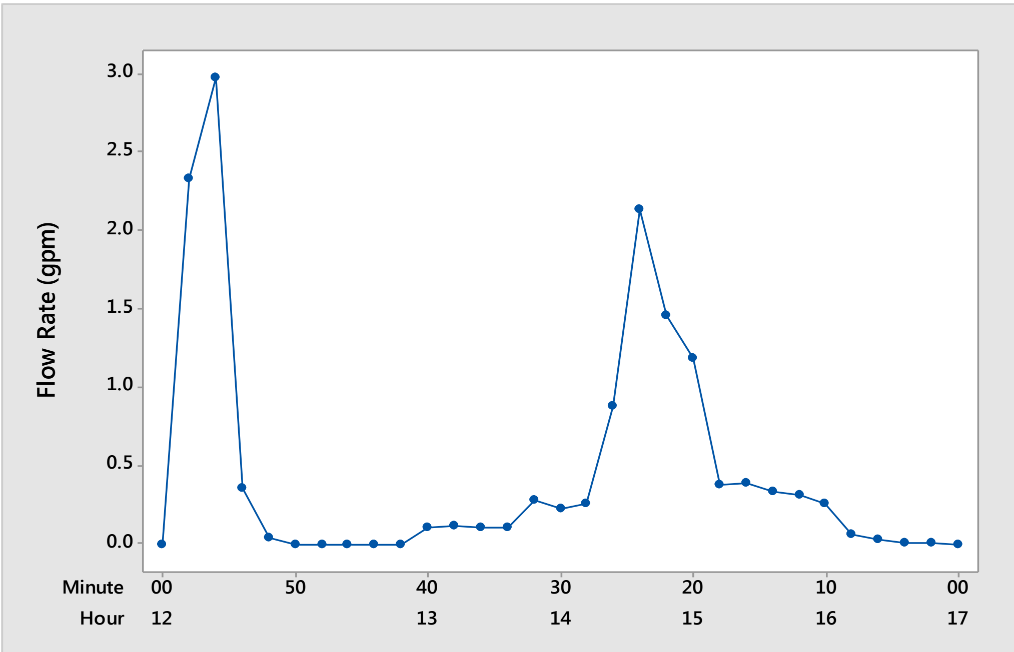

Figure A 35 Hydrograph of the flow rate for the Lorton Road runoff for the 10/16/14 storm event

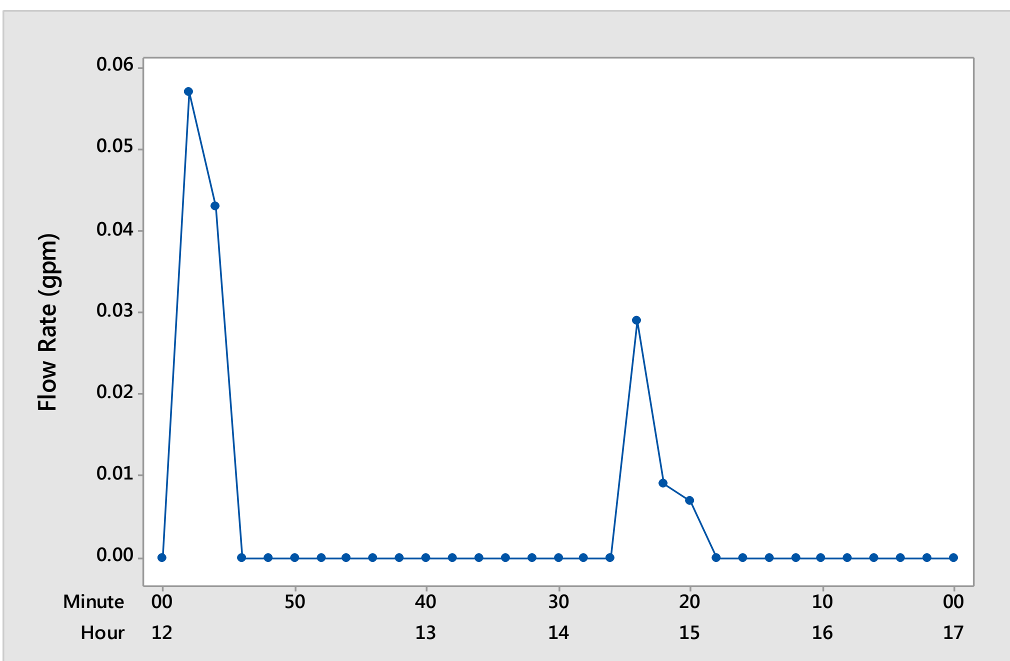

Figure A 36 Hydrograph of the flow rate for the unmanaged vegetated strip for the 10/16/14 storm event

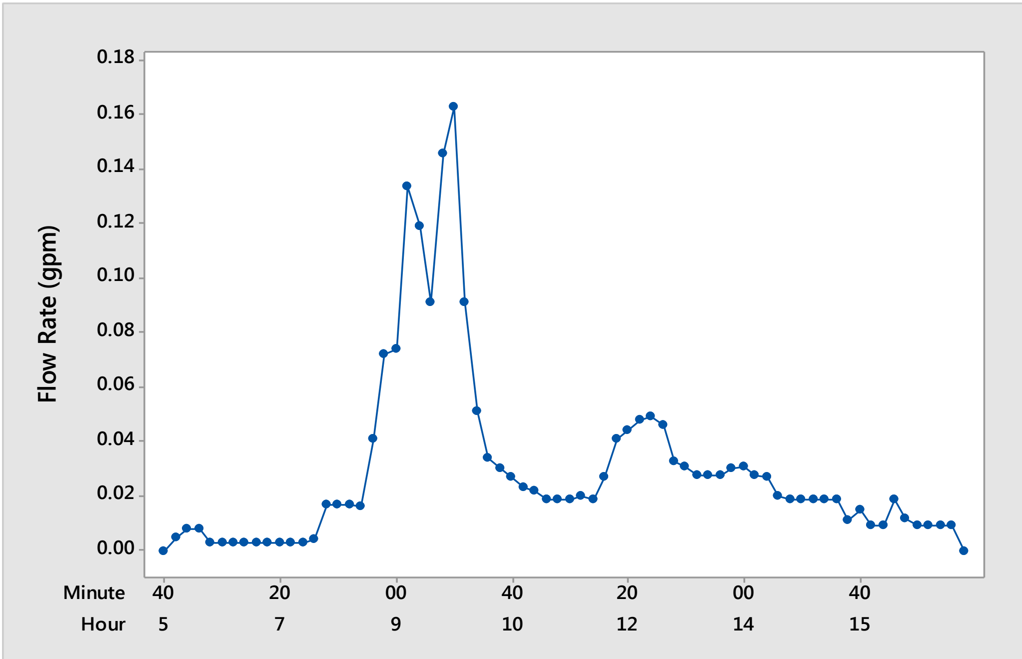

Figure A 37 Hydrograph of the flow rate for the managed vegetated strip for the 10/22/14 storm event

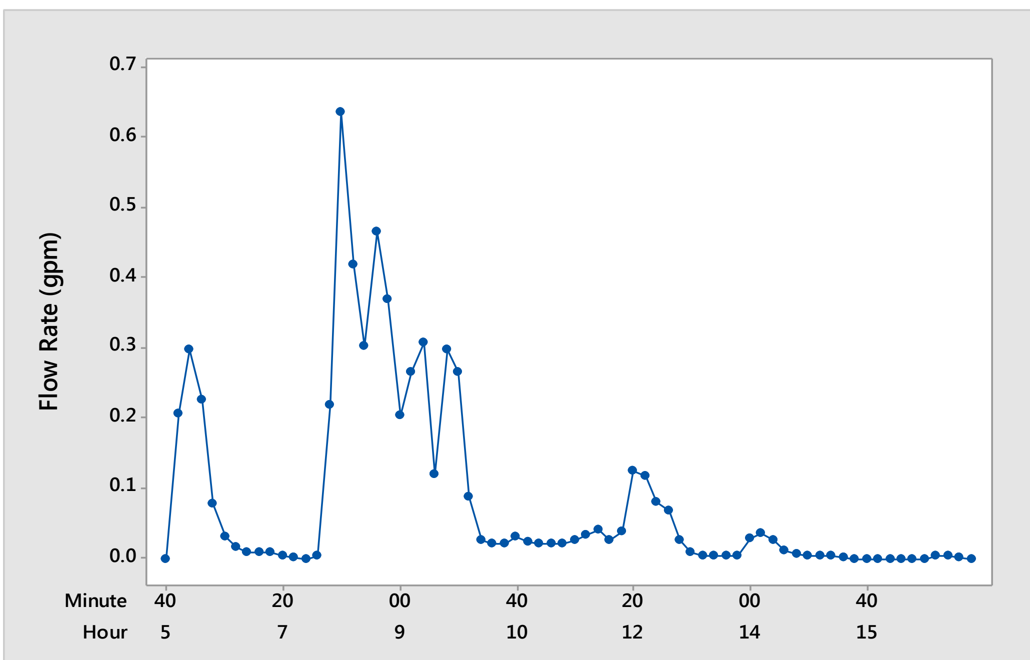

Figure A 38 Hydrograph of the flow rate for the Lorton Road runoff for the 10/22/14 storm event

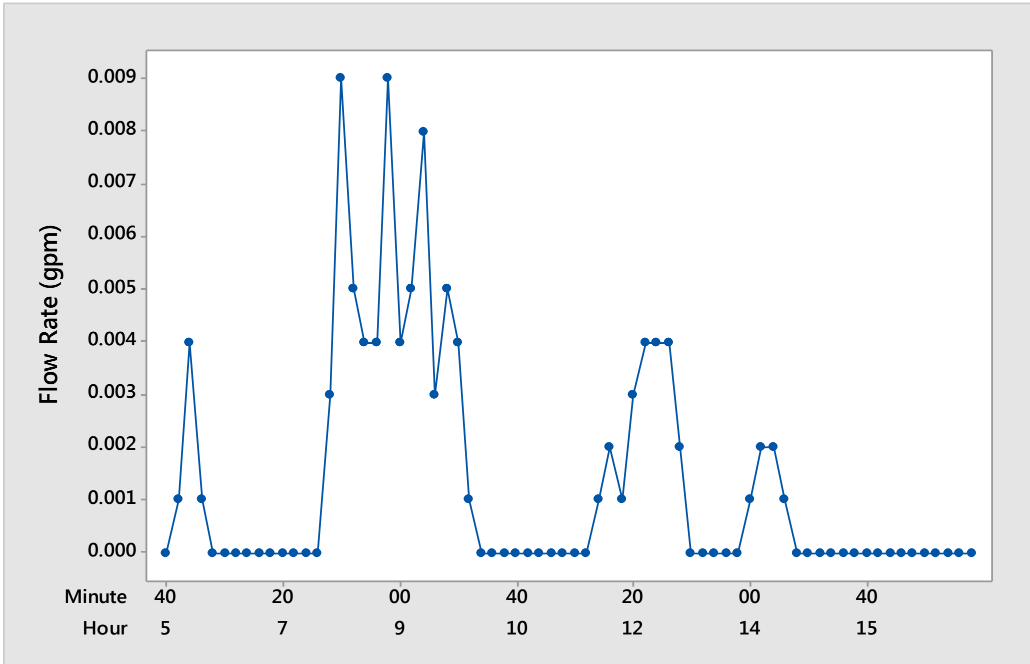

Figure A 39 Hydrograph of the flow rate for the unmanaged vegetated strip for the 10/22/14 storm event

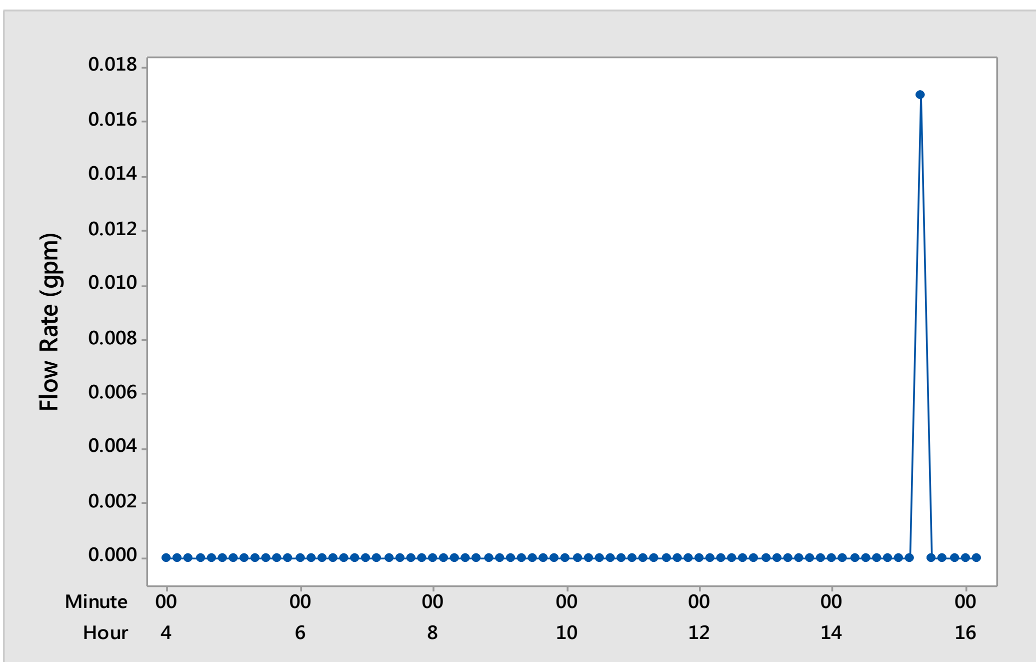

Figure A 40 Hydrograph of the flow rate for the managed vegetated strip for the 11/06/14 storm event

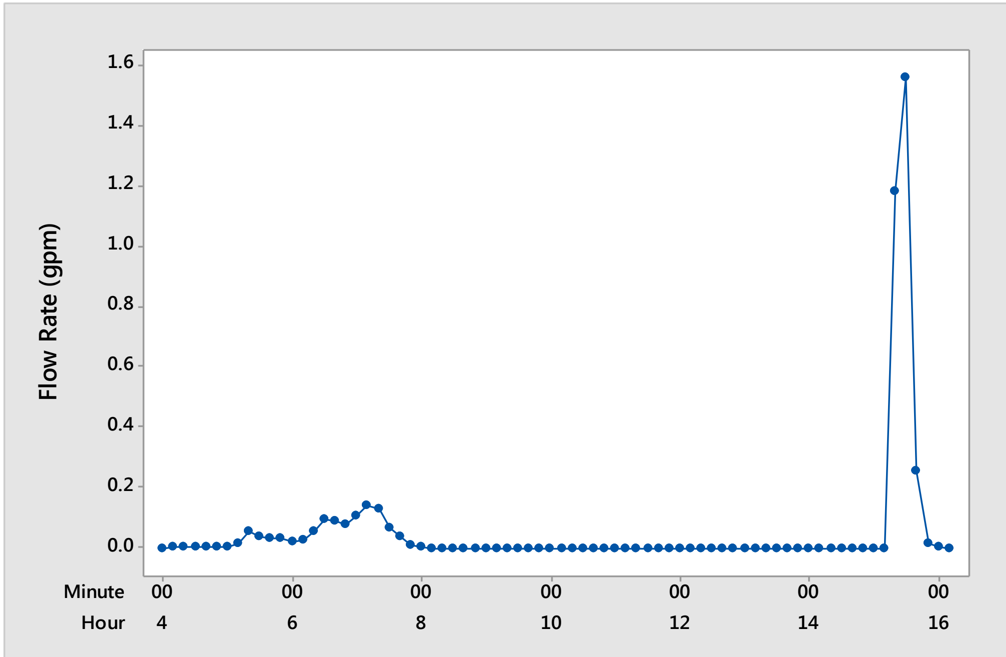

Figure A 41 Hydrograph of the flow rate for the Lorton Road runoff for the 11/06/14 storm event

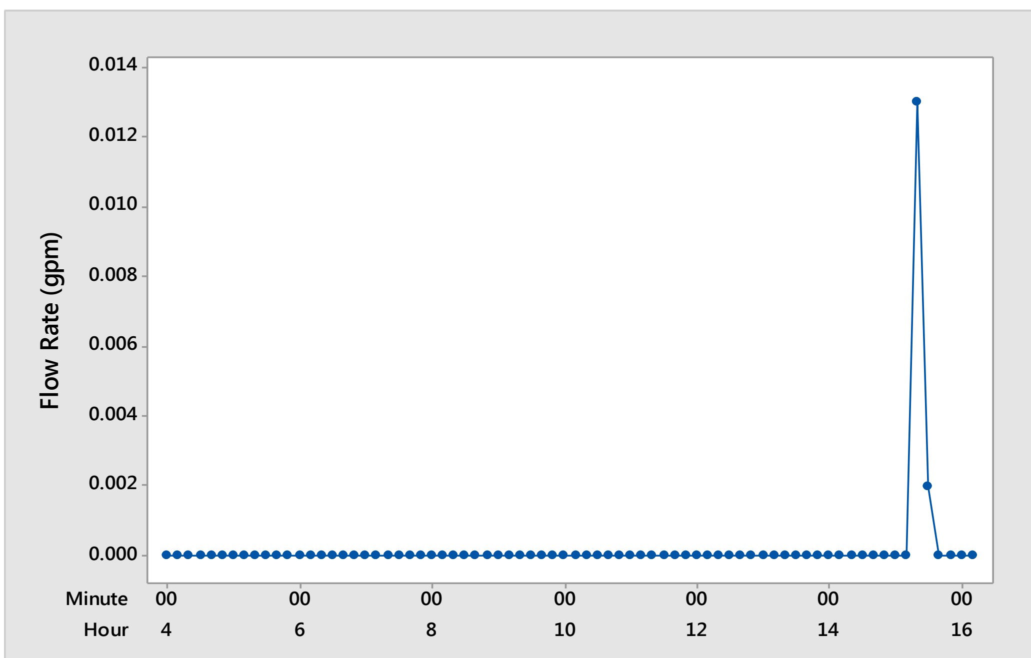

Figure A 42 Hydrograph of the flow rate for the unmanaged vegetated strip for the 11/06/14 storm event

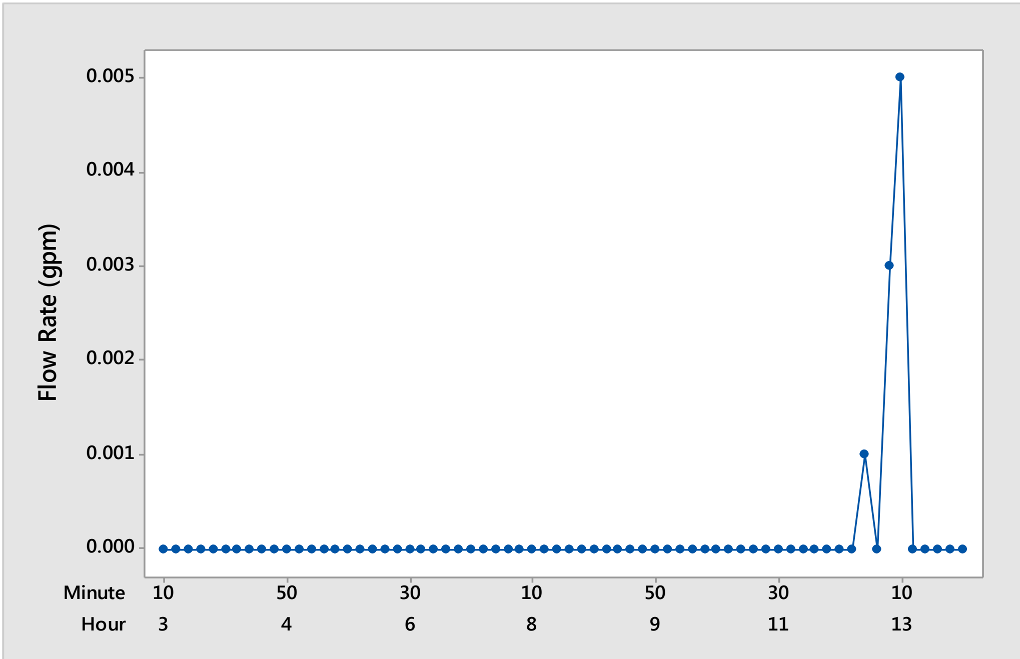

Figure A 43 Hydrograph of the flow rate for the managed vegetated strip for the 11/17/14 storm event

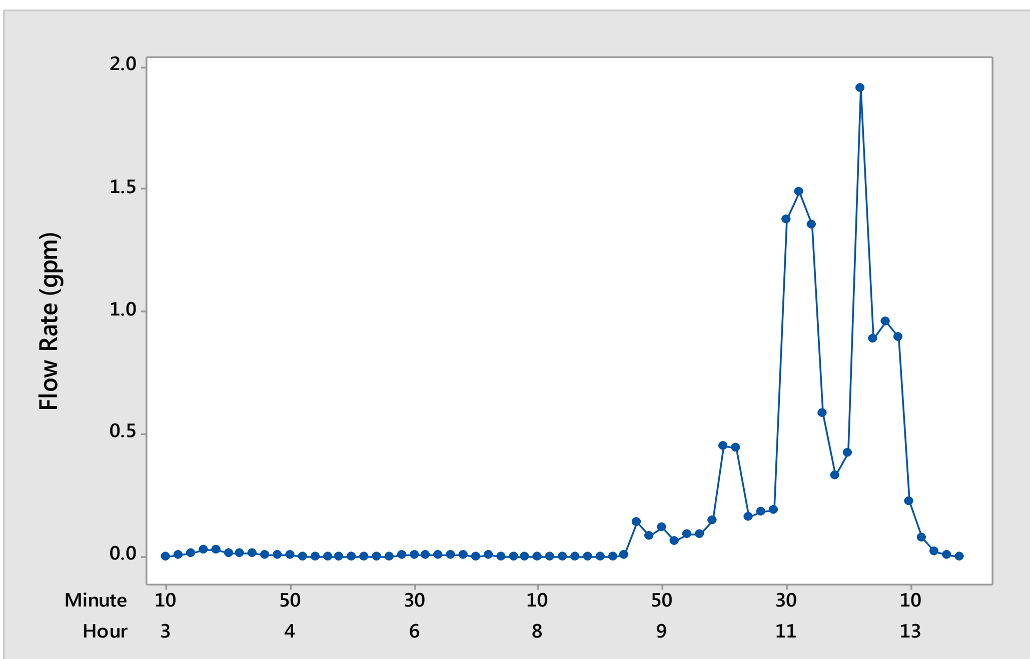

Figure A 44 Hydrograph of the flow rate for the Lorton Road runoff for the 11/17/14 storm event

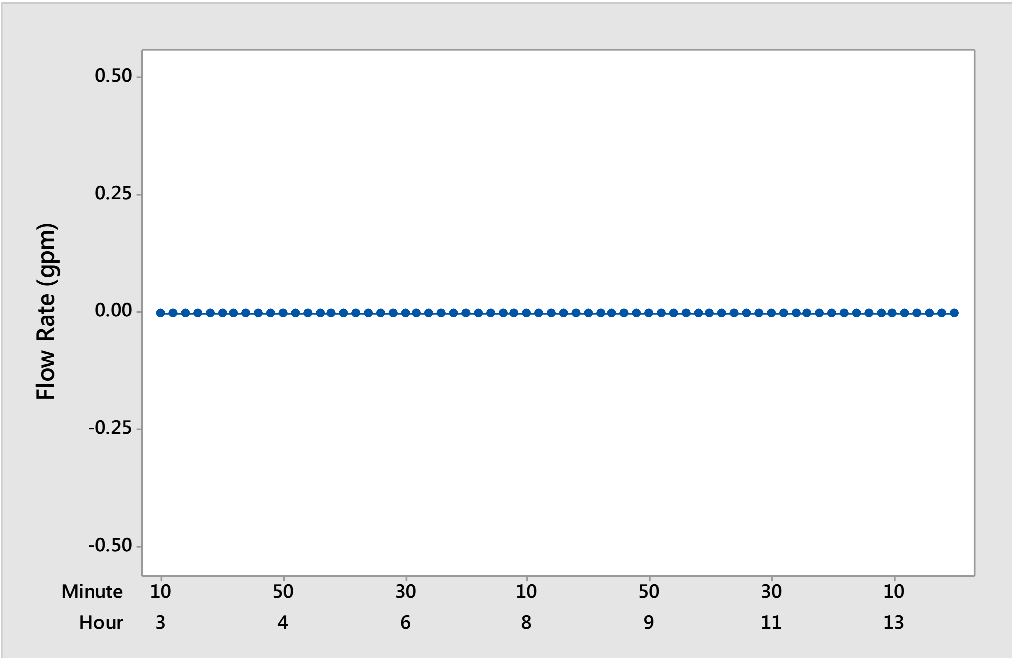

Figure A 45 Hydrograph of the flow rate for the unmanaged vegetated strip for the 11/17/14 storm event

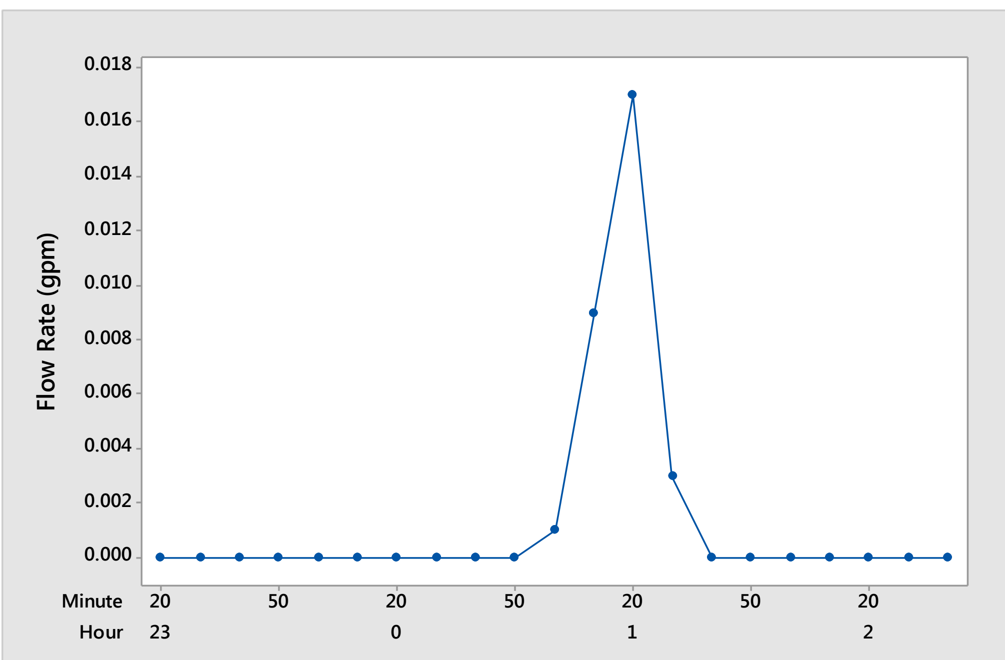

Figure A 46 Hydrograph of the flow rate for the managed vegetated strip for the 11/24/14 storm event

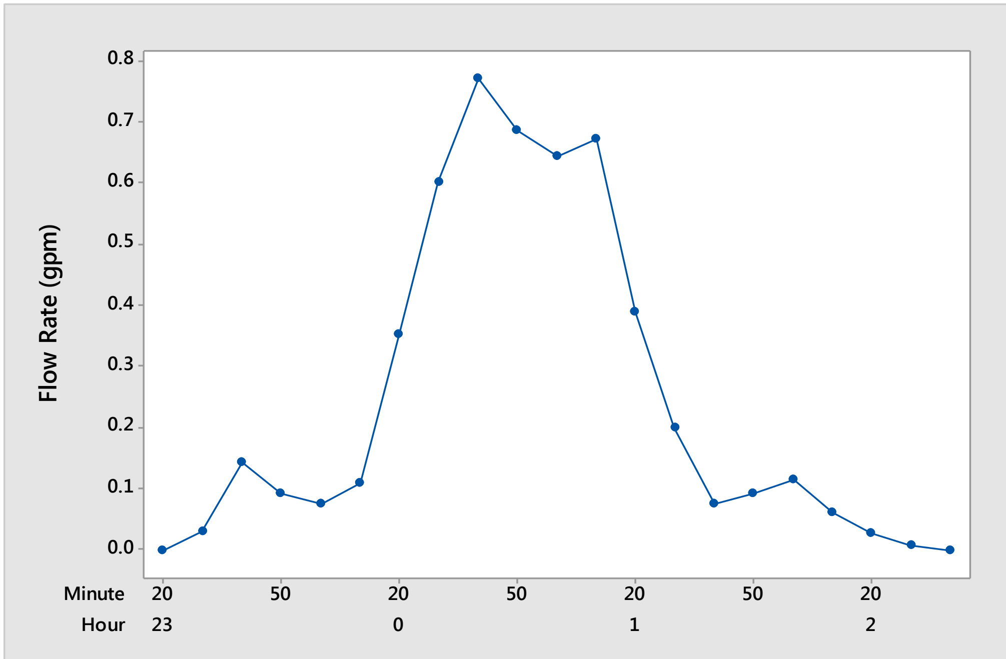

Figure A 47 Hydrograph of the flow rate for the Lorton Road runoff for the 11/24/14 storm event

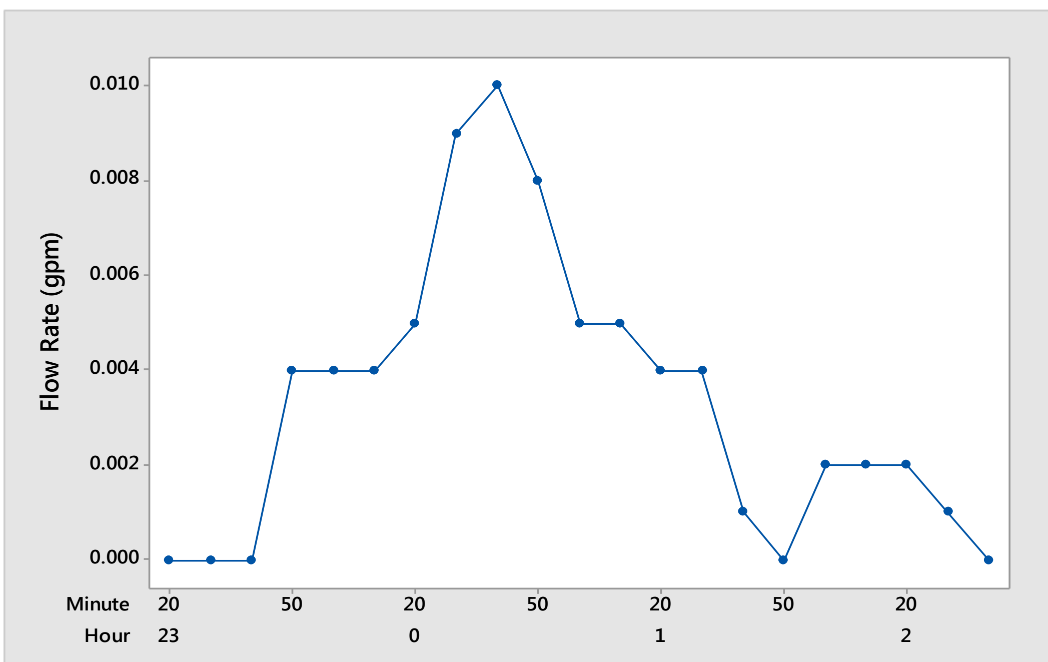

Figure A 48 Hydrograph of the flow rate for the unmanaged vegetated strip for the 11/24/14 storm event

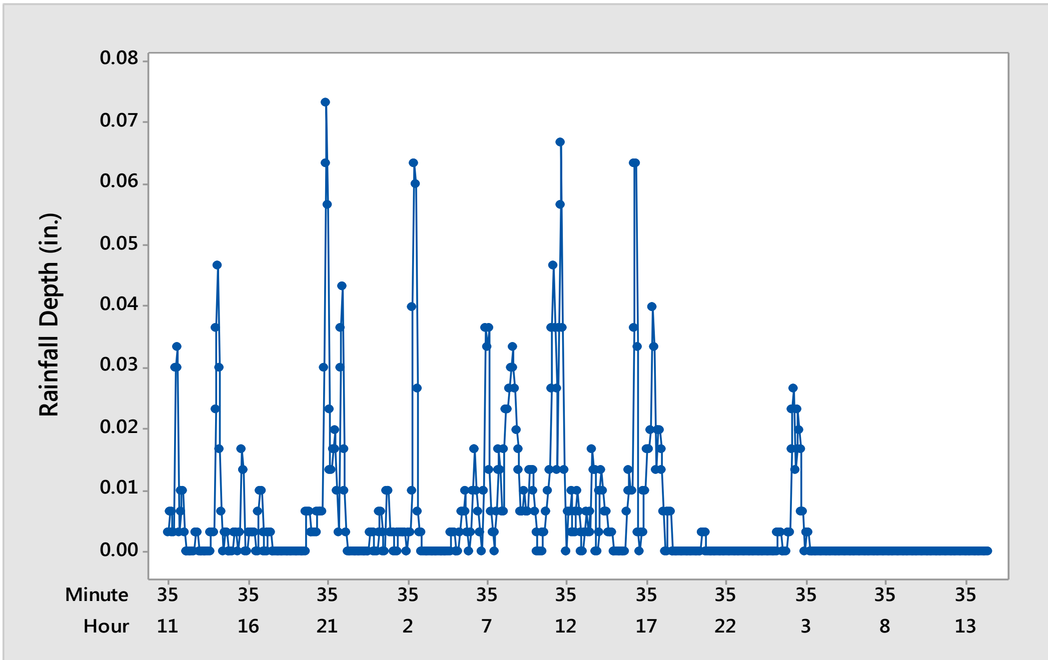

Figure A 49 Incremental rainfall depth averaged over 5 minutes for the 5/01/14 storm event

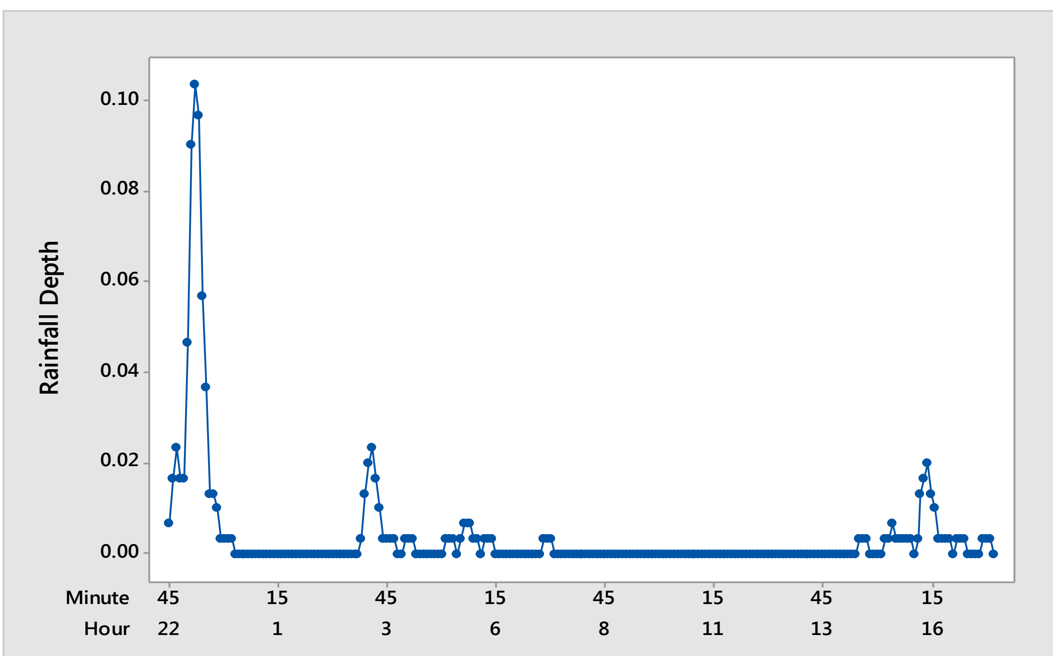

Figure A 50 Incremental rainfall depth averaged over 5 minutes for the 5/29/14 storm event

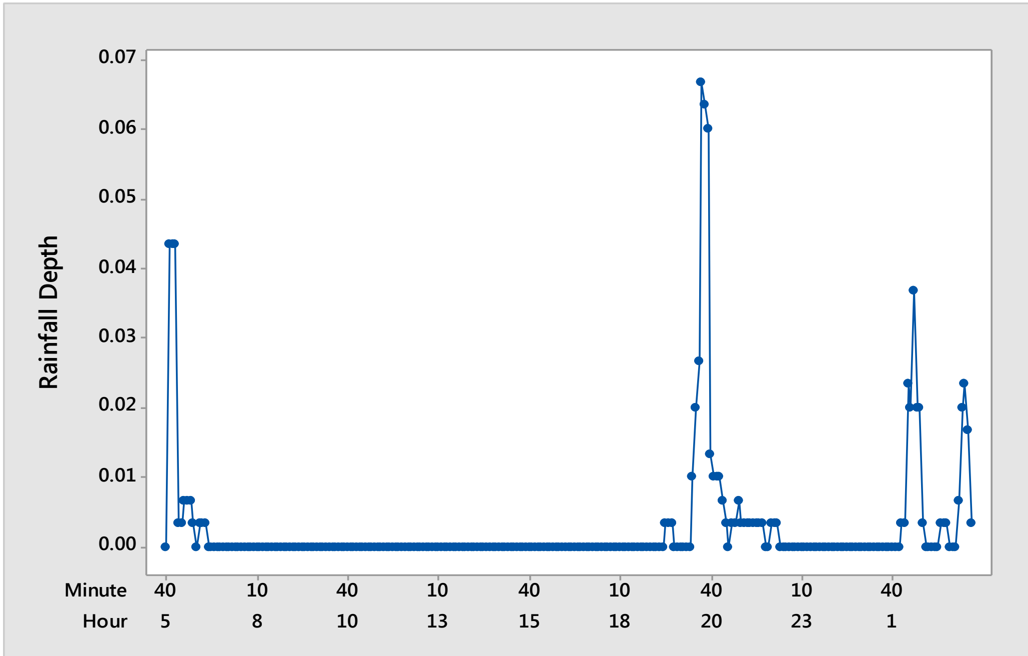

Figure A 51 Incremental rainfall depth averaged over 5 minutes for the 6/11/14 storm event

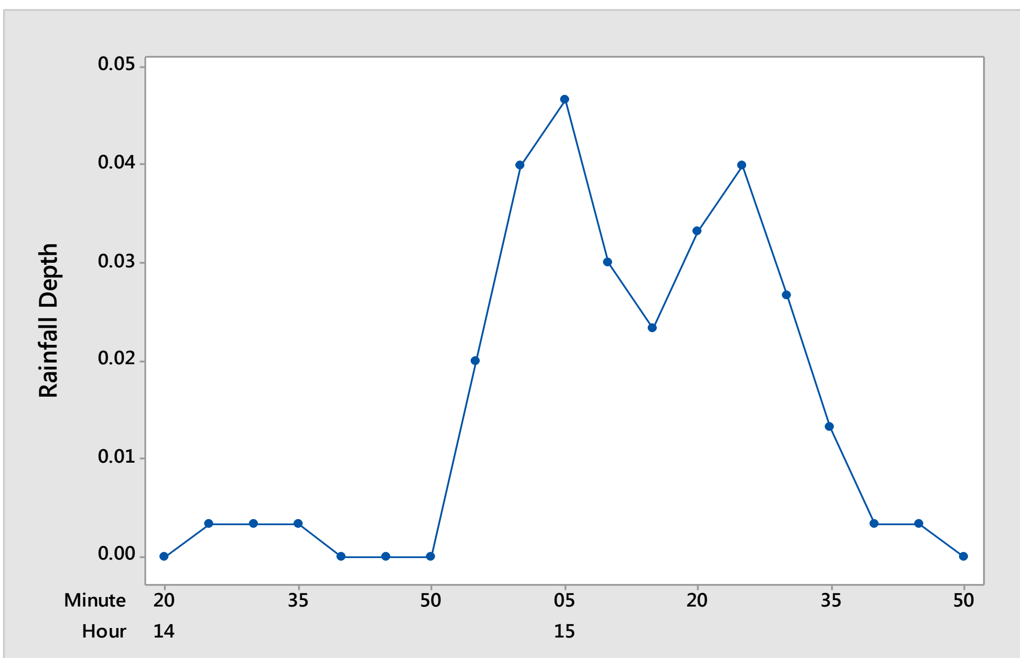

Figure A 52 Incremental rainfall depth averaged over 5 minutes for the 6/12/14 storm event

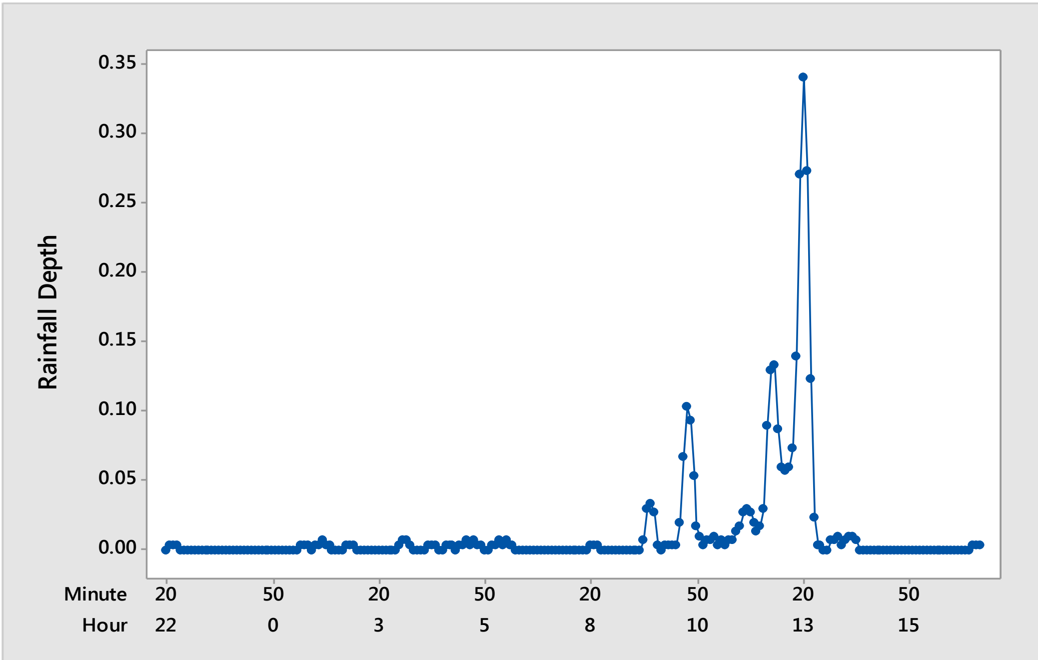

Figure A 53 Incremental rainfall depth averaged over 5 minutes for the 8/12/14 storm event

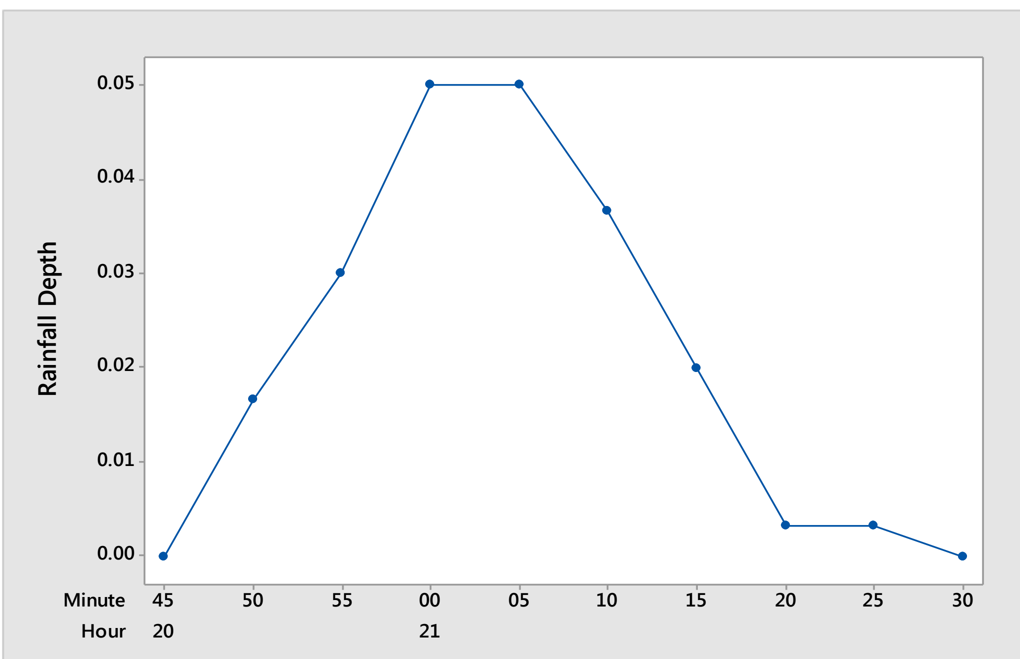

Figure A 54 Incremental rainfall depth averaged over 5 minutes for the 8/22/14 storm event

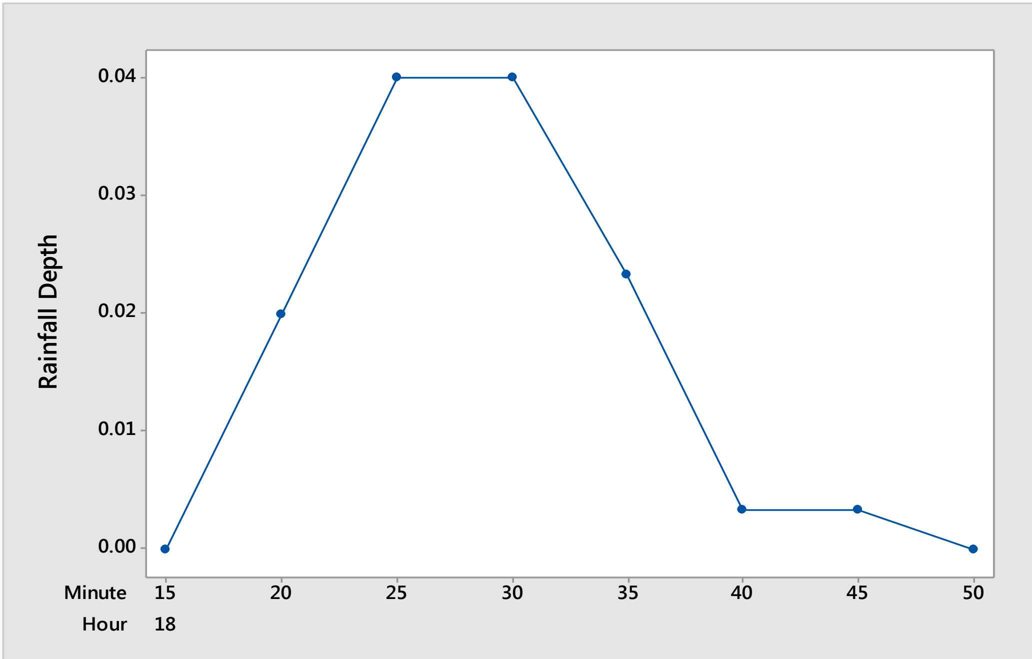

Figure A 55 Incremental rainfall depth averaged over 5 minutes for the 9/12/14 storm event

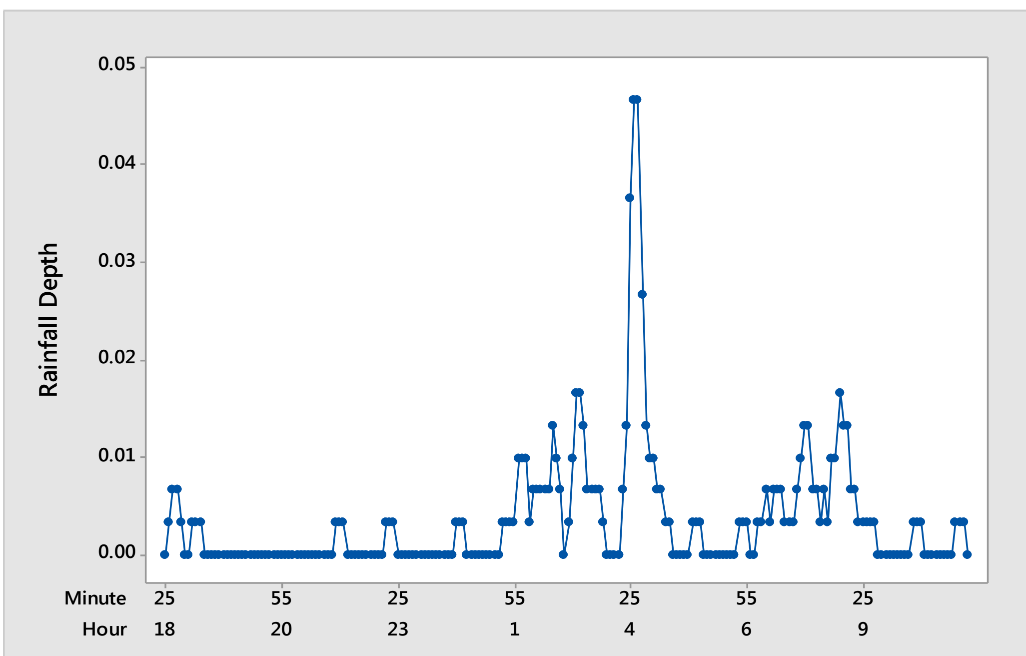

Figure A 56 Incremental rainfall depth averaged over 5 minutes for the 9/25/14 storm event

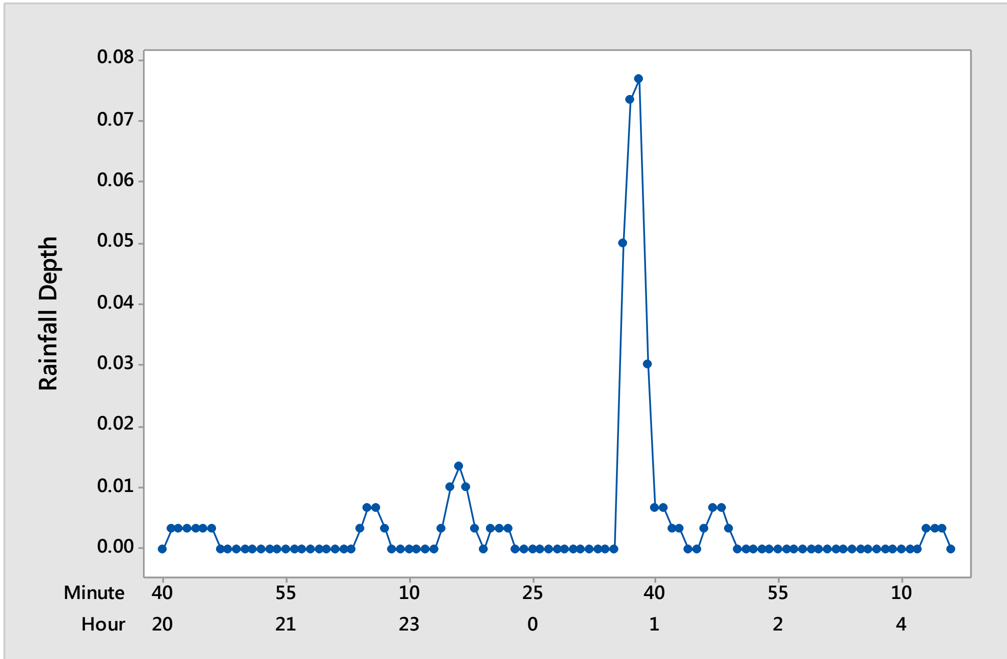

Figure A 57 Incremental rainfall depth averaged over 5 minutes for the 10/04/14 storm event

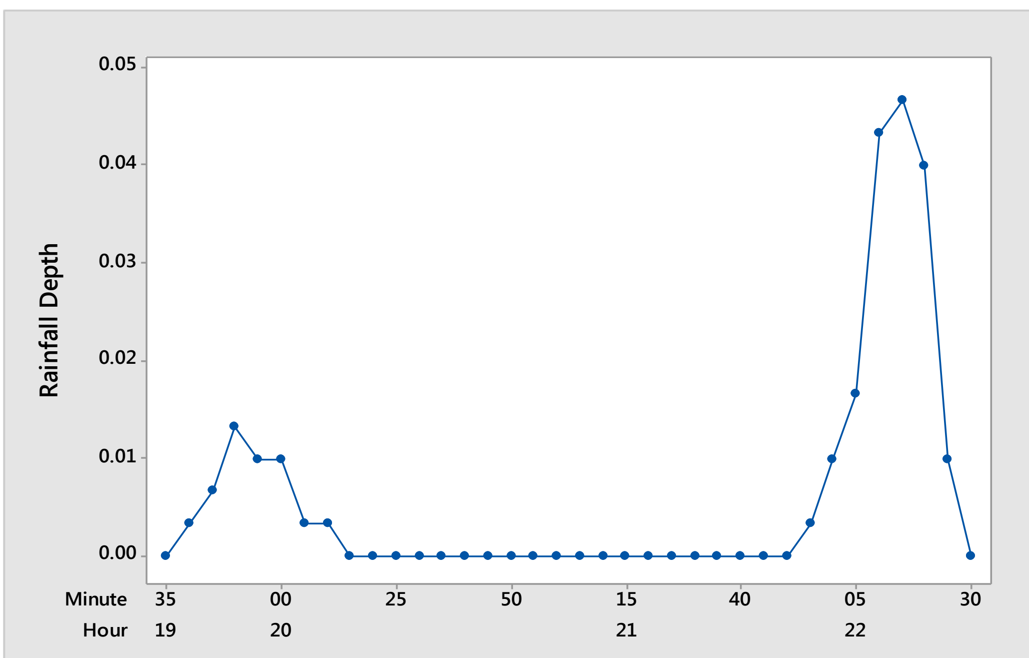

Figure A 58 Incremental rainfall depth averaged over 5 minutes for the 10/08/14 storm event

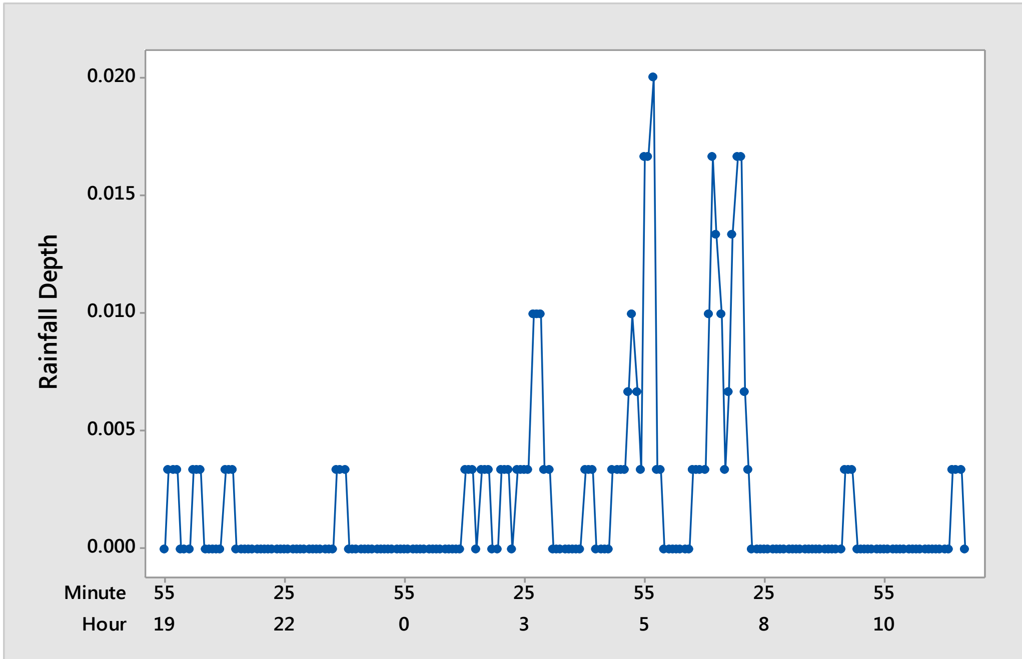

Figure A 59 Incremental rainfall depth averaged over 5 minutes for the 10/12/14 storm event

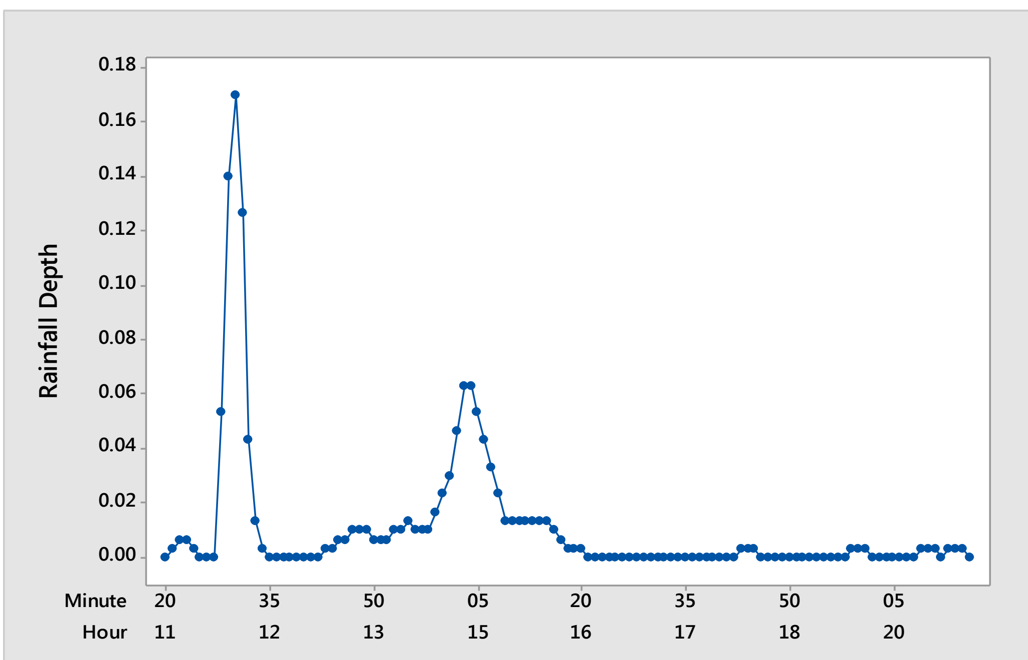

Figure A 60 Incremental rainfall depth averaged over 5 minutes for the 10/16/14 storm event

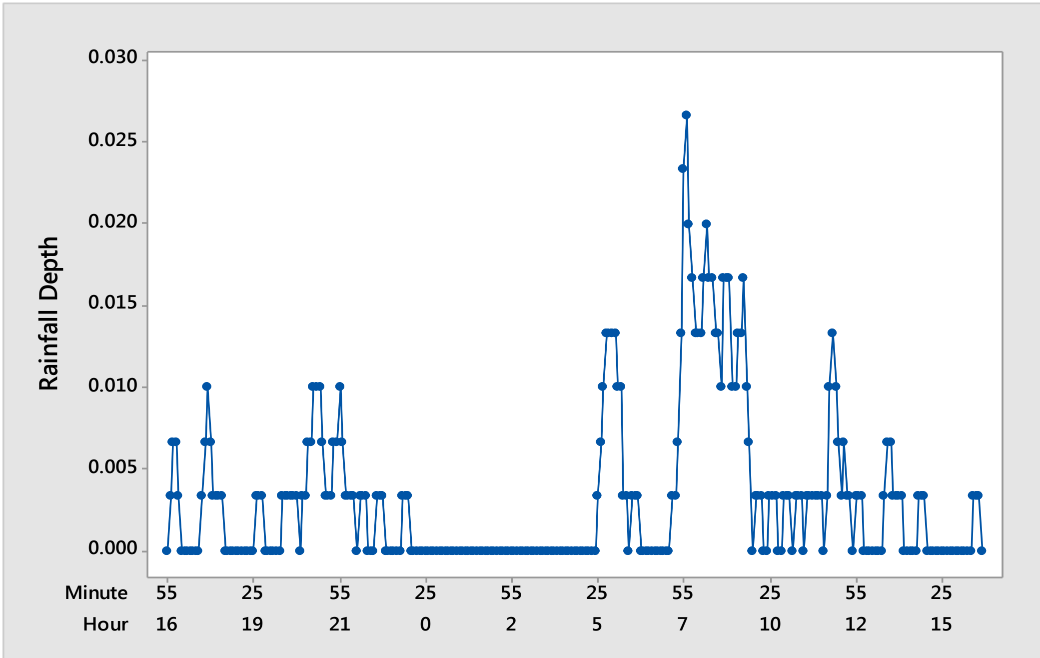

Figure A 61 Incremental rainfall depth averaged over 5 minutes for the 10/22/14 storm event

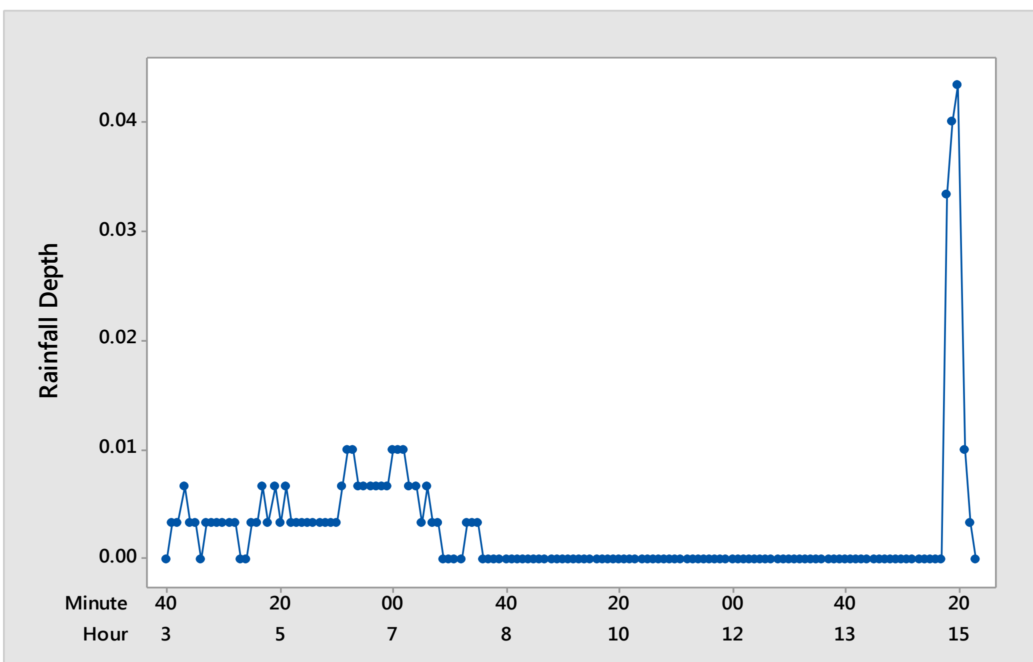

Figure A 62 Incremental rainfall depth averaged over 5 minutes for the 11/06/14 storm event

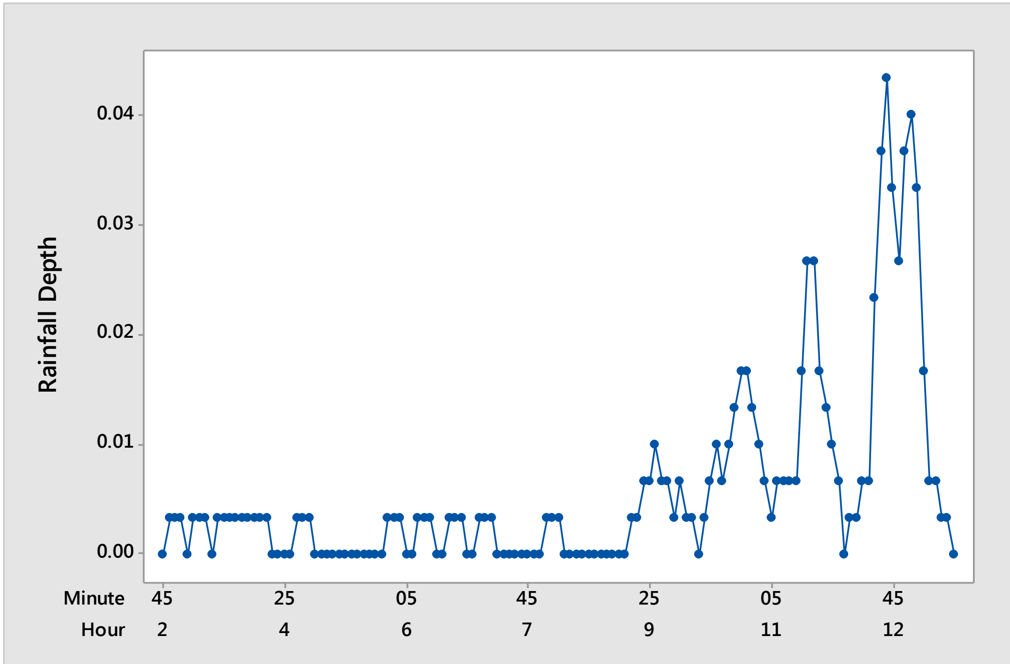

Figure A 63 Incremental rainfall depth averaged over 5 minutes for the 11/17/14 storm event

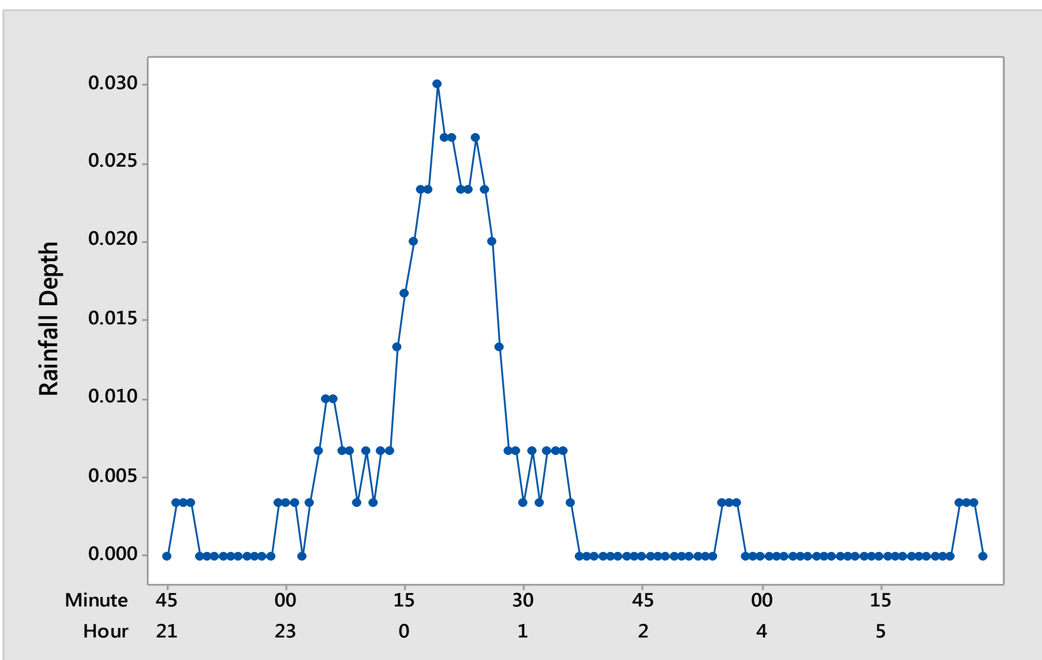

Figure A 64 Incremental rainfall depth averaged over 5 minutes for the 11/24/14 storm event