Wet Weather Performance of an Extensive Vegetated Roof in Waterloo, Ontario

By

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Abstract

Vegetated roof technologies are increasingly being adopted as treatment measures to mitigate the effects of urban stormwater. A mass balance approach was used to assess the wet weather performance of a vegetated roof on the top of city hall in Waterloo, Ontario. Vegetated and control roof sections were instrumented to measure precipitation inputs, storage and outflow for 18 storm events from June to October, 2006. Concentrations of suspended solids (SS), total phosphorus (TP), soluble reactive phosphorus (SRP), copper (Cu), zinc (Zn), chromium (Cr) and cadmium (Cd) in precipitation and roof (vegetated and control) runoff were measured. A total of 155.6 mm of rain fell during the study period. The vegetated roof retained 64.5 mm (41.5%) of the total rainfall while the control roof retained ~ 5.1 mm (3.3 %). For individual rain events, the vegetated roof retained an average of 3.5 mm (47.6 %) while the control roof retained ~ 0.3 mm (4.7 %). Water retention varied with storm size, season and was influenced by wetting history. The vegetated roof retained 80.6 % of precipitation for light storm events (≤ 3.5 mm) and 34.9 % for large storm events (> 3.5 mm). The control roof retained 7.6 % light storm events and 3.7 % for large storm events. Water quality from the vegetated roof did not show significant improvement as only Zn concentrations in runoff from the vegetated roof were significantly lower than that measured in runoff from the control roof. Concentrations of SS, Cu, Cr and Cd in vegetated roof runoff were relative to concentrations in rainfall and control roof runoff and TP and SRP concentrations were significantly higher than that in rainfall or control roof runoff. Results gained from this study may assist people in planning and stormwater management by providing insight into the monitoring, development and application of new stormwater controls.

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Chapter 1: Introduction

1.1: Problem Statement:

Urban stormwater runoff degrades aquatic ecosystems, causes flooding and poses a risk to drinking water (Marsalek *et al.,* 2006). To mitigate the impact on natural and human environments, stormwater management (SWM) programs use a variety of Best Management Practices (BMPs) as source, conveyance and end-of-pipe controls (USEPA, 1999; OME, 2003b). In Ontario, end-of-pipe controls such as stormwater ponds are primarily used to capture and treat runoff (Bradford and Gharabaghi, 2004).

Urban expansion is characterized by large areas of impervious surface which increase runoff volume (Paul and Meyer, 2001). Existing drainage systems particularly in older parts of cities cannot handle increased runoff volumes and meet quality control criteria. Many conventional SWM ponds do not reduce overall stormwater volume, but merely capture runoff (Bradford and Gharabaghi, 2004). Thus, existing facilities must be retrofitted and/or new stormwater controls constructed to manage ever increasing volumes of runoff. Expansion and maintenance of stormwater drainage systems is costly for cities and municipalities (Cameron *et al.,* 1999; Sample *et al*., 2003; Bradford and Gharabaghi, 2004) and difficult to implement in dense urban areas (Jennings *et al.,* 2003).

To implement and manage costly stormwater management programs, stormwater fees have been adopted by many municipalities in the United States and Europe whereby a property owner is charged for the stormwater services received (Lindsey, 1990; Cameron *et al.,* 1999). Canadian cities and municipalities have been slower to adopt stormwater fees as public opinion views them as additional taxation (Cameron *et al.,* 1999; Caldwell, 2006). To allow customers to reduce fees, some municipalities and cities in Germany (Cannata, 2005) and United States (Lindsey and Doll, 1999; Cameron *et al.,* 1999) offer financial rebates for the construction of onsite SWM controls such as a vegetated roof. However, Canadian vegetated roof research has not assessed wet weather performance as a criterion for a financial rebate. Consequently, city councils are hesitant to provide financial incentives for the implementation of a range of BMPs (Cameron *et al.,* 1999).

There is increasing interest by several countries to develop sustainable urban drainage systems (SUDS) whereby greater emphasis is placed on the reduction of stormwater volume with source controls (Marsalek and Chocat, 2002; Graham *et al.,* 2004). Vegetated roofs are one source control that has shown to reduce stormwater volume (TRCA, 2006) and have potential to reduce overall stormwater costs (Banting *et al.,* 2005). Vegetated roofs are broadly defined as a roof with vegetation and known also as green roofs, roof top gardens, garden roof systems, eco-roofs, sky gardens and sky rise gardens (Velazquez, 2005; Liu and Baskaran, 2005). Commercially available vegetated roofs typically consist of several layers of functional materials that include vegetation, growth medium, filter cloth, root repellent/water proof membrane. Recently, increasing amounts of vegetated roof research has been published in North America (NA) which shows that infiltration by the vegetated roofs can reduce total runoff volume by 50 % or greater, increase lag times and decrease peak flows by 50 % or greater. These BMPs can reduce levels of metals and suspended solids in runoff but they can be source of total phosphorus (TRCA, 2006; Berndtsson *et al.,* 2006), soluble reactive phosphorus (orthophosphates) and total nitrogen (Monterusso *et al.,* 2004; TRCA, 2006).

Germany has been referred to as a leader in vegetated roof technology, policy and research (Ngan, 2004; GRHC, 2005; Cannata, 2005; Getter and Rowe, 2006). Industry standardization, financial incentives and vegetated roof integration into development regulations has encouraged industry growth (Ngan, 2004; GRHC, 2006). In North America, there are several barriers to the expansion of vegetated roof technology that include financial constraints, public awareness, quantifiable research, technical expertise and accepted industry standardization (Getter and Rowe, 2006). Further, climatic conditions vary between cities/regions influencing vegetated roof wet weather performance and inhibiting the utility of vegetated roof research and broader adoption of the technology (VanWoert *et al.,* 2005a). As a result, vegetated roof implementation varies between cities/region and especially between localities that have financial incentives for vegetated roof construction (Toronto, Chicago, Portland) (Peck and Goucher, 2005; Getter and Rowe, 2006). Thus, more research is needed to: 1) assess vegetated roof performance across varying regions, to educate public and professional sectors; 2) to develop relevant policies; 3) to expand vegetated roof expertise; 4) to create vegetated roof building and performance standards; 5) to lower costs by financial incentive and to encourage green roof industry growth. This thesis examines the following two research questions in order to increase knowledge of vegetated roof wet weather performance in southern Ontario and to aid urban and stormwater management planning with recommendations based on vegetated roof stormwater treatment performance. The research questions are:

1. What is the wet weather performance of a vegetated roof on Waterloo City Hall?

2. Based upon the wet weather performance of a vegetated roof, what are the implications for planning and stormwater management?

1.2: Objectives

The specific objectives of this research are:

1. Conduct a literature review on vegetated roof wet weather performance, policies, performance and application as a best management practice for stormwater management programs as well as financing programs for stormwater management.
2. Determine the wet weather performance of a vegetated roof in Waterloo from June 1, 2006 to the end of October 31, 2006.
3. Discuss implications that vegetated roof wet weather performance data has for stormwater management planning in Southern Ontario.

1.3: Thesis Organization

Five chapters are presented in this thesis. Chapter 1 presents the problem statement, research questions and objectives and summarizes the literature concerning vegetated roof wet weather performance, application and policy in Germany and North America. Chapter 2 describes the experimental design, study site and research methods used. Chapter 3 describes the results and trends in vegetated roof wet weather performance. Chapter 4 discusses the vegetated roof wet weather performance in relation to previous studies and its implications for planning and stormwater management. Lastly, Chapter 5 presents conclusions and recommendations for future research.

1.4: Literature Review

1.4.1: Stormwater Runoff: Cause and Effects on the Watershed

Stormwater runoff is water that collects and runs off of urban surfaces during precipitation and meltwater events (Marsalek and Chocat, 2002). Stormwater runoff can seriously degrade the health of aquatic ecosystems (Novotony and Olem, 1994) and can cause flooding in areas with inadequate stormwater infrastructure (USEPA, 1999; OME, 2003). Stormwater is a problem for Canadian cities as large areas of impervious surface (Hofmann, 2001; 2005) increase stormwater volume by a factor of 5 compared to a rural or forested landscape (Paul and Meyer, 2001).

Urban runoff has several impacts on receiving waters. Runoff of water and debris from urban surfaces is the primary transport medium for nutrients, sediment, metals, organic and inorganic chemical compounds (Grapentine *et al.,* 2004). Urban runoff increases peak discharge in streams and also decreases the lag time (Watt *et al.,* 1989) thus increasing erosion, decreasing stream bed/bank stability (Booth and Jackson, 1997) and causing alteration to stream morphology (Paul and Meyer, 2001). Higher stream flow rates also decrease groundwater infiltration, lower stream base flow and groundwater levels and increase flooding risks (USEPA, 1999).

1.4.2: Stormwater Management Applications in Ontario

Most cities implement stormwater management programs to mitigate the impacts of runoff (Pyzoha, 1994; OME, 2003a, Watt *et al.,* 2003). Stormwater management (SWM) has developed from early approaches of primarily flood control to an increasingly complex program designed to treat both stormwater quantity and quality (Carlisle *et al.,* 1993; Watt *et al.,* 2003). In Ontario, SWM practicesused by most municipalities are detailed in the *Stormwater Management Planning and Design Manual* (OME, 2003b). Current SWM applications consist of best management practices (BMPs) which employ a range of structural or non-structural measures to manage stormwater quantity and/or quality (Marsalet and Chocat, 2002, p.2). BMPs are typically ordered in a treatment train characterized by a series of lot level, conveyance and end-of-pipe stormwater controls (OME, 2003a; 2003b).

1.4.3: Problem with Traditional Stormwater Drainage Design

Although a treatment train approach is recommended by the Ontario Ministry of Environment, end-of-pipe controls like SWM ponds are used primarily to reduce the water quality and quantity impacts of urban runoff on receiving waters (Lawrence *et al.,* 1996; OME, 2003b; Bradford and Gharabaghi, 2004). However, these stormwater controls are costly, land and labor intensive and fail to reduce total stormwater volume due to their lack of infiltration. Further, over use of an end-of-pipe controls can also lead to failure from continuous contaminant loading and stormwater flows that overwhelm pond holding capacity (Anderson *et al.*, 2002; Backstrom *et al.,* 2002; Marsalek and Chocat, 2002; Bradford and Gharabaghi, 2004; Marsalek *et al.,* 2006). As a result, additional stormwater controls are constructed and/or existing facilities retrofitted to handle increasing volumes of runoff and contaminant levels (Bradford and Gharabaghi, 2004).

1.4.4: Costs of Stormwater Management & Development of Stormwater Fees

Expanding stormwater infrastructure is costly for cities and municipalities (Cameron *et al.,* 1999; Sample *et al.* 2003). For example, a $ 90 million improvement to stormwater infrastructure is needed in Ottawa to reduce bacterial input into the Rideau River. A cost of $ 2.5 billion dollars is the estimated cost to clean up 16 Remedial Action Plan (RAP) sites in Ontario, equating roughly to $125 million dollar cost per site (Cameron *et al.,* 1999). To meet increasing costs, fees have been collected from the municipal tax base to finance SWM programs in the United States (Cameron *et al.,* 1999; Lindsey and Doll, 1999) and Germany (Ngan, 2004). In Canada, some municipalities have adopted a user fee system that is attached to the sanitary sewer charge (Cameron *et al.,* 1999; Caldwell, 2006).

Fees structures will depend on the number of equivalent runoff units (ERUs) originating from a parcel of property. ERUs are calculated by multiplying a standard runoff coefficient with the property area (Lindsey, 1990; Cameron *et al.,* 1999) or by predetermined impervious area defined as Equivalent Residential Units (Tufgar, 2005). The cost per ERU is determined by the revenue requirement divided by the number of ERUs for a given land use category (Lindsey, 1990, p.18). The benefit of ERUs is that individual parcels of land are charged appropriately by the number of ERUs that originate from the property (Lindsey *et al.,* 1996).

Expenses can be offset by the construction of a source control thereby reducing stormwater volume equating towards a financial rebate or credit. Some municipalities in Germany and the United States have financial incentives in place to encourage the construction of source controls (Thurston *et al.,* 2002; Cameron *et al.,* 1999). However, many municipalities in the United States are hesitant to provide financial rebates due to decreased revenues, inconsistent analysis of BMP and lack of knowledge on BMP performance (Cameron *et al.,* 1999; Bradford and Gharabaghi, 2004).

1.4.5: Alternative Solutions to Conventional Design Problems & Stormwater Costs

The transition to sustainable stormwater management began with the defining of the term "sustainability" in 1987 by the Brundtland Report and the Rio Conference in 1992 (Larson and Gujer, 1997). This led to the adoption of Local Agenda 21, a program in Europe where local authorities create and/or adopt sustainable development strategies (Ngan, 2004, p. 11). By mid-1990, countries in Europe began investigating sustainable stormwater management. Several titles for sustainable stormwater management emerged in the literature: Sustainable urban drainage (Ellis, 1995); Alternative Stormwater Management (Huhn and Stecker, 1997); Sustainable urban water management (Larsen and Gujer, 1997); Source control and distributed storage (Andoh and Declerck, 1997); Sustainable Water and Waste Management (Otterpohl *et al.,* 1997); De-centralized stormwater management (Sieker, 1998); Sustainable Urban Drainage Systems (Marsalek and Chocat, 2002); Integral water management (Mentens *et al.,* 2003) and Low Impact Development (Bradford & Gharabaghi, 2004; Graham *et al.,* 2004). Consequently, several countries have shown interest in sustainable stormwater management (Marsalek and Chocat, 2002).

In order to link the concept of sustainable stormwater management with realistic application, Marsalek and Chocat (2002) note that sustainable SWM has several practical implications. This includes; greater use of source controls, increase of green space, stable SWM funding through the adoption of stormwater fees, maintenance of stormwater infrastructure and creation of stormwater agencies within a larger organizational framework (ie. conservation authority) with the participation of both private and public sectors.

Use of source controls "seeks to control stormwater volume at the source by reducing imperviousness and retaining, infiltrating and reusing rain water on site" (Graham *et al.,* 2004, p. 331). Application of source controls has many proposed benefits such as, increased groundwater recharge, maintenance of local hydrology (Fujita, 1997; Mentens *et al.,* 2006), management of the full spectrum of rain events, reduction of total runoff volume, increased runoff lag time (CH2MHILL, 2002; Graham *et al.,* 2004) and decreases in combined sewer overflows, risk of downstream flooding and costs due to a reduction in stormwater infrastructure (Bradford and Garabaghi, 2004; Graham *et al.,*2004; Banting *et al.,* 2005). Overall, a decentralized system characterized with greater use of source controls creates a more reliable stormwater management system as failure of one source control does not mean failure for the entire system (Andoh and Declerck, 1999). However, due to lack of systematic and comprehensive monitoring of source controls, data to enable reliable information regarding wet weather performance is not necessarily available (Bradford and Gharabaghi, 2004) and municipal cost savings (Cameron *et al.,* 1999).

1.4.6: Vegetated Roofs: Description, Types, and Function

Vegetated roofs are source controls that can be broadly defined as a roof with a vegetation cover. There are three recognized types of vegetated roofs: extensive, semi-intensive and intensive. Classification helps differentiate between heavy, moderate and light weight vegetated roof systems as weight dictates a variety of structural and functional characteristics (Table 1). Extensive roofs being light weight, intensive roofs being heavy weight systems and semi-Intensive roofs have characteristics from both an extensive and intensive vegetated roof system.

Table 1: Basic Characteristics of Different Types of Vegetated Roofs

Characteristic	**Extensive**	**Semi-Intensive**	**Intensive**
Depth of Material	3-15 cm	Above and below 15 cm	> 15 cm
Accessibility	Often inaccessible	Partially accessible	Usually accessible
Plant Diversity	Low	Varies	High
Weight	12-25 lb/ft^2 72-169.4 kg/m^2	25-50 lb/ft^2 168.4-290 kg/m^2	50-200 lb/ft^2 290-967.7 kg/m^2
Plant Diversity	Low (Grasses, herbs, mosses and succulents)	Greater	Greatest (shrubs, trees, and plants)
Cost	Low	Varies	Highest
Maintenance	Minimal	Varies	Highest

Source: GRHC, 2005, p. 11

With such characteristics, all three types of vegetated roofs have advantages (Table 2). The characteristics of each type of vegetated roof vary but they all consist of the same basic material components.

Vegetated roofs are composed of: vegetation, growing medium, filter cloth, drainage layer and a water proof membrane (Peck *et al.,* 1999; GRHC, 2005, p. 13; Liu and Baskaran, 2005, p. 1) (Figure 1). Each material layer in the vegetated roof has a specific hydrologic and biological function.

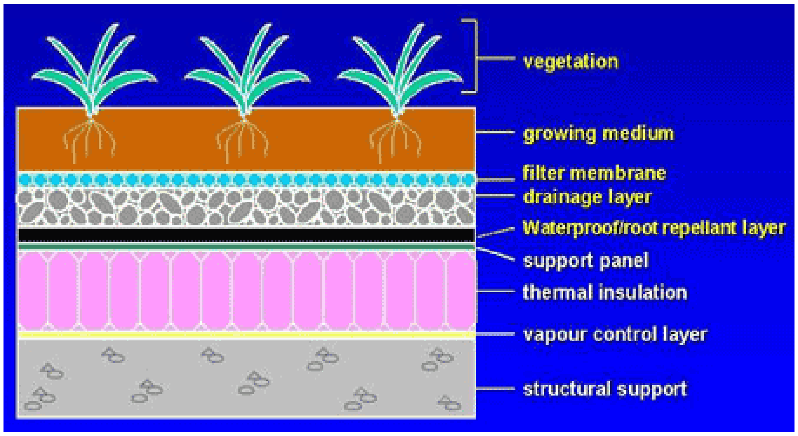
Table 2: General Advantages of Vegetated Roof Types

Extensive	**Semi-Intensive**	**Intensive**
Lightweight	Combines best features of extensive and intensive	Greater diversity of plants
Suitable for large areas	Utilizes areas with greater loading capacity	Best insulation properties and stormwater management
Low maintenance costs and no irrigation required	Greater coverage at less cost than intensive	Greater range of design
Suitable for retrofit projects	Average maintenance	Often accessible
Lower capital costs	Greater plant diversity than extensive	Greater variety of human uses
Easier to replace	Greater opportunities for aesthetic design than extensive	Greater biodiversity potential

Source: GRHC, 2005, p. 11

Typically, succulents are used for vegetated roofs due to their hardiness, ability to retain water and grow in poor soil conditions however, a variety of plants, trees and shrubs can be used. The most commonly used plant on commercially available vegetated roofs is *Sedum spp* or Stone Crop. Studies conducted in Michigan compare native vegetation and *Sedum spp.* and showed that *Sedum spp*. survival rates are higher because of its high drought tolerance and suitability in cooler climates (Monterusso *et al*., 2005; VanWoert *et al.,* 2005b). The soil layer supports plant growth, helps prevent plant mortality in cold temperatures (Boivin *et al.,* 2001) and is a medium for moisture retention and nutrient uptake. The soil layer is typically a light weight material consisting of a small percentage of organic material and a large percentage of light weight aggregate due to structural load capacities (Friedrich, 2005; Xero Flor, 2006 b).

The filter cloth prevents fine particles from escaping the growth medium and is typically constructed of polyethylene fibers. The drainage layer allows excess water to drain from the growth medium to prevent water trapping and moss growth. The root barrier and waterproof membrane is the final layer preventing root and water penetration into the building's structure (GRHC, 2005, pp.15-17).



Source: Liu, 2004, p.12
Figure 1: Vegetated Roof Structural Components

1.4.7: Vegetated Roof Application

Vegetated roofs have been part of the urban landscape for over 4 100 years. One of the most notable applications of vegetated roofs during the Ancient period was the Hanging Gardens of Babylon. During the medieval period, application of vegetated roofs in Scandinavia was evident in the construction of sod roofs to improve building insulation. In Renaissance Italy, vegetated roofs were in the form of garden terraces and roof gardens; soon many of wealthy in Europe accented their homes with vegetated roofs. Late 19th – early 20th century application of vegetated roofs was due to architects such as Le Corbusier, Frank Lloyd Wright, and Roberto Burle Max who used them to maximize green space in the confined spaces of the city (Osmondson, 1999). In Germany, vegetated roofs emerged in the 1880's due to the roofer H. Koch who tried to decrease roof fire hazard by tarring and adding gravel to the roof structure. Subsequently, windblown seeds colonized and later developed into vegetated roof (Kohler and Keeley, 2005). German use of vegetated roofs for stormwater management began in the late 1960's (Ngan, 2004). By the 1970's, significant technical research had been initiated on vegetated roofs (Ngan, 2004; Getter and Rowe, 2006). The 1980's showed significant growth in the German vegetated roof market with annual growth increases of 15-20 % (GRHC, 2005). By 2001, the annual aerial extent of vegetated roof was 13.5 km^2 (13.5 million m^2) (Ngan, 2004) and total vegetated roof area accounted for 14 % of total roof coverage in Germany (Cannata, 2005).

In North America, vegetated roofs emerged on the prairies with sod roof homes. During the 1930's, vegetated roofs decorated the skyscrapers of Rockefeller square (Osmundson, 1999). Only recently has use of vegetated roofs for technical benefits taken place. A number of vegetated roof research centers have been established at Michigan State University (MSU), British Colombia Institute of Technology (BCIT), Pennsylvania State University and Institute for Research Construction Center in Ottawa, ON (DeNardo *et al., 2004*). Overall, commercial vegetated roofs are more popular as an industry survey documented a 72 % growth in green roof square footage and 80 % industry growth in the United States (GRHC, 2006b)

There are a number of public benefits to wide-scale application of vegetated roofs. A review of literature shows vegetated roofs reduce building energy use (Liu, 2003; Liu, 2004); filter dust and particulate matter (Currie, 2005), extend building life cycle (Wong *et al.,* 2003; Kosareo and Ries, 2006) and roof life (Peck et al., 1999; Liu &

Baskaran, 2003), improve urban aesthetics (GRHC, 2005), increase biodiversity (Schrader and Böning, 2006; Köhler, 2006), decrease fire risk (Köhler, 2004; Köhler and Keeley, 2005;) improve human physical and psychological health (Peck et al., 1999), increase recreation decrease stormwater infrastructure costs (Banting et al., 2005) decrease total stormwater volume (VanWoert *et al*., 2005a; Carter and Rasmussen, 2006; Monterusso *et al.,* 2004) and remove contaminants from stormwater (Köhler and Schmidt, 2003; TRCA, 2006; Berndtsson *et al.,* 2006).

1.4.8: Stormwater Retention by Vegetated Roofs

Vegetated roofs have been recognized as a feasible stormwater control option for urban centers (Carter and Rasmussen, 2006). One of the main benefits of vegetated roofs is the reduction of stormwater volume on site (TRCA, 2006). They capture and store rainfall that is later lost through the processes of evaporation and transpiration. In the United States, tighter regulations are being established to regulate stormwater runoff from urban centers and the EPA's Phase II Final Rule encourages the use of vegetated roofs. Recently, vegetated roofs have become a more viable option because they can be constructed on existing buildings and do not require additional land (Jennings *et al*., 2003; Moran *et al*., 2005; Carter and Rasmussen, 2006).

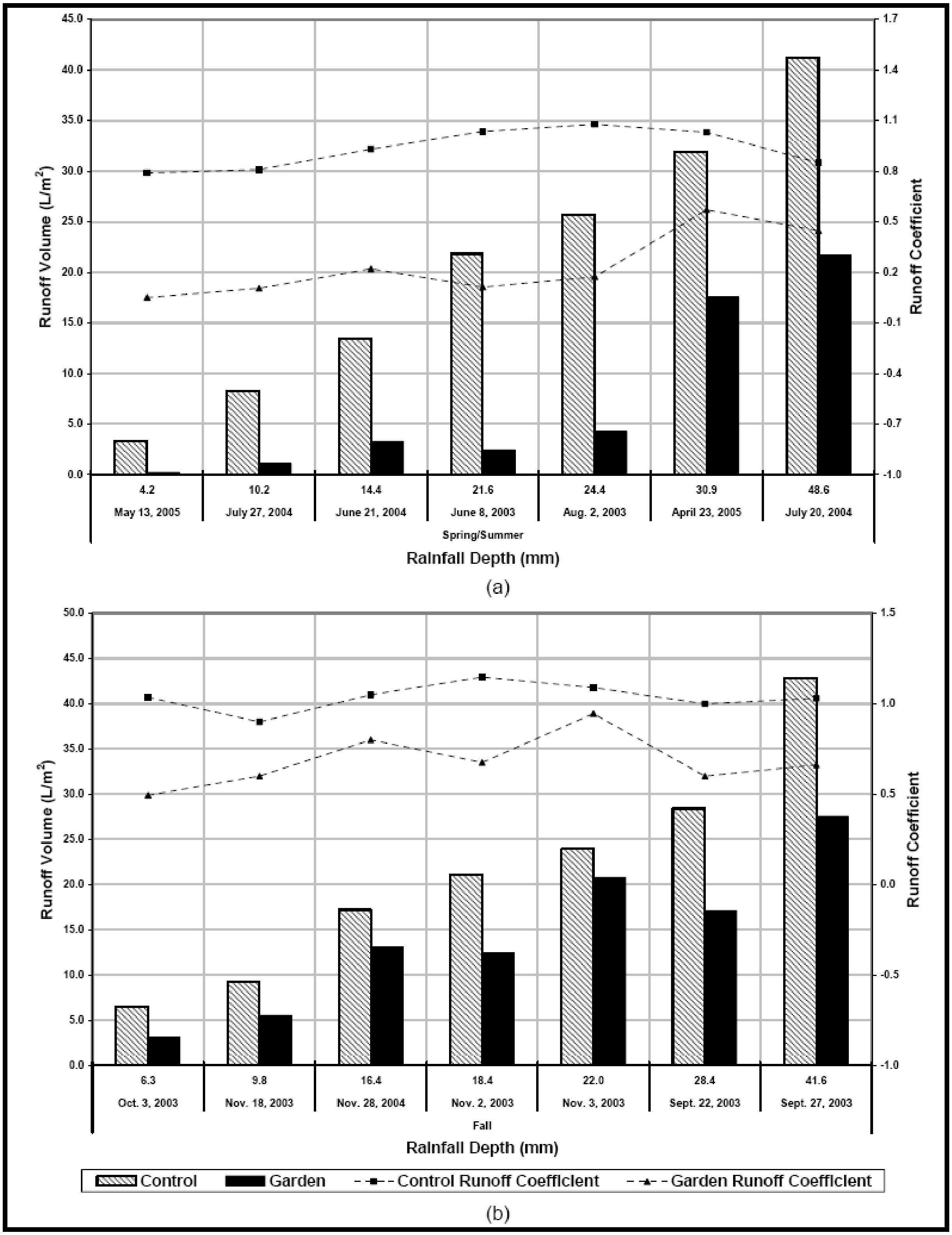
Several studies have shown that vegetated roofs can reduce total stormwater runoff by at least 50 % (Jennings *et al.,* 2003; Liu, 2003; Moran *et al.,* 2005; Liu and Minor, 2005; Liu and Connelly, 2005; La Berge *et al.,* 2005; VanWoert *et al.,* 2005a; Bengtsson *et al.,* 2005; DeNardo *et al.,* 2005; TRCA, 2006; Mentens *et al.,* 2006; Carter and Rasmussen, 2006). Other studies have shown that retention of vegetated roofs can reach 60 % or greater (VanWoert *et al.*, 2005a; Moran *et al.*, 2005; Liu and Connelly, 2005; Carter and Rasmussen, 2006). With such high retention values, it is important to understand that vegetated roof water retention values reported should be interpreted as absolute values as data sets do not always define the rain depth criteria to include a rain event in the data set.

The water retention of a vegetated roof is affected by several variables. The variables include; frequency of storm events, storm size and seasons (Banting *et al.,* 2005; Villarreal and Bentsson, 2005). Jennings *et al.,* (2003) showed that frequent storm events over a 4 day period decreased vegetated roof retention (Table 3). Similarly, a study by Liu (2003) and TRCA (2006) found that vegetated roof retention decreased during months with frequent heavy rainfall, particularly during cool, wet, fall months (Figure 2). In contrast, water retention of a vegetated roof increases when weather conditions are hot and dry for an extended period of time. Two vegetated roofs in Toronto were found to retain 15 mm storm events when preceded by a 6 day dry period (Liu and Minor, 2005). Similarly Bengtsson *et al.,* (2005) reported that a vegetated roof retained 12 mm of rainfall which exceeded the predicted field capacity of 9 mm. Higher evapotranspiration (ET) rates in the summer months free water storage space for upcoming rain events. During summer days with an average temperature of 30.7 ° C, the evaporative losses through ET reached 3.2 mm/day for planted beds of *Sedum album* (Rezaei and Jarrett, 2005).

Table 3: Vegetated Roof Hydrological Function during Frequent Rainfall

Storm Event	*Rainfall (in)*	*Greenroof Runoff (in)*	*Retained (in)*	*% Retained*
7 April 2003	0.89	0.22	0.67	75
8-9 April 2003	1.02	0.57	0.45	44
9-11 April 2003	1.63	1.11	0.52	32

Source: Jennings *et al.,* (2003) p. 10

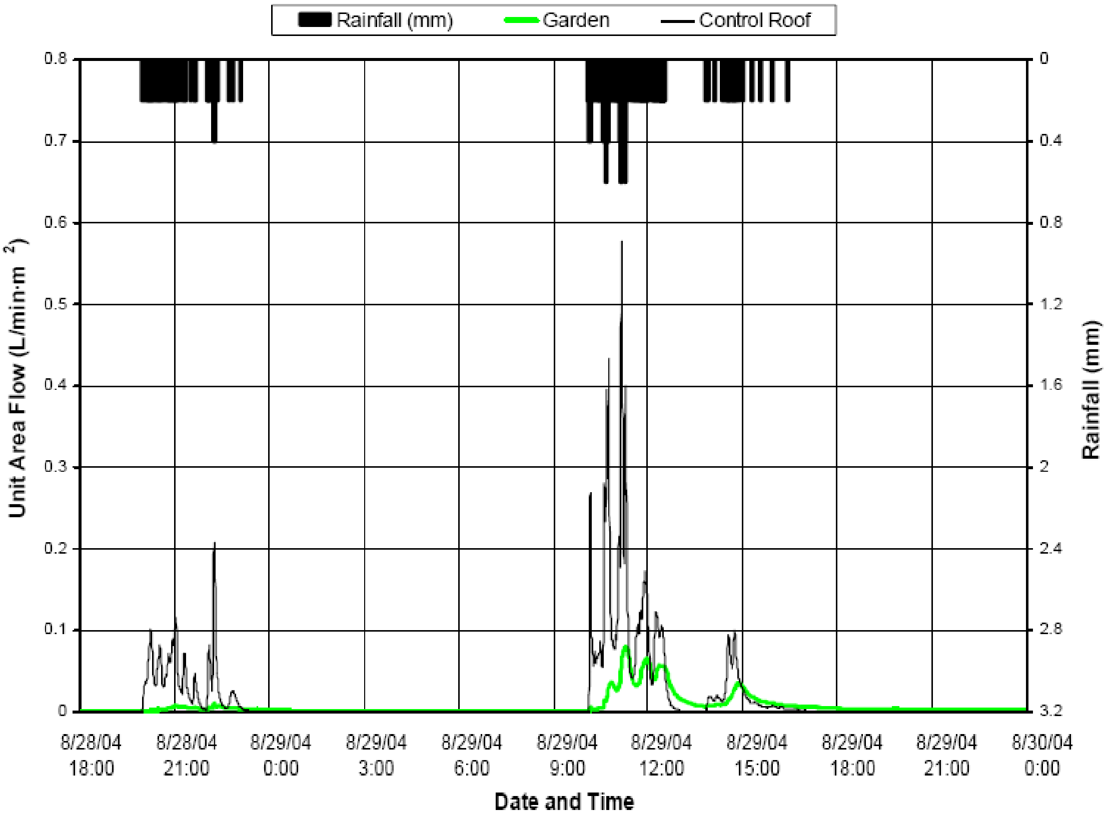


Source: TRCA, 2006, p.31

Figure 2: Vegetated and Control Roof Runoff Volumes and Runoff Coefficients for a Range of Event Sizes during the Spring/Summer (a) and Fall (b).

Storm size greatly influences vegetated roof stormwater retention. In a study documenting storm size impact on vegetated roof water retention, VanWoert *et al.,* (2005a) reported that vegetated roof retention decreased from 97.1 % for light storm events (< 2 mm) to 65.1 % for heavy storm events (> 6 mm) as vegetated roof field capacity was exceeded. Field capacity is the volume of water that is held by the vegetated roof after water has freely drained (Dunne and Leopold, 1995) and can be determined with the use of the gravimetric method or by a mass balance equation (Bengtsson *et al.,* 2005). When the rain volume does not exceed field capacity 100 % retention of an individual storm event is possible. Bengtsson *et al.,* (2005) showed that a 30 mm vegetated roof could fully retain storm water 9 mm or less. VanWoert *et al.,* (2005a) showed a 50 mm vegetated roof could retain storm water only up to 5.86 mm. Field capacity volumes differ due to the properties of the growth medium. VanWoert *et al.,* (2005) compared the retention capability of growth substrates with and without vegetation. He found that there was no significant difference between the growth medium with or without vegetation leading to the conclusion that vegetation does not greatly influence stormwater retention. However, when trying to determine the significance of varying media depths by comparing differences in stormwater retention, no strong conclusions can be drawn. A study by Liu and Minor, (2005) on two green roofs (75 mm and 100 mm) found that both green roofs had an average annual retention of 57 % despite differences in media depth. Similarly, a study by Jarrett *et al.,* (2006) noted that increasing media depth does not greatly improve stormwater retention. Results showed that a 30 mm growth substrate can still retain 25 % to 40 % of the annual rainfall.

When field capacity is exceeded and runoff is initiated from the vegetated roof, it flows at much slower rate. A study by DeNardo *et al.,* (2005) showed that a vegetated roof reduced peak flow from a rain fall intensity of 4.3 mm/hr to a runoff rate of 2.4 mm/hr. Miller (1998) measured peak maximum rainfall at 1.0 mm/minute and vegetated roof peak runoff flow at 0.3 mm/minute. However, other studies have shown that peak flow reduction is impacted by storm size. TRCA (2006) showed that a vegetated roof's peak flow reduction decreased from 87.6 % for storm events between 10 mm to 19 mm to 50.3 % for storm events greater than 40 mm. Overall, attenuation of peak flow rates is due in part to the delay of runoff release. Vegetated roofs increase lag time and time to reach peak flow (Figure 3). A study on vegetated roof hydrometric performance by DeNardo *et al*., (2005) documented an average vegetated roof lag time of 5.7 hours. Results by TRCA (2006) showed an average lag time of 29.8 minutes for the vegetated roof and 2.9 minutes for the control. Carter and Rasmussen (2006) found the time to reach peak flow for the vegetated roof was 34.9 minutes and 17.0 minutes for a bituminous roof. In a study with varying storm sizes, VanWoert *et al*., (2005a) showed that during storm events < 2 mm vegetated roof lag time was 55 minutes and during rain fall > 6 mm lag time decreased to 5 minutes. A study with varying rain intensities by Liu (2003) showed that a vegetated roof initiated runoff after 1.5 hrs during a light intensity rain event (0.05 mm/min) and initiated runoff after 4 minutes during an intense rain event (1 mm/min). Overall, lag time varies with wetting history, size and intensity of the storm event (Villareal and Bengtsson, 2005). One cause of the delay and extended



Source: TRCA, 2006

Figure 3: Vegetated Roof (Garden) Hydrograph During an 8.8 mm and 24.2 mm Rain Event

release of runoff is due to water flow through the vegetated roof substrate. Neither slope nor length of a vegetated roof significantly influences runoff flow (VanWoert *et al.,* 2005a). Rather, water infiltration within the various vegetation and soil layers governs runoff processes (Bengtsson *et al.,* 2005) that result in runoff extensions of 3 hrs after cessation of rainfall (VanWoert *et al.*, 2005a).

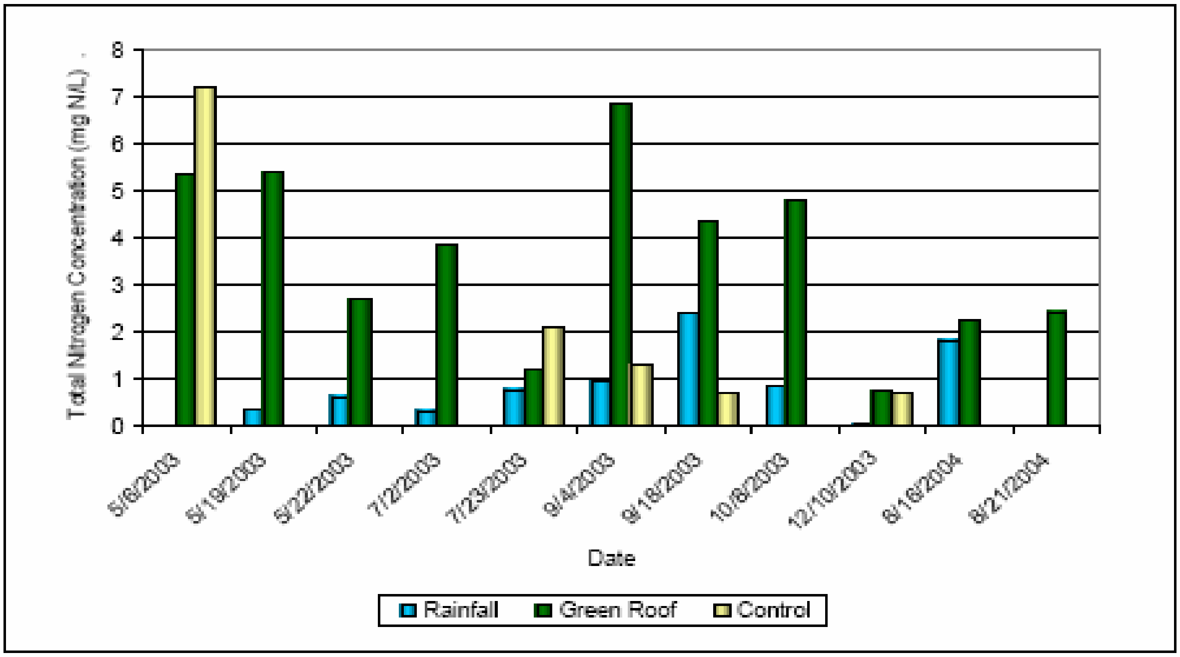
In North America, vegetated roofs have not been widely applied. Thus, physical measurements of stormwater volume on a watershed or regional scale with wide-scale vegetated roof application are not possible. However, computer modeling allows for estimates to be made on regional vegetated roof stormwater volume reduction. Studies with computer modeling results have shown that there is a measurable reduction in the magnitude and timing of urban runoff at a regional scale. One such study by the TRCA (2006) estimated stormwater volume reduction for the city of Toronto with 100 % vegetated roof coverage of viable roofs at 4 % and 1.7 % with 50 % vegetated roof coverage of viable roofs. Another study in Athens, Georgia, estimated a 15 % stormwater volume reduction with 100 % vegetated roof coverage of viable roofs. However, the authors also noted that reductions to regional stormwater volume would be limited by storm size (Carter and Jackson, 2006). Overall, vegetated roof stormwater volume reduction is believed to be due to increases to regional evapotranspiration rates (ET). TRCA (2006) noted that regional ET rates would increase by 37 % with a 100 % vegetated roof coverage of viable roofs.

1.4.9: Nutrient Concentrations in Vegetated Roof Runoff

Studies have shown that conventional roofs are sources of pollution primarily due to the wash off of atmospherically derived pollutants during storm events and/or contaminants from the break down of roofing materials (Förster, 1999; Zobrist *et al.,* 1999). Analysis of roof runoff showed high concentrations of contaminant metals such as Al, Mn, Cu, Pb and Zn (Chang *et al.,* 2004) and chemical compounds from agricultural pesticides and construction chemicals used in roof sealing (Bucheli *et al*., 1998). During a storm event, the "first flush" effect is a common observed occurrence where roof runoff initially has elevated concentrations of pollutants which then decrease with time (Berndtsson *et al.,* 2006). There is a general perception in earlier research literature that vegetated roofs can improve water quality (ie. Peck *et al.,* 1999) as studies in Germany have reported decreased concentrations of lead, cadmium, nitrate and phosphates from a

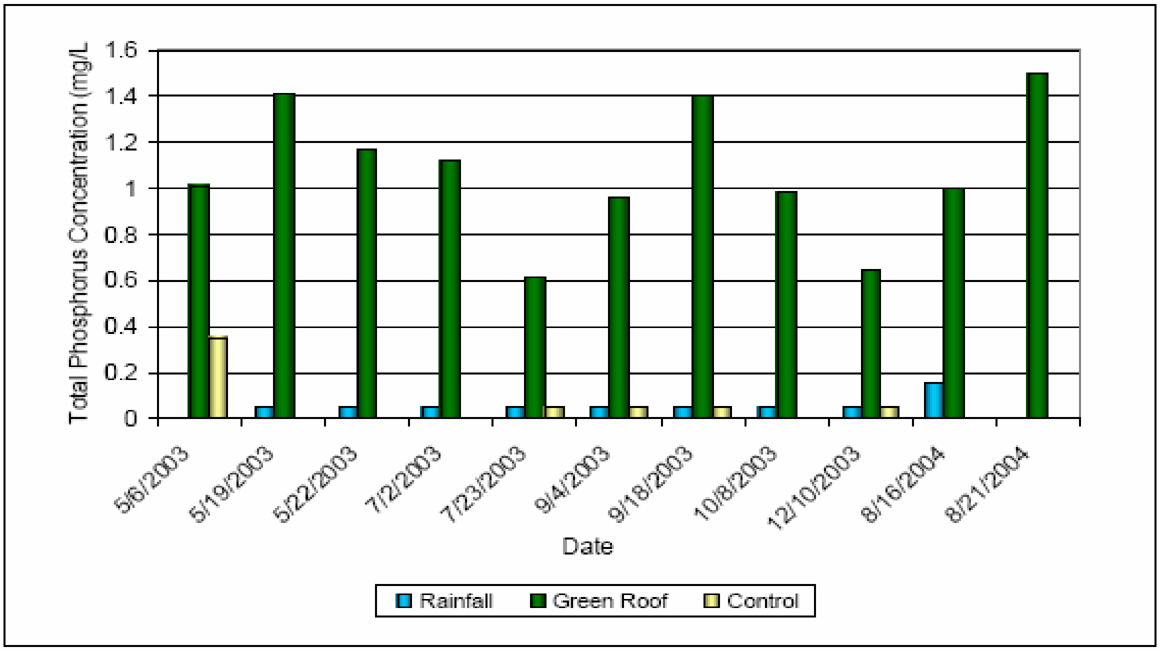
15 year old vegetated roof over a 4 year period (Köhler and Schmidt, 2003). However, a Swedish study by Berndtsson *et al.,* (2006) notes that runoff quality is impacted by the age of the roof as runoff from newly established vegetated roofs tend to be a source of nutrients (ie. nitrogen). In addition, the authors note that water quality is also influenced by the depth of the growth medium, fertilizer inputs, organic composition and surrounding land forms. In North America there is a lack of research directed towards quantifying specific pollutant concentrations in vegetated roof runoff.

Research suggests that pollutant removal capabilities of vegetated roofs vary across North America. Previous studies have shown that vegetated roofs are a nitrogen source. An earlier study by Moran *et al.,* (2005) found that total nitrogen concentrations and export in vegetated roof runoff were significantly higher than concentrations in rainfall and runoff from the control roof (Figure. 4). Another study by Monterusso *et al*., (2005) measured nitrogen concentrations on a variety of green roof systems and plant types subjected to slow release fertilizer inputs. Similarly, the study found that nitrogen levels had increased on all green roof systems and plant types except for a selection of native plants on a Sarnafil green roof system. However, a study by TRCA (2006) documenting vegetated roof influence on water quality noted a decrease in mean nitrogen levels from the vegetated roof compared to the control roof.



Source: Moran *et al.,* 2005, p. 520.
Figure 4: Total Nitrogen Concentrations in Vegetated Roof Runoff

Phosphorus levels from vegetated roof runoff are typically higher in concentration than from rainfall or control sites. Fertilizer inputs, bird droppings and atmospheric deposition can contribute to vegetated roof phosphorus input (Moran *et al*., 2005; TRCA, 2006; Emilsson *et al.,* 2007). Both Moran *et al*. (2005) and Berndtsson *et al*. (2006) report that vegetated roof phosphorus levels are higher in concentration than in rainfall or control roof runoff (Figure 5). TRCA (2006) report phosphorus concentrations exceeding *Provincial Water Quality Objectives* (OMEE, 1999) levels for all events sampled in Toronto during the 2 year period. However, the authors reported a significant drop in phosphorus concentration from 2003 to 2004 in vegetated roof runoff due to initial high phosphorus loss which dissipated over time.



Source: Moran *et al.,* 2005, p. 521
Figure 5: Total Phosphorus Concentrations of Vegetated Roof Runoff

The above studies all showed greatest phosphorus loss from vegetated roof systems while in contrast Köhler and Schmidt (2003) found a 67.5 % decrease in runoff phosphorus concentrations from a 15 year old vegetated roof compared to rainfall. Similarly, these results indicate that phosphorus leaching from the growth medium takes place in the first years of a vegetated roof lifespan due to fertilization during production, installation and initial maintenance (Emilsson *et al.,* 2007). More research is needed to assess the influence of vegetated roof age on water quality treatment.

1.4.10: Suspended Solid Concentrations in Vegetated Roof Runoff

There is little research completed on total suspended solids (TSS) concentrations in vegetated roof runoff. The only documented values are from TRCA (2006) which showed a reduction in TSS concentrations compared to the control roof and precipitation inputs. Results were based upon averages only from the 2003 monitoring year.

Vegetated roofs reduced TSS mean concentration by 68.3 % from precipitation inputs and 65.1 % from control roof outputs. Percent differences in TSS load over the monitoring period showed that the vegetated roof reduced TSS load inputs by 88.16% over the monitoring period.

1.4.11: Metal Concentrations in Vegetated Roof Runoff

Prior to 2006, there was a lack of information regarding the capability of vegetated roofs to remove metal contaminants. Two recent studies (TRCA, 2006; Berndtsson *et al.,* 2006) found that vegetated roofs typically do not have elevated metal concentrations. Berndtsson *et al*., (2006) showed that concentrations of zinc and lead in vegetated roof runoff met Swedish water quality objectives and were below concentrations measured in rainfall. Copper concentrations in vegetated roof runoff were high, but relative to concentrations measured in runoff from a conventional tile roof. Similarly, TRCA (2006) found high copper concentrations in rainfall and runoff from a bituminous and vegetated roof that exceeded values set by the Ontario PWQO due to copper piping. However, the vegetated roof runoff had a smaller copper load than that measured in bituminous roof runoff. In addition, aluminum, cadmium, iron, lead and zinc loads in the vegetated roof runoff were all smaller than that measured in the bituminous roof and loads that were higher such as with calcium and magnesium were due to sources in the growth medium. Although the two previous studies do not show drastic reductions in metal contaminants, a study completed in Germany on an older vegetated roof showed improved metal removal capabilities. Köhler and Schmidt (2003) documented 94.7 % and 87.6 % retention of lead and cadmium in rainfall inputs with a

15 year old vegetated roof. Whether such results could be replicated, needs to be further investigated within North America.

1.4.12: Cost Savings Equated from Vegetated roof Wet Weather Performance

When equating vegetated roof wet weather performance to financial savings for cities or municipalities, studies have shown promising results. A vegetated roof study for the City of Toronto showed a reduction in stormwater storage cost from $\$ 58.80/m^3$ per annum over 10 years for underground storage tanks to $\$ 24.26/m^3$ per anuum over 10 years for vegetated roofs (Bass and Baskaran, 2003). In addition, a vegetated roof feasibility study for the City of Waterloo estimated vegetated roof stormwater reduction at $\$ 42/m^3$ and projected total annual stormwater benefits for one green roof of $ 2 892 based upon stormwater reduction, pollutant removal and erosion control (Waterloo, 2005). However, pollution removal and erosion control rates were based upon those of a grass swale and not a vegetated roof. Overall, the estimated financial savings from vegetated roof wet weather performance do not take into account the high initial costs to construct a vegetated roof as well.

1.4.13: German Policy, Legislation and Standards

The success of the German vegetated roof industry is in part due to the establishment of vegetated roof policy, standards and legislation (Peck *et al.,* 1999; VanWoert *et al.,* 2005a, 2005b). Four types of policies are used to encourage green roof development through direct financial incentives, indirect financial incentives, vegetated roofs as ecological replacement measures and integration of vegetated roofs into development regulations (Ngan, 2004, p. 9). Direct financial incentives are those that cover the cost of vegetated roof construction to a set maximum amount. Typically, vegetated roof owners receive a benefit of $ 0.50 to $ 6.00 per square foot (Cannata, 2005). Indirect financial incentives are those that are in the form of stormwater fee rebate/credit. Vegetated roofs typically earn between 50 % - 100 % rebate towards the stormwater fee (Ngan, 2004; Cannata 2005). Overall, both direct and indirect financial incentives are popular as 43 % of all German municipalities offer some form of financial incentive (Cannata, 2005). The third policy type, ecological compensation or intervention rule, is a policy that demands that the destruction of green space be replaced or compensated with the creation of an equivalent area of green space. Lastly, the fourth vegetated roof policy is the integration of vegetated roofs into building regulations; thereby, requiring vegetated roof application on all flat roofs of new buildings.

German legislation provides the framework from which policy can develop. There are several pieces of legislation that are important to vegetated roof policy. The Federal Building Code demands that urban development be sustainable. The Federal Nature Conservation Act provides the basis for ecological compensation. Ecological compensation or the “interventional rule” requires that natural areas loss to human incursions is replaced with an equivalent area of green space. Its objective is to protect and sustain the function of the natural environment by regulating development with the intervention rule. The Environmental Impacts Assessment Act assesses the impact that development has on the environment and whether ecological compensation is required or met with a vegetated roof. Lastly, the Wastewater Charges Act is the basis for waste water or stormwater fees and stipulates a fee when wastewater is emitted into a receiving body of water. It prohibits unnecessary pollution and provides finances to fund vegetated roof construction (Ngan, 2004).

To ensure vegetated roof quality, Germany has developed vegetated roof standards that ensure consistency in vegetated roof construction and performance. The Landscape Construction and Development Research Society, known as the FLL (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V) published in *Guidelines for the Planning, Execution & Upkeep of German-Roof Sites* in 1998 (Peck *et al.,* 1999; Phillipi, 2005; GRHC, 2005). The guidelines were developed over 25 years and contain standards for vegetated roof application including vegetated roof design, construction and maintenance with attention paid to growing media, stormwater retention, component material requirements and the testing process for waterproof membranes and root repellent layer durability (Ngan, 2004; Phillipi, 2005). Many German municipalities require vegetated roofs to meet FLL standards in order to qualify for financial incentive or meet green space compensation requirements (Ngan, 2004). Overall, Germany's industry standardization, legislation and development incentives have translated into measurable degrees of growth for their vegetated roof industry.

1.4.14: North American Vegetated Roof Policy, Standards & Legislation

Currently, there is no Federal or Provincial policies in Canada that relates directly to vegetated roofs (Liu, 2004). However, there are indirect policies that provide financial incentives for vegetated roofs. For example, the Ontario Provincial government sponsors a $25 000 municipal green fund that can be used for green roof research or construction (Waterloo, 2005). In addition, cities and municipalities in both Canada and the United

States have either established or are developing their own vegetated roof policy (Peck and Goucher, 2005; Getter and Rowe, 2006). The cost of a vegetated roof in North America is typically twice the cost of a conventional roof membrane which translates to an average of \$ 12 to \$18 / ft^2 (GRHC, 2005). To reduce vegetated roof costs, many cities, municipalities and government agencies have initiated financial incentives along with policy. In Canada, the city of Toronto has established a pilot program whereby the owner can receive \$ 1 / ft^2 up to maximum of \$ 20 000 for a vegetated roof. However, the roof must meet design and performance criteria such as 50 % vegetation cover, have a minimum 150 mm growth substrate for new vegetated roofs and have a maximum runoff coefficient of 50% (City of Toronto, 2006). In 2003, the Quebec Energy Board recognized vegetated roofs as measure for energy conservation and established a financial incentive of \$ 6 / ft^2 (Lawlor *et al.,* 2006; Young, 2006). In the city of Portland, Oregon, vegetated roofs are recognized as a stormwater BMP and all new City-owned buildings and roof replacements must be vegetated. In addition, the city offers floor area increases for developers that construct a vegetated roof. The city of Chicago offers a stormwater retention credit and has a limited number of \$ 5000 grants for small residential vegetated roofs. The city also recognizes vegetated roofs as a means to meet the city's minimum reflectance requirement of 0.25 and offers floor area bonuses to developers who construct a vegetated roof that covers 50 % of the roof (Lawlor *et al.,* 2006).

LEED TM (Leadership in Energy & Environmental Design) green building certification is sustainable building program that encourages vegetated roof implementation. LEED TM standard certification is awarded on a basis of points earned on several platforms such as energy savings, habitat creation, and stormwater reduction (Kula, 2005; Lawlor *et al.,* 2006). A building with 50 % vegetated roof cover is awarded 1 LEED point each for reduction in stormwater volume and heat island effect (Oberlander *et al.,* 2002) with a maximum of 15 LEED points capable of being earned (Kula, 2005). Although vegetated roofs are assessed on the listed criteria and LEED certification increases the buildings value and occupancy rate (Oberlander *et al.,* 2002), the stringency of LEED ™ testing is difficult to determine in that standards for stormwater retention or temperature reduction are not explicit (Kula, 2005).

The building codes in Canada do not specifically address vegetated roofs (Lawlor *et al.,* 2006). For any roof, it requires assessment on structural loading, roof drainage, water proofing, wind protection, fire risks, public accessibility and exit planning (Lawlor *et al.,* 2006 p. 21). However, vegetated roofs have different physical properties than a conventional roof and a lack of technical knowledge makes fire risks and wind rating for vegetated roofs difficult to assess. Currently in British Columbia, insurance companies do not insure buildings with vegetated roofs for fear of fire risk although research has shown that vegetated roofs act as a fire retardant (Bula, 2007). In addition, adoption of German FLL vegetated roof standards are not all applicable for the North American vegetated roof industry due to differences in climate. Recently, the American Society for Testing and Materials (ASTM) has published several vegetated roof standards on load determination, growth medium permeability, growth medium water retention and plant selection and maintenance (Lawlor *et al.,* 2006). However, there is no agreement within the commercial vegetated roof sector to adopt such standards or regulatory body to enforce adoption of ASTM standards (Getter and Rowe, 2006).

1.4.15: Summary

Vegetated roof research in North America often lacks credibility, accessibility and replication (VanWoert *et al.,* 2005a). In recent years, there has been increasing amount of studies to provide much needed data for vegetated roof programs being established in the United States and Canada. Researchers have addressed issues with plant species, stormwater retention, water quality treatment, energy loss and cost/benefit analysis (Getter and Rowe, 2006). Vegetated roofs have shown to reduce total stormwater runoff by 50 % to 60 % and under certain conditions, can fully retain an individual storm event (Liu, 2003; VanWoert *et al.,* 2005a; Carter and Rasmussen, 2006). Under certain conditions where rain falls upon the vegetated roof, the growth medium can be saturated thereby delaying runoff initiation and increasing lag time. Once field capacity is reached, runoff is initiated and released at a slower rate compared to a non-vegetated roof as water flows through the multiple layers of the vegetated roof thereby, reducing runoff peak flow and extending runoff release time. Studies from North Carolina and Toronto analyzing vegetated roof runoff have shown that they are a source of phosphorus (Moran *et al.,* 2003; Jennings *et al.,* 2005; TRCA, 2006). However, older vegetated roofs in Germany have shown to retain phosphorus from atmospheric inputs (Köhler and Schmidt, 2003). Vegetated roofs also reduce suspended solid concentrations and shown not to contribute little to metal concentrations in runoff. Further, vegetated roofs have smaller metal loads than that originating from most conventional roof types (Berndsston *et al.,* 2006; TRCA, 2006). In Germany, research on an older vegetated roof has shown decreased metal concentrations in runoff compared to rainfall metal concentrations

(Köhler and Schmidt, 2003). The monetary benefits of vegetated roofs for the city of Toronto are estimated at over $ 300 million (Banting *et al.,* 2005).

Although several stormwater benefits by vegetated roofs have been shown by research, there are still many barriers to the adoption and implementation of vegetated roof technology in North America. Germany's success with the vegetated roof industry is due in part to available research, financial incentives, vegetated roof policies and legislation that encourage vegetated roof construction (Ngan, 2004; Cannata, 2005). However, due to a lack of quantifiable data, public awareness, financial incentives, standards, technical expertise, policy, costs (Hendricks, 2005; Getter and Rowe, 2006) and insurance industry skepticism (Bula, 2007) vegetated roof application in North America is hindered. In order to make progress, cities such as the city of Toronto are developing vegetated roof policy based upon regional research and interest from stakeholders (City of Toronto, 2005; Lawlor *et al.,* 2006). However, access to vegetated roof research is still limited (Getter and Rowe, 2006) and data is not always transferable due to climatic differences (VanWoert *et al.,* 2005a). As a result, there is lack of public and professional knowledge and awareness of vegetated roofs (Peck *et al.,* 1999; Getter and Rowe, 2006). Thus, regional research is needed to determine vegetated roof wet weather treatment performance and its implications for planning and stormwater management to help develop vegetated roof policy, construction standards, technical expertise and awareness in the public and private sectors.

Chapter 2: Methods

2.1: Experimental Design

A mass balance approach was used to assess the wet weather performance of an extensive vegetated roof in the City of Waterloo. The vegetated roof and the control roof were instrumented to measure precipitation inputs, storage and outflow (Figure 6). The hydrological data was collected from a series of storm events from June 2, 2006 to October 22, 2006 and used to determine the hydrologic mass balance and quantify the relative storage and loss from the vegetated roof and a control roof. Concentrations of suspended solids (SS), total phosphorus (TP), soluble reactive phosphorus (SRP), copper (Cu), zinc (Zn), chromium (Cr) and cadmium (Cd) metals were measured during a series of storm events from July 26, 2006 – October 1, 2006

The mass balance equation (Equation 1) was used

$$Q_i - (ET + Q_o) = \Delta S \qquad (1)$$

to quantify the hydrologic function of the vegetated roof. Where Q_i = precipitation, ΔS = storage, E = evaporation, T = transpiration and Q_o = runoff (Black, 1991; Mulamoottil *et al.,* 1999). A second mass balance equation (Equation 2) was used

$$M_i - M_o = \Delta S \qquad (2)$$

to quantify the contaminant concentration and storage on the vegetated roof (Fig. 11). Where M_i = mass concentration in, ΔS = Storage and M_o = mass concentration out (Black 1991; Mulamoottil *et al.,* 1999).

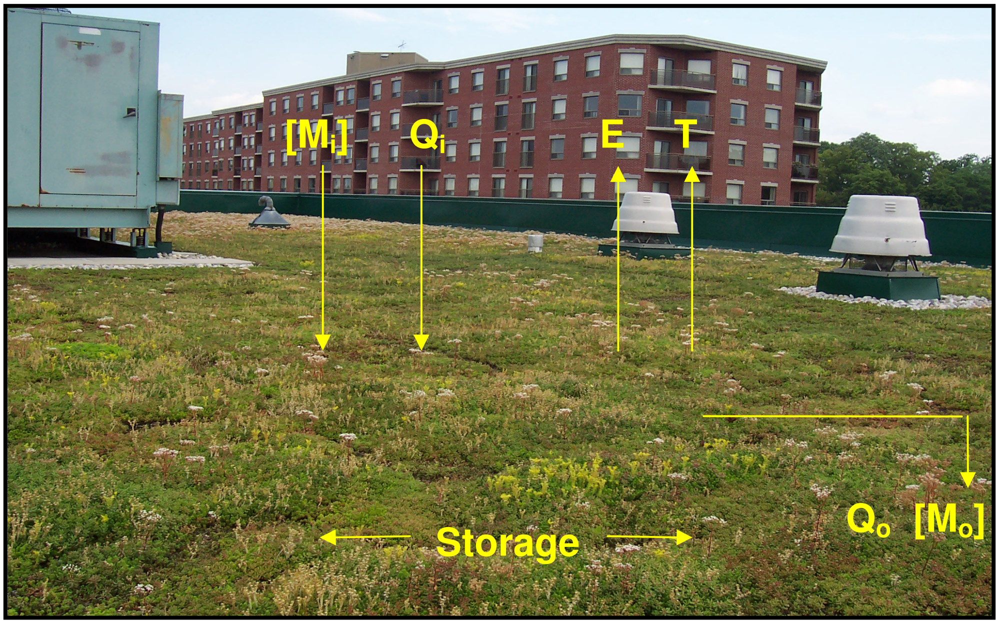


Figure 6: Conceptual Diagram of Water and Contaminant Balance on the Vegetated Roof Source: Vander Linden, 2006

2.2: Site Description:

2.2.1: Vegetated Roof Description

The vegetated and control roof are located on top of the Waterloo City Hall building in Waterloo, Ontario (43°28'02.16"N, 80°30'59.44"W). The vegetated roof was built in August, 2005, to "enhance the environment" through improvements to air quality, providing building insulation, extending roof life, reducing ambient air temperature, stormwater reduction and increases in green space (City of Waterloo, 2005, p.6). Total area of the vegetated roof is 1650 m^2 (City of Waterloo, 2005), but the portion of the vegetated roof monitored covers an area of 424.3 m^2 which drains an area of 450.5 m^2 (Figure 7). The study site was chosen because of the drain location and the direction of water flow. City surveyors determined drainage pathways which provided a basic outline of the drainage basin for the vegetated and control roof study site (Figure 8).

2.2.2: Control Roof Description

A control roof was monitored throughout the study period which is located approximately 30 m from the vegetated roof study site. The area of the control roof is 246.61 m^2 (Figure 7) and consists of a bituminous single ply roof.

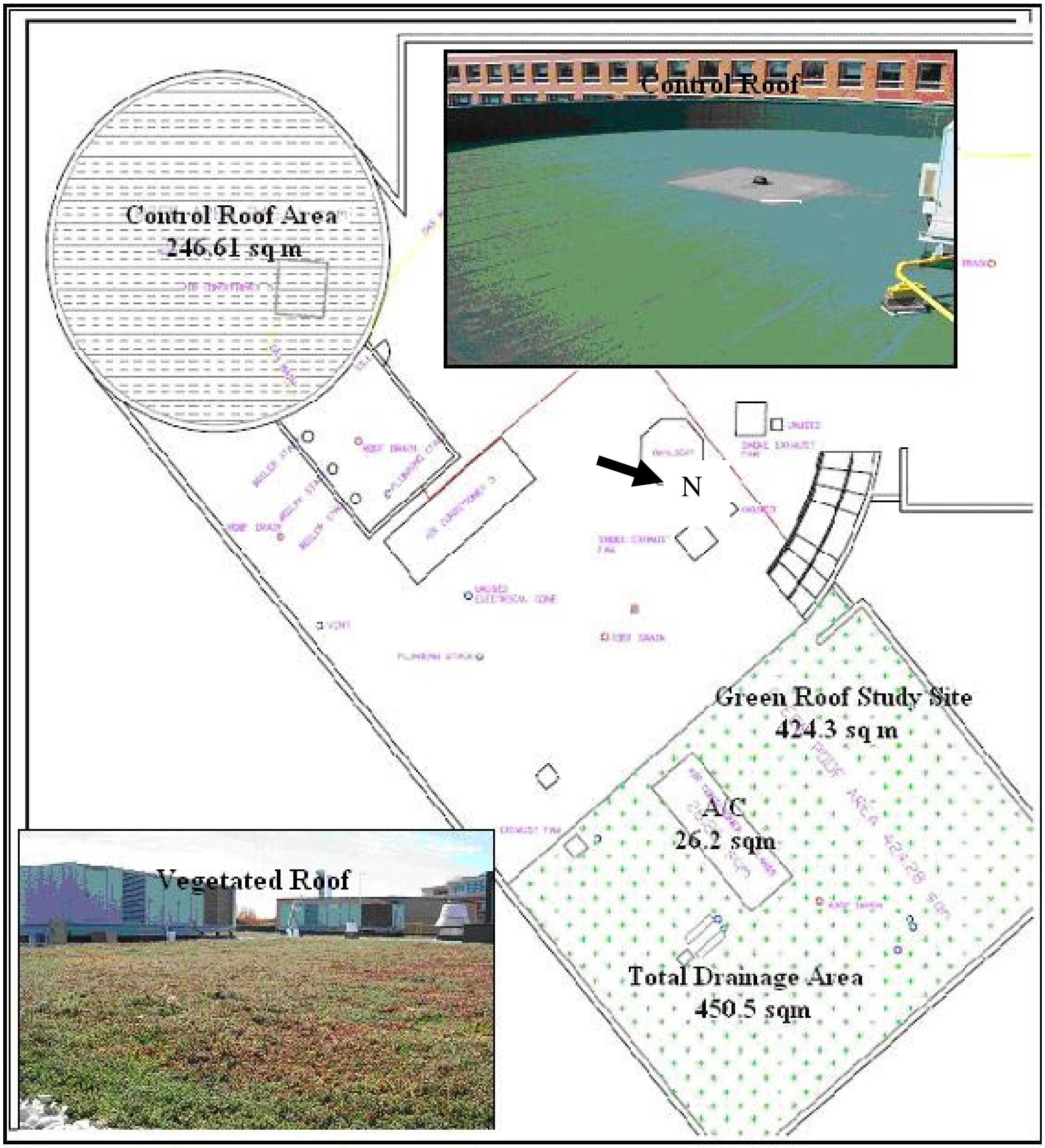


Figure 7: Area Map of the Control and Vegetated Roof at Waterloo City Hall
Source: City of Waterloo, 2006

The control roof is elevated above the vegetated roof by approximately 4 m and a wall

(Approximately 1.2 m × 0.3 m) that encloses the site permitting precipitation to drain directly into the centre of the roof (Figure 7; Figure 8).

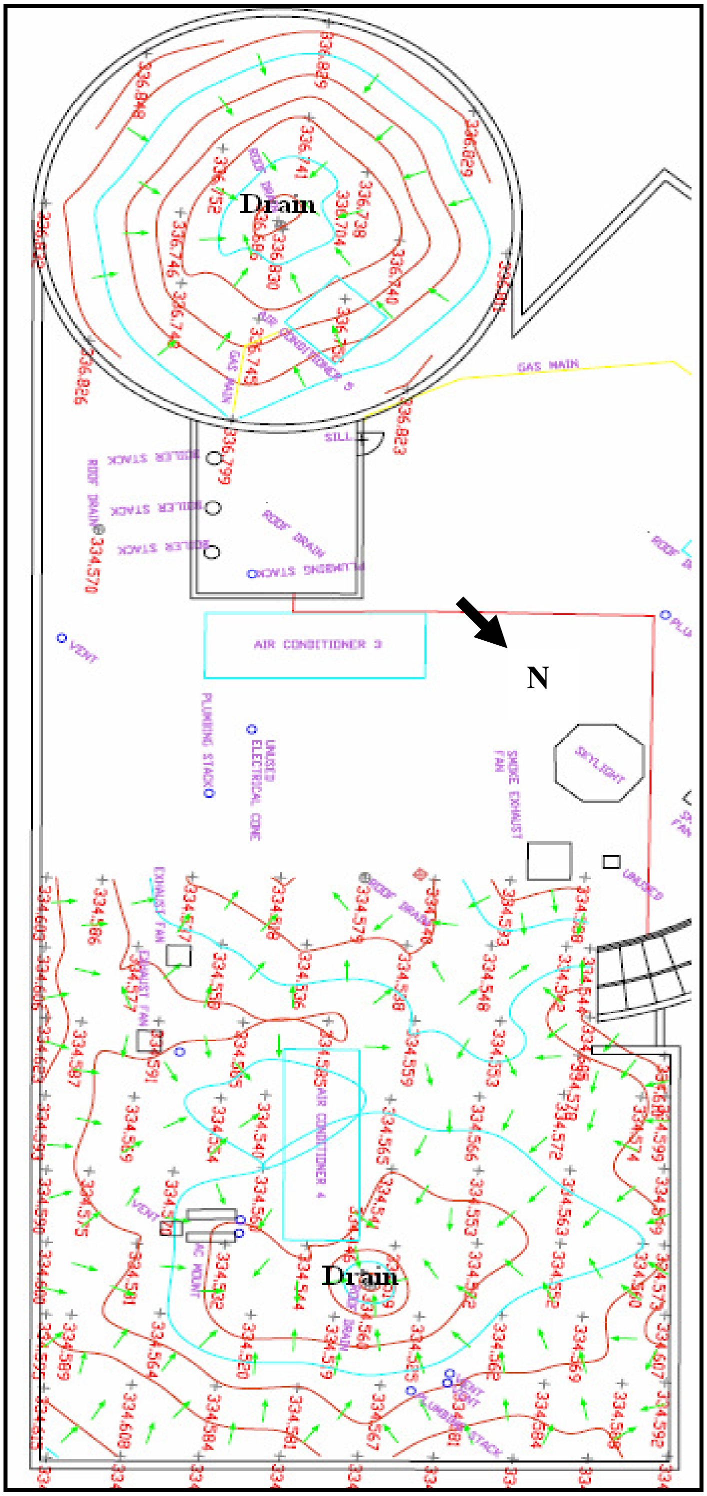


Figure 8: Runoff Flow Path of the Vegetated and Control Roofs
Source: City of Waterloo, 2006

2.2.3: Functional Layers of the Vegetated Roof

The vegetated roof consists of light weight pre-grown Sedum *spp.* vegetation mats. This product can be used on slopes of 0° to 3°. The vegetated roof is rated to meet LEED project certification for credits in stormwater management (Credit 2) and urban heat island effect (Credit 6) (Xero Flor, 2006b, p. 94). The vegetated roof consists of vegetation and growth medium, water retention fleece, drainage layer and root resistant waterproof membrane (Figure 9). The vegetation layer is composed of a *XF 301* pre-cultivated sedum-moss combination blanket which is composed of 8 species of *Sedum spp*. and nylon mesh filled with a growth substrate. The growth substrate is the *XF xero terr® growing mix* and consists of a 20 mm mineral substrate composed of 60 % porous materials (inert crushed brick, pumice or expanded slate) with a maximum particle size of 1 mm; 25 % fine washed sand; 14 % organic compost – weed free and 1 % Dolomite (Xero Flor, 2006b). Beneath the growth substrate is a 12 mm *XF 158 D* water retention fleece with a water holding capacity of 1200 g/m^2 composed of synthetic fibers of polyester, polyamide, polypropylene, and acrylic (Xero Flor, 2006b, p. 95). Underneath is the *XF 108 H* drainage filter fleece with water holding capacity of 800 g/m^2 of water which filters excess draining water. The bottom layer of the vegetated roof is the *XF 112* root resistant water membrane composed of a polyethylene sheet that prevents root and water penetration (Xero Flor, 2006b). The entirety of the vegetated roof is 6.2 cm thick, weighs 45.9 kg/m^2 and when full saturated holds 28.8 l/m^2 (Table 4).

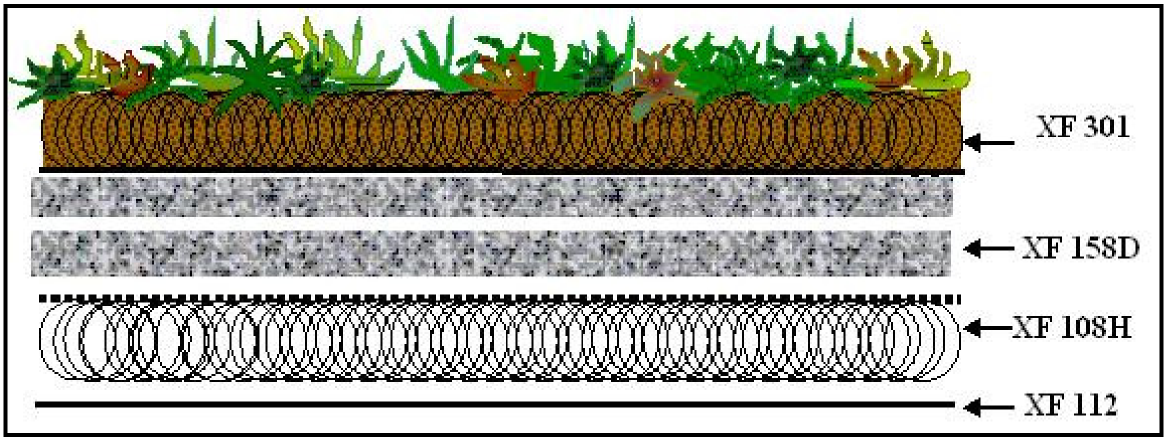


Figure 9: Functional layers of the Extensive Vegetated Roof
Source: Xero Flor, 2006b, p. 82

Table 4: Vegetated Roof Layer Thickness, Weight & Water Storing Capacity

Functional Component	Approximate Thickness of layer; (cm)	Approximate Fully Saturated Weight (kg/m^2)	Approximate Rain Depth Storage (mm)
XF 301	**3.5**	**34.5**	**19.0**
XF 158D	**1.2**	**10.6**	**9.4**
XF 108H	**1.5**	**0.8**	**0.4**
XF 112	**-**	**-**	**-**
TOTAL	**6.2**	**45.9**	**28.8**

Source: Xero Flor, 2006b, p. 82

2.2.4 Fertilizer Inputs

During the study period, the vegetated roof was fertilized once from June 2, 2006 to October 22, 2006. The slow release organic fertilizer comes in powder and granular form (Xero Flor, 2006a) and is composed of several plant and soil nutrients (Table 5). According to Joy Schmidt, President of Xero Flor Canada, fertilizer application rates are estimated at 80 g/m^2 however, nutrient loading is difficult to estimate due to variability in fertilizer breakdown.

Table 5: Fertilizer Material Components

Components	Average Values	Analysis Method
Nitrogen	8.0 %	DIN 38409-T12
Phosphorus (as P_20_2)	3.5 %	DIN 38495-T29
Potassium (as K_2O)	1.3 %	DIN 38406-T27
Magnesium (as MgO)	0.4 %	DIN 38406-T22
Calcium (as CaO)	0.5 %	DIN 38406-T22
Total Carbon	37 %	DIN 38409-T3
pH (25 °C)	6.5	DIN 38409-T5
C/N ratio	4.5	BGGK-94/11-11
Humidity	Max. 6 %	DIN 38414-T2
Organic substance	75 %	DIN 38414-T3
Residue on ignition	Max. 30 %	DIN 38414-T3
Heavy Metals (Pb, Cd, Cr, Hg, As)	Max. 100 ppm	DIN 38406-T22

Source: Xero Flor, 2006a

2.3: Meteorological Data

Data was collected with a HOBO® meteorological station (Figure 10). Wind speed was measured with a Wind Speed Smart Sensor (± 1.1 m/sec (2.4 mph)). Ambient air temperature (0.7°C at 25°) and relative humidity (±3%; ±4% in condensing environments) were measured with Temperature/RH Smart Sensor. Solar radiation was measured with a Silicon Pyranometer Smart Sensor (drift < ±2 % a year) and soil moisture was measured with a soil moisture sensor ($\pm 0.031 m^3/m^3$). Soil temperature was measured with an 8-Bit Temperature Smart Sensor (± 0.7°C at 25°C) and precipitation was measured with a tipping bucket rain gauge (±1.0 % at up to 20 mm/hour). Data from all sensors were collected with the Onset Computer Data Logger at 5 minute intervals and downloaded with a USB cable into a laptop computer displayed by HOBO® weather station software (Figure 10).

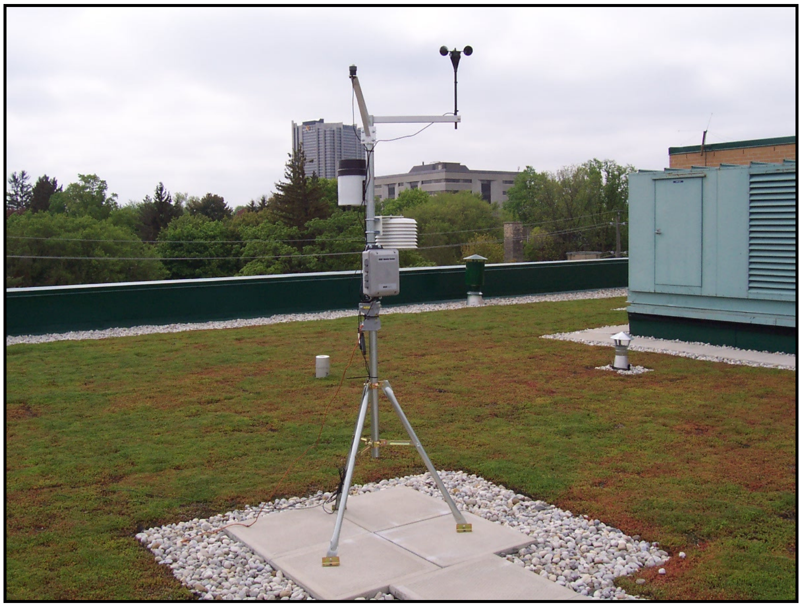


Figure 10: HOBO® Meteorological Station
Source: Vander Linden, 2006

2.4: Hydrological Data

2.4.1: Rain events: Definition and Categories

In order to distinguish between individual rain events, storms were separated by a set period of time between rain events. The present study used guidelines indicated in VanWoert *et al.,* (2005a) which required at least a 6.0 hour time period between rainfalls. However, rain events were combined if runoff was flowing from either roof at the beginning of a proceeding rain event. Rain events were categorized based upon the average storage capacity of the vegetated roof. Storm events were separated into two categories: those that were ≤ average storage capacity (3.5 mm) and those that exceeded storage capacity (> 3.5 mm).

To calculate total rainfall volume and/or total runoff volume for the drainage basin the following equation was used:

$$Q_i = (R \times D_a) \times \frac{1000\text{ L}}{1\text{ m}^3} \tag{3}$$

where Q_i is Precipitation input (L), R is rainfall depth (m) and D_a is drainage area (m^2).

2.4.2: Roof Drainage Weirs

The roof drainage system was not accessible within the building because drainage pipes ran within the walls of Waterloo City Hall drain directly into municipal storm sewers. To measure runoff from roofs, cylinder weirs were constructed and inserted and sealed with a marine sealant into the drains of both the vegetated and control roofs (Figure 11). Before weirs were inserted, drains at both study sites were cleaned and sanded. After, drains were painted with white Tremclad® Rust Proof Spray Paint to prevent further rusting and provide a clean surface.

Figure 11: Green Roof Drainage Weir
Source: Vander Linden, 2006

2.4.3: Measuring Runoff Flow

To determine runoff flow rates over the weir, several trial flows were simulated with the use of a hose, stop watch and 1 L graduated cylinder. Unknown flow rates (L/s) from a hose were determined with triplicate time (seconds) measurements to fill a 1 L graduated cylinder with water and averaged. A range of flow rates were measured and for each, a corresponding weir height (m) was measured with a 730 Bubble Module® (± 0.0015 m) (ISCO, 2003). A rating curve was created plotted with the range of flow rates and corresponding weir heights (Appendix 1). Using the rating curve, weir height measurements recorded by the ISCO 6700 were used to calculate weir flow rate where x is the recorded weir height and y is corresponding flow rate.

$$\frac{x}{0.81\ \text{m}} = \frac{y}{0.33\ \text{L/s}} \qquad (4)$$

Runoff from the roof was defined as water that crests and flows over the weir. Sampling intervals were initially measured every five (5) minutes however, these intervals were not sensitive enough to changes in rain intensity and therefore changed to every one (1) minute accordingly.

2.4.4: Temporary Storage

Both the vegetated and control roofs stored water during and after a storm event. Water that was stored on the roofs either was lost to evapotranspiration or was discharged during the proceeding rain event. Thus, water storage by the vegetated and the control roofs was temporary. The following mass balance equation was used to determine vegetated and control roof temporary storage

$$\Delta S = Q_i - Q_o \qquad (5)$$

where ΔS is storage, Q_i is rainfall inputs, and Q_o is runoff (Black et al., 1991).

2.4.5: Potential Evapotranspiration

Actual water loss from the control and vegetated roofs to evaporation could not be measured directly with available equipment. However, daily potential evapotranspiration rates could be estimated based on weather conditions on the roof of Waterloo city hall and for the region. According to Mansell (2003), it is appropriate to use the Food and Agriculture Organization of the UN Penman-Monteith equation (FAO P-M) to estimate potential evapotranspiration that accounts for aerodynamic and vegetation surface resistances. The FAO P-M requires weather measurements 2 m above an extensive grass surface with full ground cover and available moisture.

The FAO P-M equation is described as:

$$ET_o = \frac{0.408\Delta\,(R_n - G) + y\,\dfrac{900}{T_a + 273.16}\,u_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34u_2)} \qquad (6)$$

where ET_o is potential evapotranspiration (mm/day), T_a is average daily temperature (°C), u_2 is average daily wind speed at 2 m height (m/s), G is soil heat flux (MJ/m^2/day), $e_s - e_a$ is saturation vapor pressure deficit (kPa), e_s is saturation vapour pressure (kPa) given by:

$$e_s = \frac{e^o(T_{max}) + e^o(T_{min})}{2} \qquad (7)$$

where e°(T) is saturation vapor pressure and is given by the following two equations:

$$e^o(T)_{max} = 0.6108\exp\left[\frac{17.27\,(T_{max})}{T_{max} + 237.3}\right] \qquad (8)$$

$$e^o(T)_{min} = 0.6108\exp\left[\frac{17.27\,(T_{min})}{T_{min} + 237.3}\right] \qquad (9)$$

where T_{max} is maximum daily temperature and T_{min} is minimum daily temperature; e_a = actual vapour pressure (kPa) and is given by Allen *et al.,* (1998):

$$e_a = \frac{e^{o}(T_{min})\,\frac{RH_{max}}{100} + e^{o}(T_{max})\,\frac{RH_{min}}{100}}{2} \qquad (10)$$

where RH_{max} is maximum daily relative humidity (%) and RH_{min} is minimum daily relative humidity (%); Δ is the slope vapor pressure curve [kPa] (Mansell, 2003):

$$\Delta = \frac{4098\left[0.6108\exp\left[\frac{17.27\times T_a}{T_a + 237.3}\right]\right]}{(T_a + 237.3)^2} \qquad (11)$$

γ = the psychometric constant (kPa/ °C) and is given by:

$$\gamma = \frac{c_p P}{\varepsilon\,\lambda} = 0.665 \times 10^{-3} \qquad (12)$$

where P is the atmospheric pressure (kPa/°C), *cp* is the specific heat at constant pressure (1.013 MJ/kg/°C), ε is the ratio molecular weight of water vapour/dry air (0.622) and λ is the latent heat of vaporization (2.45 MJ/kg); R_n is net radiation and is a measure of the difference between shortwave and longwave radiation. Only shortwave radiation was available, however a R_n equation by Davies (1967) developed a relationship between incoming shortwave radiation and net radiation for grass and crops with reflectivity (α) value of 0.20 – 0.30. Vegetated roofs have a α value of 0.23 (Lazzarin *et al.,* 2005). The R_n equation given by Davies (1967) is

$$R_n = 0.62Q_s - 24 \text{ cal/cm}^2\text{/day} \qquad (13)$$

where R_n is net radiation and Qs is incoming shortwave radiation.

2.5: Runoff and Rainfall Sample Collection

Runoff samples from the vegetated and control roofs were collected with an ISCO 6700 ® automatic sampler (Figure. 12). The sampler contained 24 bottles, each able to hold a 1 L water sample. The sample program consisted of duplicate 200 ml samples taken every 28 L (≈1 ft^3) for the first 6 samples and duplicate 200 ml samples taken every 280 L (≈10 ft^3) for the next six samples for a total of 12 duplicate samples.

Figure 12: ISCO 6700 Automatic Sampler
Source: Vander Linden, 2006

Composite rainfall samples were collected in an 18 L bottle connected to a tipping bucket rain gauge and bucket attached to the meteorological station (Figure 13).

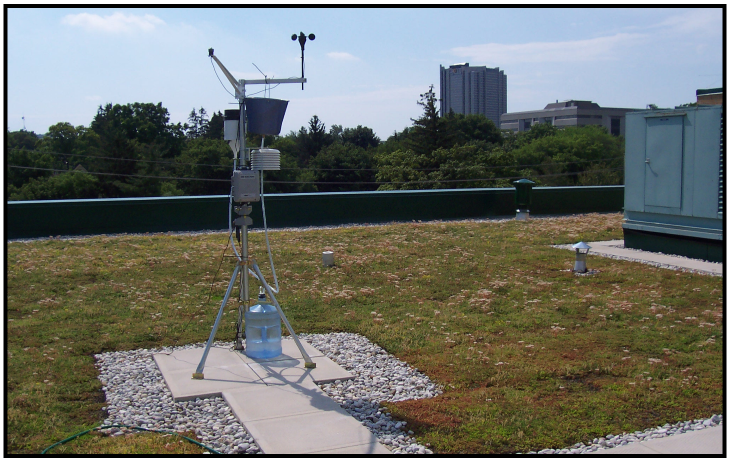


Figure 13: Meteorological Station and Rainfall Collection Equipment
Source: Vander Linden, 2006

After a storm event, samples were collected when the sampling program was completed. If the rain event took place on a Friday or on the weekend, samples were collected on the following Monday as access to the roof was not permitted on the weekends. Data recorded by the ISCO 6700® was downloaded and bottles were collected and replaced with acid washed triple rinsed sample bottles (Figure 14).

Figure 14: Water Sample and Data Collection with the ISCO 6700
Source: Vander Linden, 2006

2.6: Water Chemistry

2.6.1: Sample temperature, conductivity and pH

The temperature, conductivity and pH of each sample were measured in lab. Sample temperature and conductivity was measured with an Orion 105A+ Conductivity Meter and Orion Conductivity Cell (± 2%) following Standard Method 2510 B. The pH of each sample was measured with a calibrated Orion 250A and Orion pH triode (± 2%) according to Standard Method 4500 H^+(Eaton *et al.* eds., 1995).

2.6.2: Suspended solids and total dissolved solids

The total suspended solids concentrations were determined by filtering water samples through a pre-weighed 0.45 µm glass fiber filter. The filter and residue was oven dried at 100° C for 24 hours and weighed (Standard Method 2540 D) (Eaton *et al.* eds., 1995. The following equation was used to determine TSS (mg/L):

$$\text{TSS} = \frac{(a - b) \times 1000}{\text{Sample volume (L)}} \tag{14}$$

where *a* is initial filter weight (mg) and b is dried filter weight (mg) (Eaton *et al.* 1995). Total dissolved Solids were calculated with equation 15 where *C* is conductivity (µS/cm) and *T* (˚C) is sample temperature (APHA, 1995).

$$\text{TDS} = \left[\frac{C}{(1 + (0.02 \times (T - 25)))} \right] \times 0.666 \tag{15}$$

2.6.3: Phosphorus and Metal Analysis

Water samples collected for phosphorus and metal analysis were preserved and prepared the day of collection. For total phosphorus (TP), 100 ml runoff samples were preserved with 1 ml of 20 % Sulfuric Acid (H_2SO_4). TP concentrations were determined using the stannous chloride ammonium molybdate colorimetric method after a persulfate digestion (Standard Method 4500 P B; D). For soluble reactive phosphorus (SRP), 15 ml runoff and rainfall samples were filtered with a 0.45 µm filter into a plastic vile and stored in a refrigerator (Standard Method 4500 P A). Total and soluble reactive phosphorus concentrations were measured using a Technicon Autoanalyzer (Eaton *et al.* eds. 1995).

Dissolved metals were filtered with a 0.45 µm filter and preserved with HNO_3 to pH 2 (Standard Method 3030 B). A number of heavy metals were analyzed (Cu, Cr, Cd, Zn) with an inductively coupled plasma mass spectrometer (Standard Method 3120 B) (Eaton *et al*. eds. 1995).

2.6.4: Wet Weather Performance

The wet weather performance of the vegetated roof was determined by measuring % effluent reduction and % contaminant reduction. The following equations were used to determine vegetated roof wet weather performance

$$\%\ \text{Effluent Reduction} = 100(Q_i - Q_o)/Q_i \quad (16)$$

$$\%\ \text{Concentration Reduction} = 100(\text{Mi-Mo})/Mi \quad (17)$$

where Q_i = Precipitation Input, Q_o = Runoff, M_i = Mass of Contaminant Input and M_o = Mass of Contaminant Output (Mulamoottil *et al.,* 1999, p. 20).

2.7: Quality Assurance/ Quality Control

Quality assurance protocols described in Standard Method 1020 were followed. At least 10 % of samples per batch were duplicates and reagent blanks constituted at least 5 % of the sample. During metal, TP and SRP analysis, a minimum of 5 standards were measured at the initiation and end of analysis and a chart with standard deviation, r^2 and correlation coefficient values was given (Eaton *et al.* eds., 1995).

Quality control protocols described in Standard Methods 1030 B and C were followed appropriately. Data quality is a measure of bias and precision and overall a measure of error that incorporates two parts: error due to the method and error due the laboratory’s use of the method. Method error was determined by interlaboratory analysis and laboratory error was assessed by analysis of triplicate samples to measure standard deviation (Table 6) (Equation 18). In a few cases, only analysis of duplicate samples was possible due to time constraints and difficulty in determining the volume needed for triplicate samples for each water quality parameter after samples had been collected and prepared. When determining laboratory error the following equation was used:

$$SD = (\sum D_i / n) / 1.128 \qquad (18)$$

where SD = Standard Deviation, D_i = the difference between replication values and n = total number of samples (Eaton *et al.* eds. 1995).

Table 6: Quality Control Measurements

Water Quality Parameter	Method Detection Limit	Laboratory Error	Range
Total Phosphorus (TP)	1 µg/L	1 µg/L	1 µg/L – 205 ug/L
Soluble Reactive Phosphorus (SRP)	1 µg/L	1 µg/L	1 µg/L – 98 ug/L
Copper (Cu)	0.001 mg/L	0.017 mg/L	0.11 mg/L – 6.86 mg/L
Zinc (Zn)	0.001 mg/L	0.004 mg/L	0.05 mg/L – 2.25 mg/L
Chromium (Cr)	0.001 mg/L	0.006 mg/L	0.001 mg/L – 0.050 mg/L
Cadmium (Cd)	0.001 mg/L	0.002 mg/L	0.001 mg/L – 0.14 mg/L

2.8: Statistical Analysis

Hydrological and water quality data were analyzed with SPSS 14.0 statistical software. Descriptive analysis was performed on water quality results and Pearson correlation tests were used to assess significant relationships between roof rainfall responses and hydrological data. Since there was single paired observations across the study period, T –tests were appropriate to determine significant differences in stormwater retention rates and runoff quality results between the control and vegetated roofs.

Chapter 3: Results

3.1: Introduction

This chapter presents study limitations and reports the meteorological, hydrological and water quality data collected at the City of Waterloo vegetated roof. Meteorological data from the vegetated roof are compared to data collected at the University of Waterloo (UW) weather station and to long term averages for the Region of Waterloo (1970 – 2000). Descriptive statistics for hydrological and water quality data are reported as absolute values.

3.2: Limitations

In order to present and interpret the results of this study, the study limitations are discussed from a technical and logistical perspective. Technical problems arose from attempts to instrument the stormwater drains on the control and vegetated roofs. Storm water drains were not accessible from inside the building, so drainage weirs were constructed and inserted into the existing drains the roof surface which led to some difficulties measuring discharge. The extreme weather conditions on the roof caused several technical difficulties. On some occasions, the severe temperatures on the roof caused the battery power to drain which led to the failure of the ISCO 6700 ® auto-sampler and 730 Bubble Module®. In addition, the 730 Bubble Module ® malfunctioned on both the vegetated and control roofs in cold temperatures below 5° C missing three storm events.

Further technical problems resulted from the Flow Link ® software not being updated prior to installation of the ISCO 6700 ® auto sampler on the control and vegetated roof. The samplers were supposed to be equipped with the latest software. Consequently, sample collection failed on both the vegetated and control roofs several times until software was updated on July 21, 2006.

However, software routines for flow weighting of the sampling intervals continued to malfunction with the ISCO 6700 sampler. Thus, water quality analysis of storm runoff from the two roof treatments includes three storms events with sampling of the entire flow regime and three storm events with partial sampling of the flow regime. Sampling intervals for 6 storms are shown in Appendix 1.

The shortwave radiation sensor on the meteorological station did not work properly and therefore incoming shortwave data from the University of Waterloo's weather station was used. The station is located in Waterloo, ON, adjacent Columbia Lake on the north campus of the University of Waterloo approximately 2.5 km northwest of Waterloo City Hall with an elevation of 334.4 m (University of Waterloo, 2006). Due to the inability to measure shortwave radiation on site, only potential evapotranspiration (ET) could be measured. Potential ET calculations assume 100 % saturation of the growth medium and values can thus exceed actual rainfall and storage. Therefore, potential ET values were not applied to the mass balance equation.

Logistical problems also placed limitations on this study. For example, a micro-scale study was planned to accompany the macro-scale vegetated roof study for comparison purposes. However, securing a micro-scale vegetated roof on top of Waterloo city hall posed safety risks during high wind conditions. In addition, a small vegetated roof sample was planned for laboratory analysis to determine vegetated roof growth medium porosity, storage (field capacity) and ET rates. However, access to a vegetated roof sample was not possible and field capacity was determined by mass balance equation.

Additional logistical problems were due to restricted access to the study site. City hall personnel did an exceptional job to accommodate data collection and ensure roof top safety. However, access to the roof was limited to work hours of city hall employees and staff availability to provide access to the roof. Accordingly, water samples from Friday and weekend storm events could not be collected until the following Monday or until staff were available to allow access to the rooftop.

Despite technical and logistical difficulties, meteorological data were collected for 31 storm events, hydrometric data were collected for 18 storm events and a complete set of water chemistry is available for 6 storm events except for metal concentrations which are available for 4 storm events.

3.3: Meteorological Data:

A total of 31 rain events were monitored from May 26, 2006, to October 31, 2006. Storm magnitude varied from 0.6 mm to 48.4 mm. In Waterloo, total monthly rainfall was 28.2 mm, 136.4 mm, 72.2 mm, 113.2 mm and 113.0 mm for June, July, August, September and October, respectively (Table 7). Compared to long term averages (1970 - 2000) for the region of Waterloo, total monthly precipitation levels were above average during the months of May, July, September and October (Table 7 and Figure 15).

According to Environment Canada data, summer and autumn temperatures for the Great Lakes/St. Lawrence region were average. Compared to long term averages (1948 – 2006) for the Great Lakes/St. Lawrence region, summer temperatures increased by an average of 1.0 ºC and fall temperatures increased by an average of 0.3 ºC. In Waterloo, temperatures were characterized as moderate for summer and autumn when compared to long term averages (1970 – 2000) for the region of Waterloo (UW, 2006). However, temperatures recorded on the roof of Waterloo City Hall vegetated roof were not comparable to those measured at the University of Waterloo (Table 8). Maximum and minimum daily temperatures on the vegetated roof for June were (60.6 º C/ 2.9 º C), July (56.6 / 6.6 º C), August (51.8 / 3.7 º C), September (39.7 / -0.2 ºC) and October (27.5 / -1.1 º C) (Table 8). Average daily maximum and minimum temperatures were 45.7 / 10.6 º C, 41.22 / 15.1 º C, 40.0 / 12.0 º C, 23.3 / 9.3 º C and 17.7 / 3.4 º C for the months of June, July, August, September and October, respectively (Table 9).

Table 7: Comparison of Total Monthly Rainfall (mm) During the Sample Period

Meteorological Station Location	May	June	July	August	September	October	Total June - October
Waterloo City Hall Vegetated Roof	N/A*	28.20	136.40	72.20	113.20	113.00	463.00
University of Waterloo	113.40	32.80	152.20	52.40	117.20	131.40	486.00
Region of Waterloo Rainfall Averages (1970 - 2000)**	75.70	80.00	92.90	87.00	87.50	67.10	

* Weather Station inoperable until May 17, 2006

Source: University of Waterloo Weather Station, 2006; Environment Canada, 2006 b; 2006d

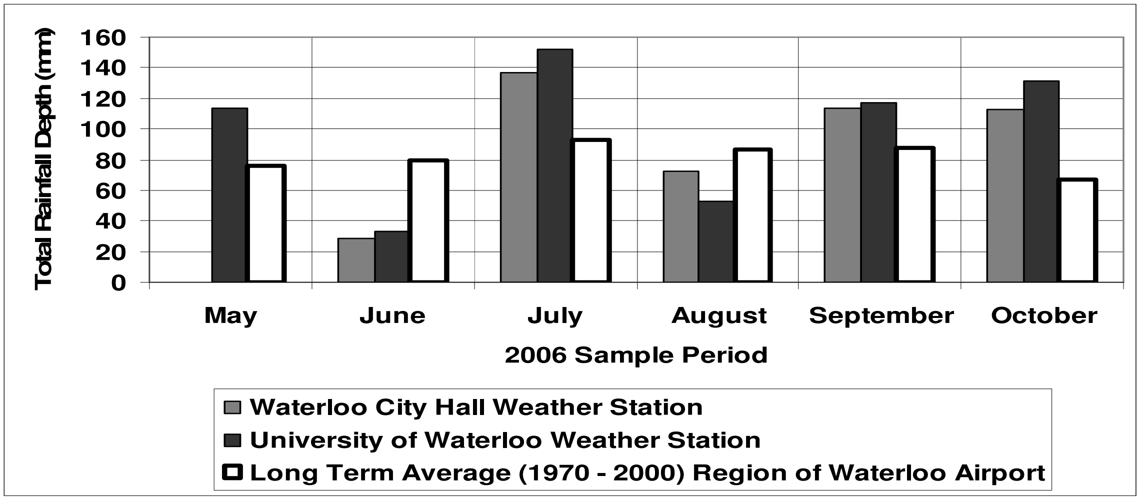


Figure 15: Monthly Precipitation Depths
Source: University of Waterloo Weather Station, 2006; Environment Canada, 2006a; 2006c

Table 8: Daily Maximum and Minimum Temperatures (˚C) from the Waterloo City Vegetated Roof and the University of Waterloo Weather Station

Month	Waterloo City Hall Green Roof Maximum and Minimum Daily Temperatures (ºC)		University of Waterloo Maximum and Minimum Daily Temperatures (ºC)	
June	60.6	2.9	31.1	6.0
July	56.6	6.6	31.9	6.0
August	51.8	3.7	33.7	7.7
September	39.7	-0.2	25.7	2.3
October	27.5	-1.1	22.6	-1.1

Source: UW, 2006

Table 9: Average Daily Maximum/Minimum Temperatures (ºC) from the Waterloo Vegetated Roof and the University of Waterloo Weather Station

Month	Waterloo City Hall Average Maximum and Minimum Temperature (ºC)		University of Waterloo Average Maximum and Minimum Temperature (ºC)	
June	45.7	10.6	23.7	13.1
July	41.2	15.1	26.9	16.9
August	40.0	12.0	24.5	13.9
September	23.3	9.3	18.6	10.3
October	14.5	2.7	12.1	3.1

Source: UW, 2006

3.4: Stormwater Retention and Storage Capacity

Retention of stormwater on the vegetated roof had absolute values that varied from 0.0 % to 100.0 % during the sample period and retention on the control roof (bituminous single ply roof) had absolute values that varied from 0 % to 16.7 % (Table 10; Figure 16; Figure 17). Overall, the vegetated roof retained 41.5 % (64.5 mm of 155.6 mm) of total rainfall and the control roof retained 3.3 % (5.1 mm of 155.6 mm) of total rainfall, a difference of 38.2 % (59.4 mm). During individual rain events, storage capacity (the volume of water retained) of the vegetated roof varied from 0 mm to 17.4 mm while storage capacity of individual storm events varied from 0 mm to 1.4 mm for the control roof. The mean vegetated roof storage capacity was 3.5 mm and mean stormwater retention was 47.6 %. The mean control roof storage capacity was 0.3 mm and absolute mean stormwater retention was 4.7 %. This represents an increase in average storage capacity and stormwater retention by the vegetated roof of 3.2 mm (42.9 %). On four occasions, the vegetated roof retained 100 % of rainfall during the month of June when a minimum of five antecedent dry days occurred between rain events. The largest storm event to be completely retained was 2.6 mm. The three other storm events did not exceed 0.8 mm (Table 10). Negative retention rates (runoff volume exceeds rainfall input) for the vegetated roof (- 25.5 %) and the control roof (- 0.3 %) were both observed during the month of October. During October, potential ET rates were low indicating that the vegetated roof was most likely to remain saturated after a storm event.

Table 10: Summary of Vegetated and Control Roof Stormwater Retention Results

Storm Event (Jul - ian Day)	Storm Size (mm)	Vegetated Roof Runoff (mm)	Control Roof Runoff (mm)	Vegetated Roof Retention (mm)	Control Roof Retention (mm)	Vegetated Roof Retention (%)	Control Roof Retention (%)	Storm water Retention Difference (%)
153-154	12.6	7.5	12.5	5.1	0.1	40.5	0.8	39.7
159	2.6	0	2.3	2.6	0.3	100.0	11.5	88.5
170	0.8	0	0.7	0.8	0.1	100.0	12.5	87.5
170	0.6	0	0.5	0.6	0.1	100.0	16.7	83.3
178	0.8	0	0.8	0.8	0.0	100.0	0.0	100.0
179-180	11.0	2.6	10.9	8.4	0.1	76.4	0.9	75.5
207	7.8	4.1	7.6	3.7	0.2	47.4	2.6	44.9
226	6.8	1.1	5.9	5.7	0.9	83.8	13.2	70.6
231	4.0	0.9	3.8	3.1	0.2	77.5	5.0	72.5
237	7.6	1.5	6.5	6.1	1.1	80.3	14.5	65.8
245-246	13.0	7.9	12.3	5.1	0.7	39.2	5.4	33.8
261	17.6	7.3	17.6	10.3	0.0	58.5	0.0	58.5
265-267	17.4	16.9	16.6	0.5	0.8	2.8	4.5	-1.7*
270	20.8	1.5	19.4	17.4	1.4	83.7	6.7	76.9
273-274	13.8	9.8	13.7	4.0	0.1	29.0	0.7	28.3
276	3.4	3.3	3.5	0.1	-0.1*	2.9	-2.9*	5.9
292	5.8	11.3	5.8	-5.5*	0.0	-94.8*	0.0	-94.8**
295	9.2	16	9.3	-6.8*	-0.1*	-73.9*	-1.1*	-72.8**
Mean	**8.2**	**5.2**	**8.4**	**3.5**	**0.3**	**47.6**	**4.7**	**42.9**
Total Jun	**28.4**	**10**	**27.6**	**18.4**	**0.8**	**64.8**	**2.8**	**62.0**
Total Jul	**7.8**	**4.1**	**7.6**	**3.7**	**0.2**	**47.4**	**2.6**	**44.9**
Total Aug	**18.4**	**3.5**	**16.2**	**14.9**	**2.2**	**81.0**	**12.0**	**69.0**
Total Sept.	**68.8**	**33.6**	**66.8**	**35.2**	**2.9**	**51.2**	**4.2**	**47.0**
Total Oct.	**32.2**	**40.4**	**32.3**	-8.2*	-0.1*	**-25.5***	**-0.3***	**-25.2****
Total	**155.6**	**91.1**	**150.5**	**64.5**	**5.1**	**41.5**	**3.3**	**38.2**

* negative retention values are shown when runoff volume exceeds rainfall volume input

** control roof retention values are greater than vegetated roof retention values

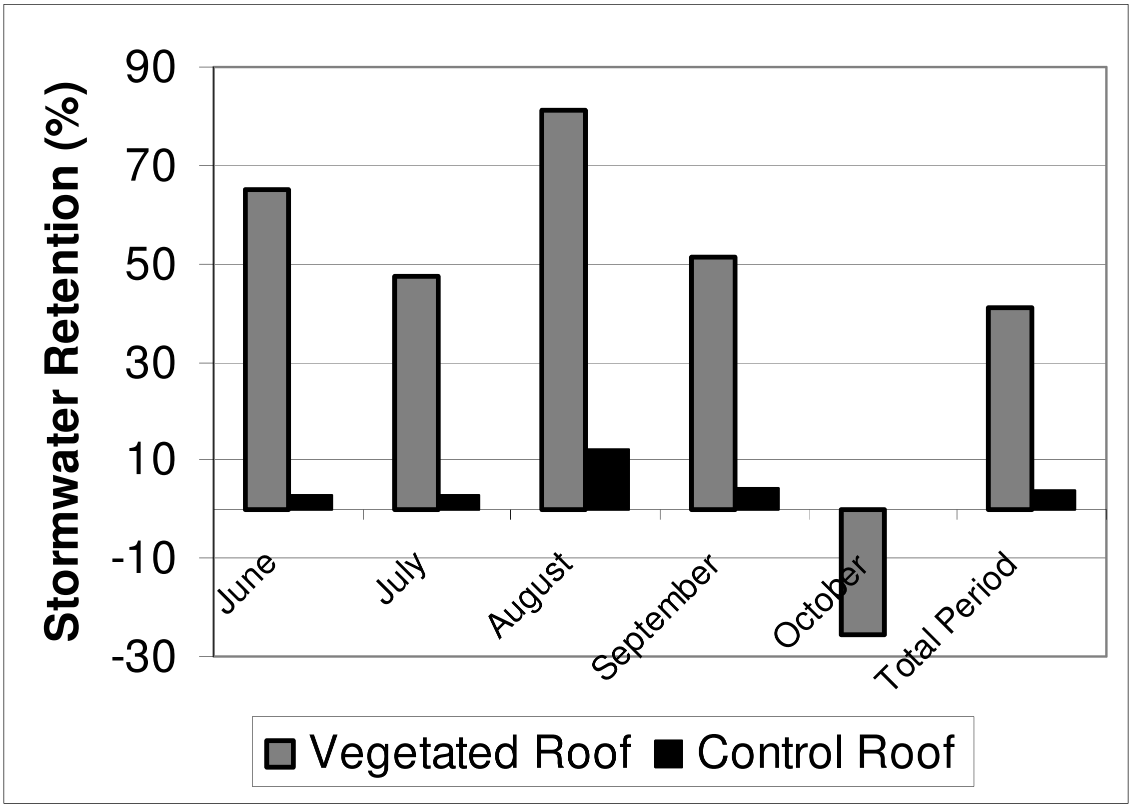


Figure 16: Vegetated and Control Roof Total Stormwater Retention Rates

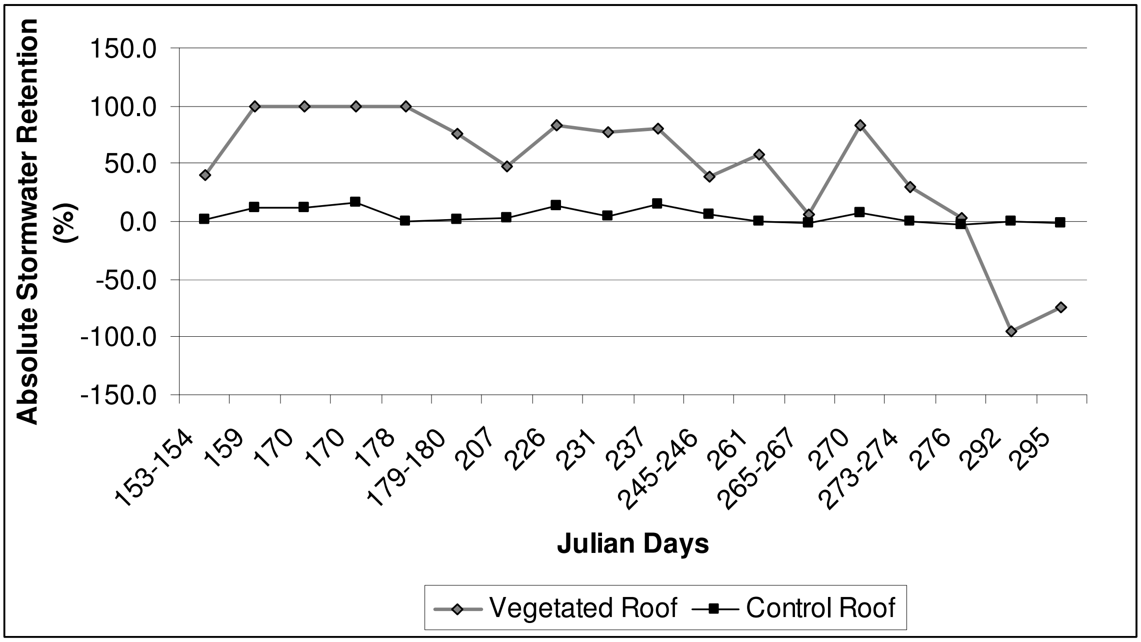


Figure 17: Vegetated and Control Roof Stormwater Retention (%) during the Study Period

3.4.1: Influence of Storm Size on Stormwater Retention and Storage Capacity

Vegetated and control roof absolute stormwater retention values varied with storm size. Increasing storm size notably decreased stormwater retention for the vegetated roof and slightly for the control roof (Figure 17). The mean storage capacity of the vegetated roof was 3.5 mm and for rain events ≤ 3.5 mm the absolute mean retention rate of the vegetated roof was 80.6 %. However when rain events were > 3.5 mm, mean vegetated roof retention decreased to 34.9 %. The control roof absolute mean retention rate was 7.6 % for storm events ≤ 3.5 mm and decreased to 3.7 % when storm events were > 3.5 mm. Overall, with increases in storm size, greater storm volumes were stored by the vegetated and control roofs. Increases in storm size caused increases in vegetated roof storage capacity while increases in control roof storage capacity were smaller (Figure 19). For storm events ≤ 3.5 mm, vegetated roof mean storage capacity was 1.0 mm and for storm events > 3.5 mm, storage capacity increased to 4.4 mm. Control roof storage capacity only increased slightly when rain events exceeded 3.5 mm with mean storage capacity increasing from 0.1 mm to 0.3 mm for storm events > 3.5 mm.

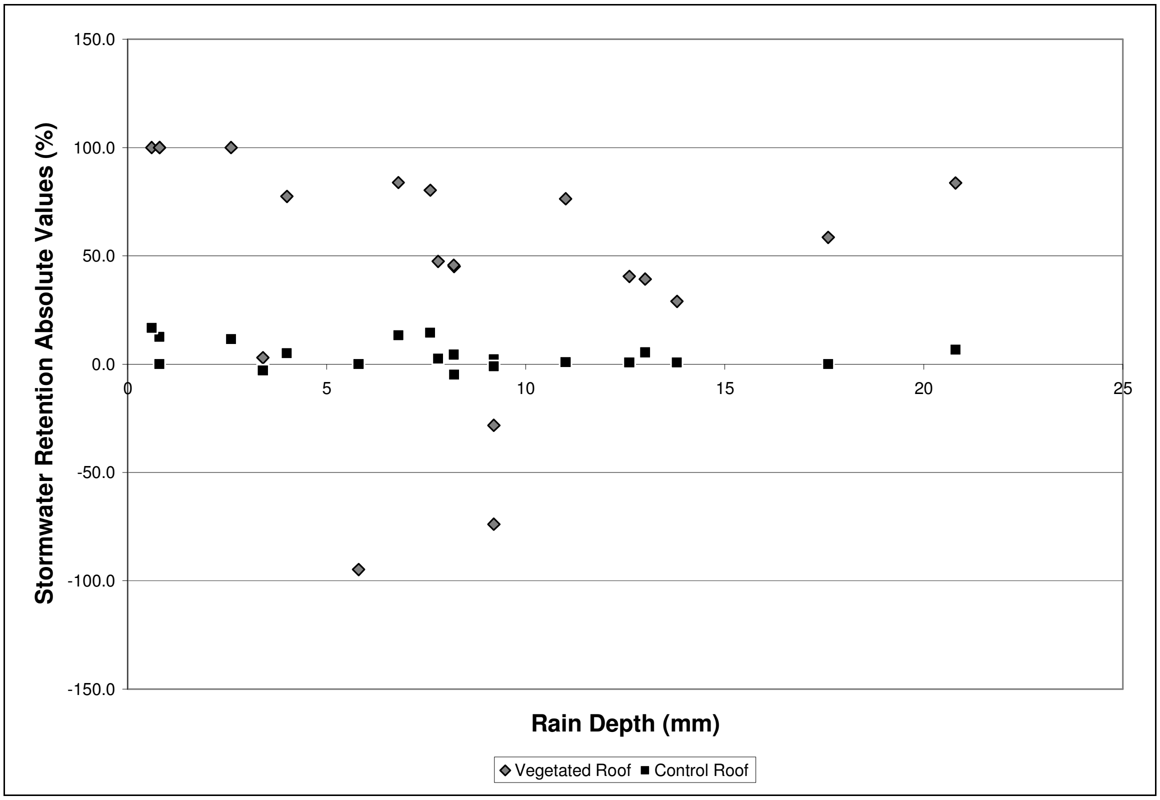


Figure 18: The Influence of Storm Size on Vegetated and Control Roof Stormwater Retention (%)

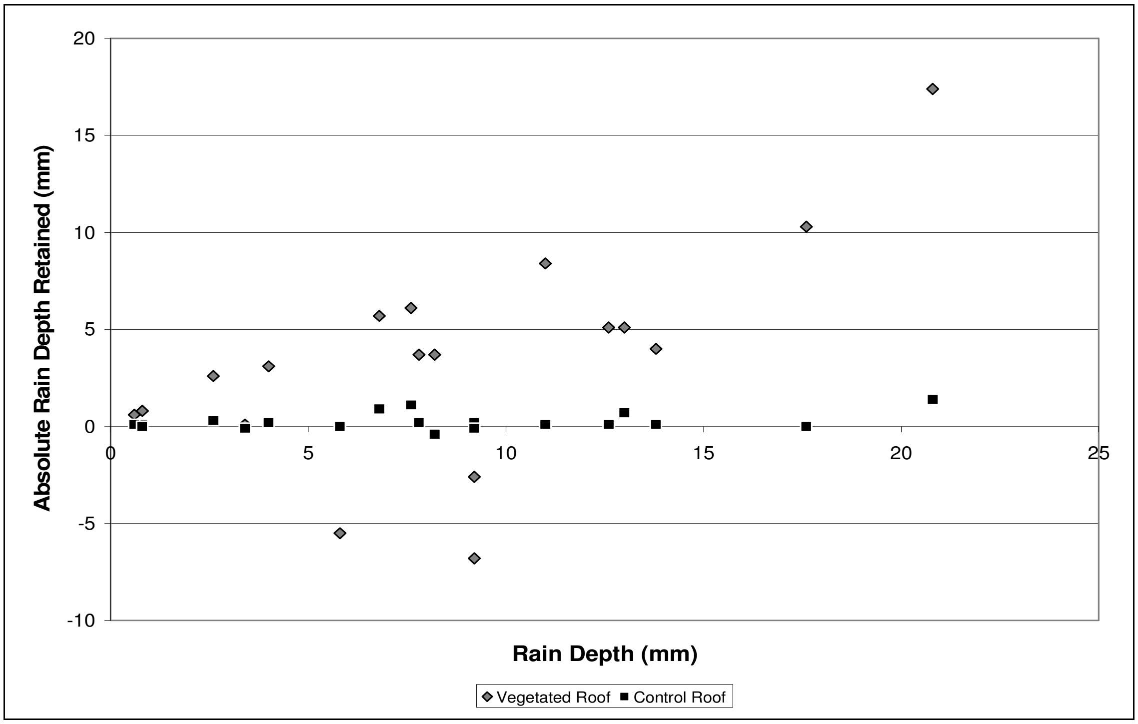


Figure 19: The Influence of Storm Size on Vegetated and Control Roof Storage Capacity (mm)

3.4.2: The Influence of Wetting History on Stormwater Retention Rates

The wetting history also influenced stormwater retention rates. Wetting history shows that storm size and frequency of prior storm events will impact vegetated roof retention of the present rain event (Table 11). Of three (3) respective rain events within a six (6) day time period, the vegetated roof had the lowest stormwater retention rate for the third and smallest rain event. On Julian day 270, a rain storm of 20.8 mm fell with 17.8 mm retained (83.7%) by the vegetated roof; on Julian days 273 – 274, a rain storm of 13.8 mm fell with 4.0 mm retained (29 %) by the vegetated roof and on Julian day 276, a 3.4 mm rain storm fell with 0.1 mm retained (2.9 %) by the vegetated roof. However, it is difficult to determine whether wetting history influenced control roof retention rates with 1.4 mm, 0.1 mm and -0.1 mm retained for the three respective rain events.

Table 11: The Influence of Wetting History on Absolute on Retention Values

Storm Event (Julian Day)	Storm Size (mm)	Vegetated Roof Runoff (mm)	Control Roof Runoff (mm)	Vegetated Roof Retention (mm)	Control Roof Retention (mm)	Vegetated Roof Retention (%)	Control Roof Retention (%)	Storm water Retention Difference (%)
270	20.8	1.5	19.4	17.4	1.4	83.7	6.7	76.9
273-274	13.8	9.8	13.7	4.0	0.1	29.0	0.7	28.3
276	3.4	3.3	3.5	0.1	-0.1*	2.9	-2.9*	5.9

***Runoff volume exceeds rainfall depth**

3.4.3: Evapotranspiration

The amount of water stored on the vegetated and control roofs is influenced by loss due to evapotranspiration (ET). Actual ET could not be measured due to technical limitations and only potential ET could be measured. Potential ET values were not applied to the mass balance equation as they can exceed rainfall and storage levels; rather they were only used as a reference. Mean potential ET rates on both roof types varied daily and are reported as absolute values (Table 12). On the vegetated roof, the mean daily potential ET ranged from 0.91 mm/day to 3.5 mm/day and from 1.3 mm/day to 5.4 mm/day for the control roof. Daily high potential ET rates from June to October ranged from 0 mm/day to 6.7 mm/day for the vegetated roof and 0 mm/day to 9.6 mm/day for the control roof.

Table 12: Potential Evapotranspiration for the Vegetated and Control Roofs

Month	**Average Daily ET Rate from the Vegetated Roof (mm/day)**	**Average Daily ET Rate from the Control Roof (mm/day)**
June	**3.5**	**5.4**
July	**3.0**	**5.0**
August	**2.7**	**4.5**
September	**0.91**	**1.5**
October	**0.90**	**1.3**

***Average potential ET Rates are based until October 20, 2006 due to missing net radiation data**

3.5: Lag Time, Peak Flow and Runoff Flow Time

The two roof types demonstrated common rain response characteristics for individual events. A representative hydrograph (Figure 20) of the two roof types illustrates that the vegetated roof increased runoff lag time, decreased runoff peak flow and increased runoff release time compared to rainfall response of the control roof. The mean vegetated roof lag time had an absolute value of 74 minutes (1.23 hrs) and the mean control roof lag time had an absolute value of 15 minutes (0.25 hrs). This is an increase in lag time by the vegetated roof of 59 minutes (0.98 hrs) or 79.7 %. The mean vegetated roof peak flow had an absolute 0.0056 L/minute/m^2 and the mean control roof peak flow was 0.0124 L/minute/m^2 which is a reduction in peak flow of 54.8 % or

0.0068 L/minute/m^2 by the vegetated roof. With decreased flow rates, the vegetated roof would sometimes increase the runoff release time by several hours. Average vegetated roof flow time was 26 hrs and 1 minutes and for the control roof 19 hrs and 48 minutes. This represents an increase in average flow time by the vegetated roof of 6 hrs and 12 minutes.

Overall, the rainfall response by the vegetated roof was more consistent with varying storm conditions. An increase in storm size and rain intensity showed greater changes in roof rainfall response from the control roof characterized by reduction in lag time and increased runoff peak flow. The roof rainfall response from the vegetated roof did not vary to the same extent with reduction in lag time and increases in peak flow.

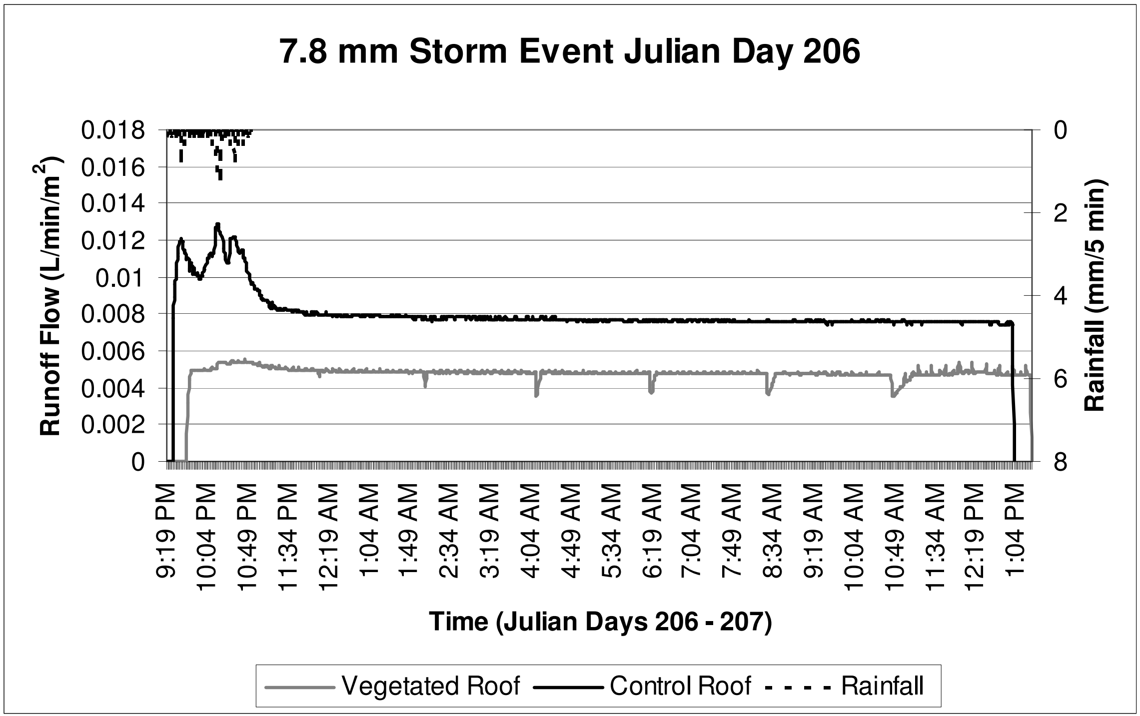


Figure 20: Roof Responses from the Vegetated and Control Roofs Julian Day 206

3.5.1 Influence of Storm Size on Rain Response Characteristics

Rainfall responses varied with storm size and roof type. Increases in storm size did not impact runoff lag time. However, storm size had an impact on peak flow from the control roof (0.0081 L/ minute/m^2 - 0.0140 L/minute/m^2) but not the vegetated roof (0.0047 L/minute/m^2 – 0.0063 L/minute m^2) (Figure 21). During rain events ≤ 3.5 mm, control roof mean peak flow was 0.0103 L/ m^2/minute and 0.0048 L/ m^2/minute for the vegetated roof. During rain events > 3.5 mm, mean peak flow from the control roof was 0.0127 L/minute/m^2 and 0.0058 L/minute/m^2 from the vegetated roof. This represents a mean peak flow reduction of 54.3 % by the vegetated roof (Table 13). Storm size also influenced runoff flow time. Larger storms increased runoff flow times from both roofs. Storm events ≤ 3.5 mm had an average runoff flow time from the control roof of 7 hrs and 12 minutes and 7 hrs and 58 minutes from the vegetated roof. Storm events > 3.5 mm average runoff flow time from the control roof was 21 hrs and 54 minutes and 29 hrs and 2 minutes from the vegetated roof.

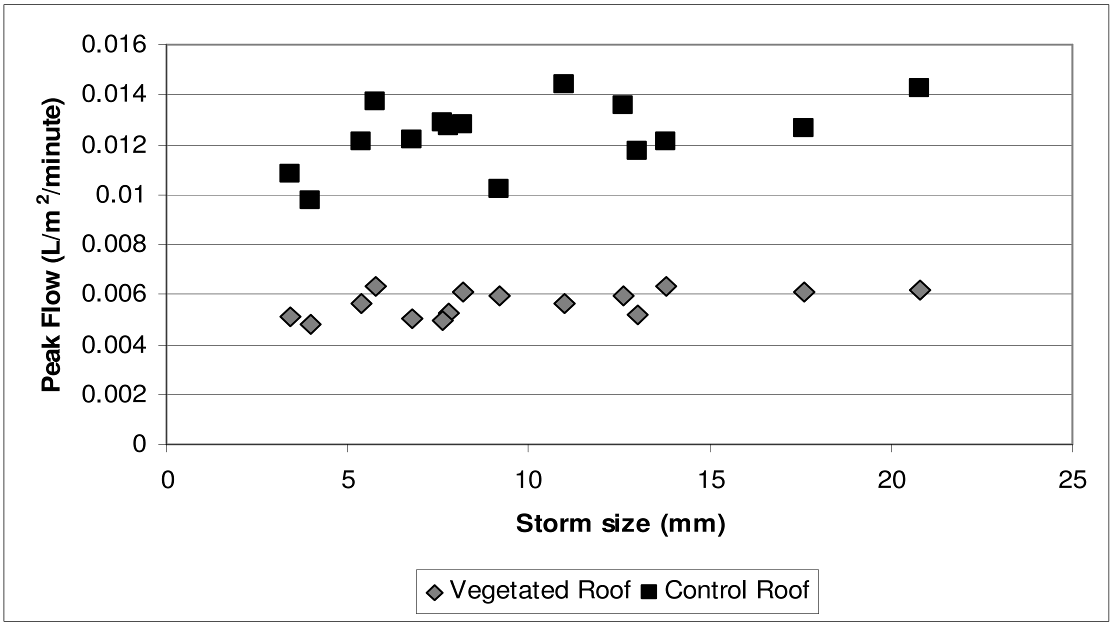


Figure 21: Influence of Storm Size on Vegetated and Control Roof Peak Discharge

Table 13: Influence of Storm Size on Vegetated and Control Roof Peak Discharge

Roof Type	≤ 3.5 mm Rain Event Flow Rate (L/minute/m^2)	> 3.5 mm Rain Event Flow Rate (L/minute/m^2)
Vegetated Roof	0.0048	0.0058 ± 0.0005
Control Roof	0.0103 ± 0.0007	0.0127 ± 0.0012

3.5.2: Influence of Storm Intensity on Roof Rainfall Responses

Runoff lag times varied with rainfall intensity (mm/hr) (Figure 22). Hydrographs (Figure 23 – Figure 25) of increasing storm intensities: 0.75 mm/hr, a 5.6 mm/hr and an 8.4 mm/hr illustrate differences in runoff delay between the vegetated and control roof treatments. When categorized into low (0 mm/hr – 2.5 mm/hr), moderate (2.6 mm/hr to 7.0 mm/hr) and heavy (> 7.0 mm/hr) storm intensities, the greatest lag time was recorded during low storm intensity for both roof types. Mean vegetated roof lag time during low intensity was 110.2 minutes (1.84 hrs) and 21.6 minutes (0.36 hrs) for the control roof. During moderate storm intensity, the vegetated roof delayed runoff by an average of 17.3 minutes (0.29 hrs) and the control roof by 8.7 minutes (0.12 hrs). During heavy storm intensity (> 7.0 mm/hr), average vegetated roof lag time was 17.5 minutes (0.29 hrs) and 0 minutes (0 hrs) for the control roof.

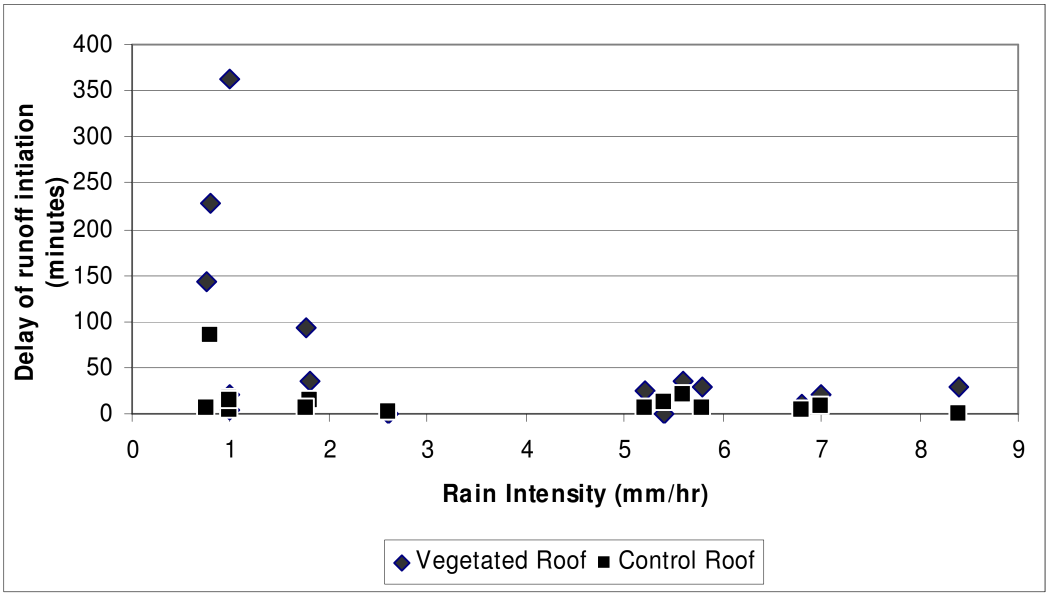


Figure 22: Influence of Storm Intensity on Vegetated and Control Roof Lag Time

Changes in storm intensity influenced peak flow. The control roof showed greater variability in peak flow as rain intensities changed (Figure 23 – Figure 25). Increasing storm intensity corresponded with increasing peak flow from the control roof while vegetated roof peak flow did not increase with greater storm intensities (Figure 26).

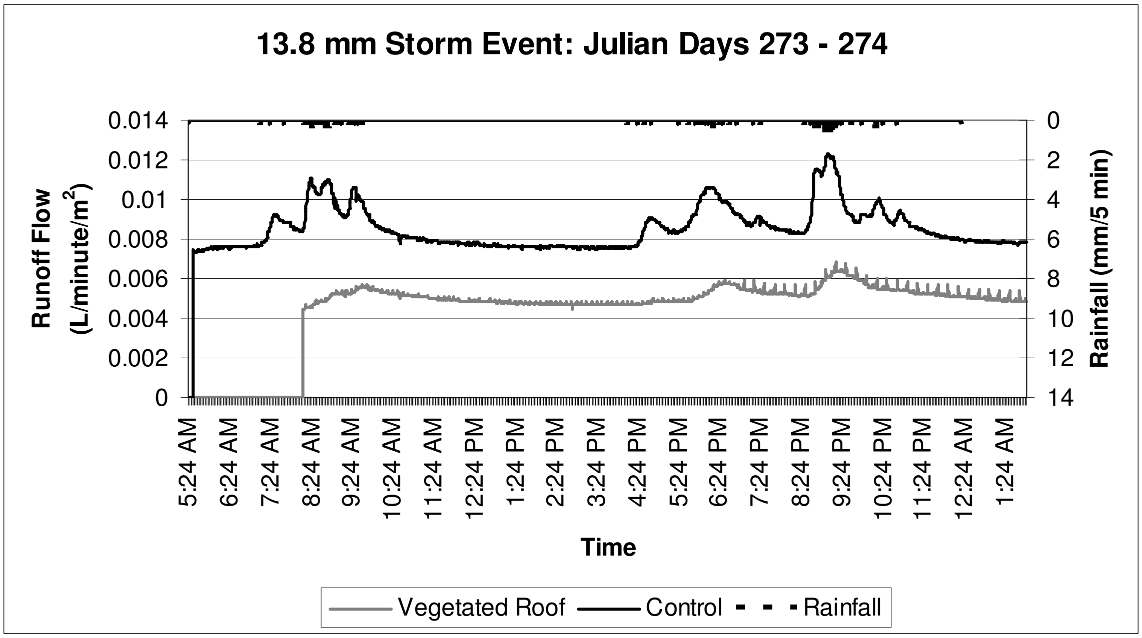


Figure 23: Hydrograph of a 0.75 mm/hr Intensity Storm Event

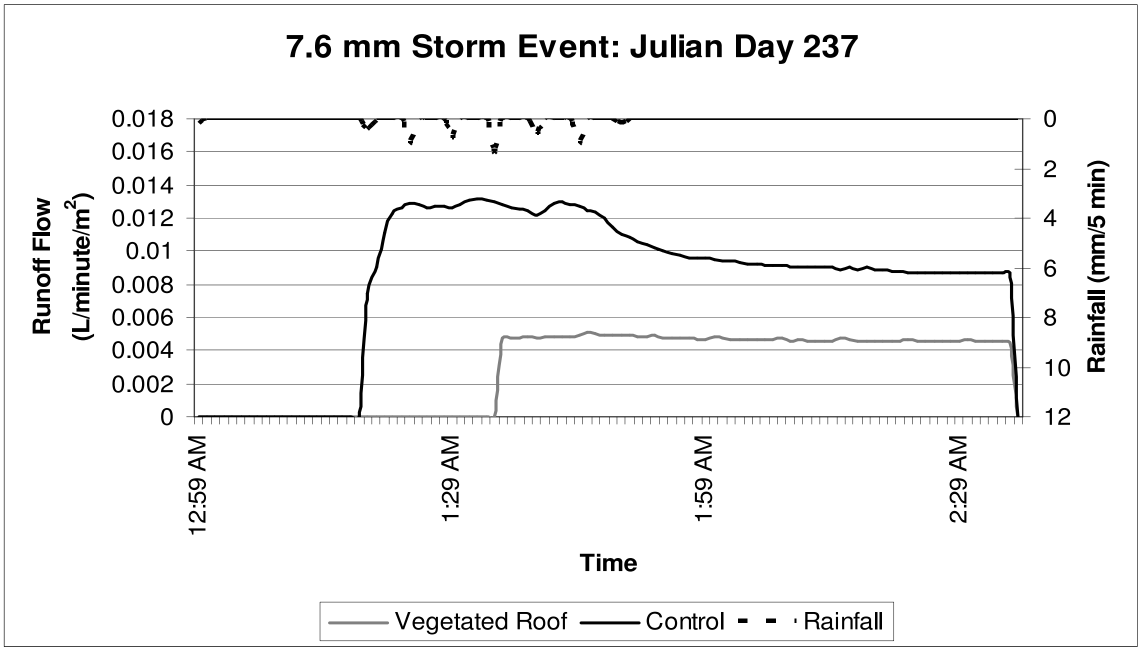


Figure 24: Hydrograph of a 5.6 mm/hr Intensity Storm Event

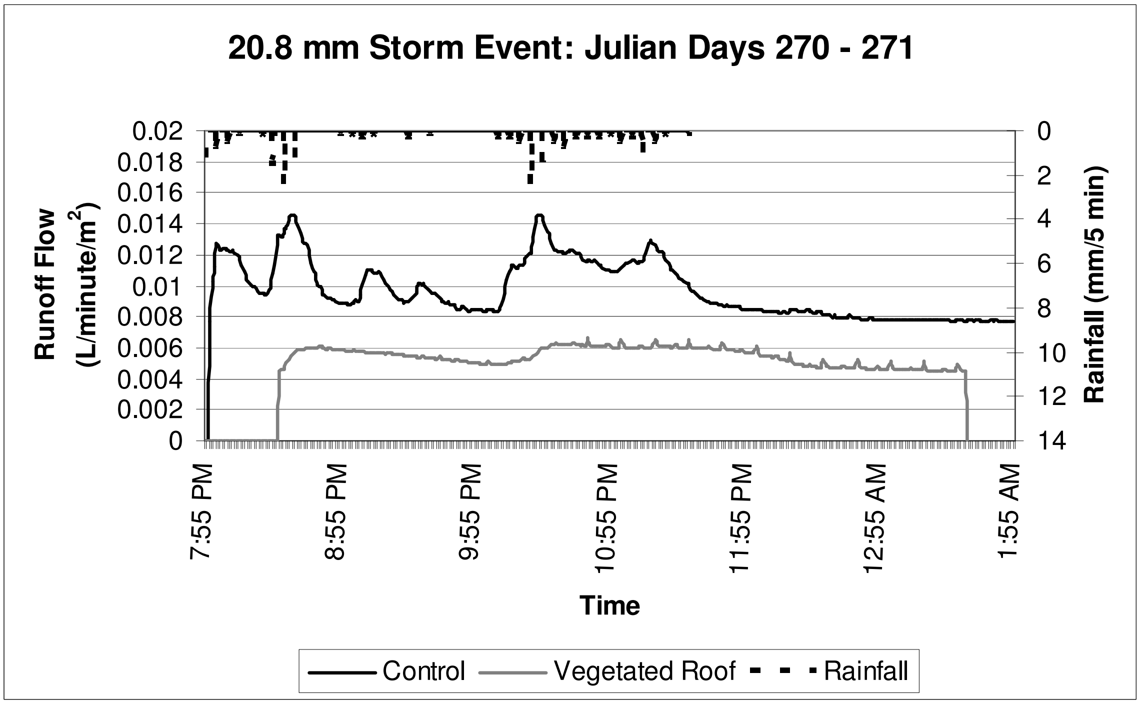


Figure 25: Hydrograph of an 8.4 mm/hr Intensity Storm Event

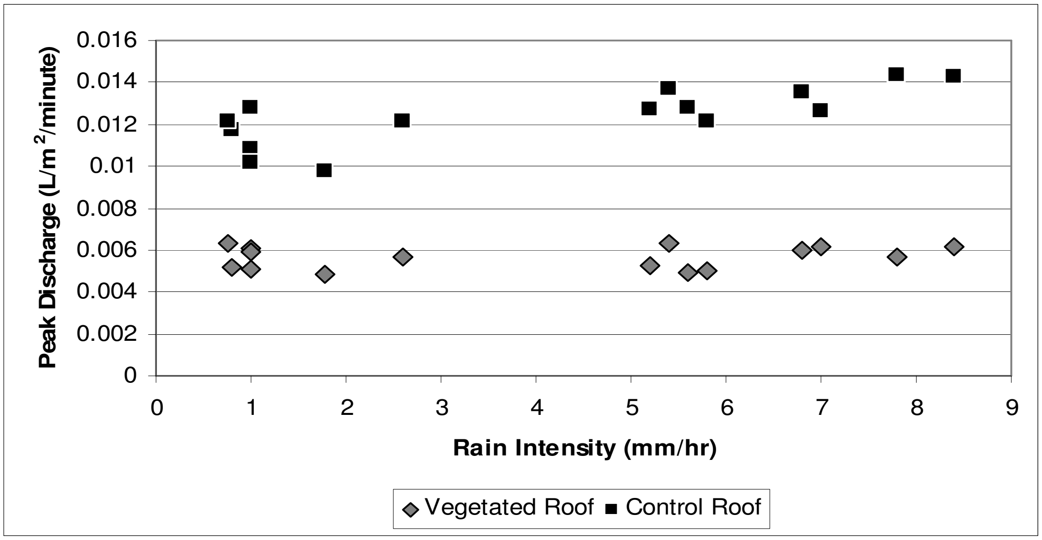


Figure 26: Influence of Storm Intensity on Vegetated and Control Roof Peak Flow

3.6: Water Quality

Several water quality parameters (pH, conductivity, sample temperature, total dissolved solids, suspended solids, total phosphorus, soluble reactive phosphorus, copper, zinc, chromium and cadmium) were measured for six storm events from July 26, 2006 to October 1, 2006 (Appendix 2) and are reported in the following sections. Values reported for each water quality parameter are absolute values.

3.6.1: pH

Vegetated roof runoff had a mean pH of 7.8 and a range of 6.8 to 8.4. Runoff from the control roof had a mean pH of 6.1 with a range of 4.0 to 7.2. The mean pH of rainfall was 6.3 with a range of 5.3 to 7.3. Overall, the vegetated roof increases runoff pH compared to the control roof.

3.6.2: Conductivity

Runoff from the vegetated roof had the highest conductivity. The mean conductivity of water samples from the vegetated roof was 181.1 µS/cm and ranged from

51.6 µS/cm to 338.0 µS/cm over the sample period. Mean conductivity of runoff from the control roof was 48.9 µS/cm and ranged from 4.7 µS/cm to 198.5 µS/cm. Rainfall samples had the lowest conductivity with a mean of 17.9 µS/cm and a range of 13 µS/cm to 33.6 µS/cm.

Runoff conductivity measured during most storm events had two characteristic trends (Figure 27). Conductivity from the vegetated roof typically increased over the storm event but conversely decreased in the control roof samples.

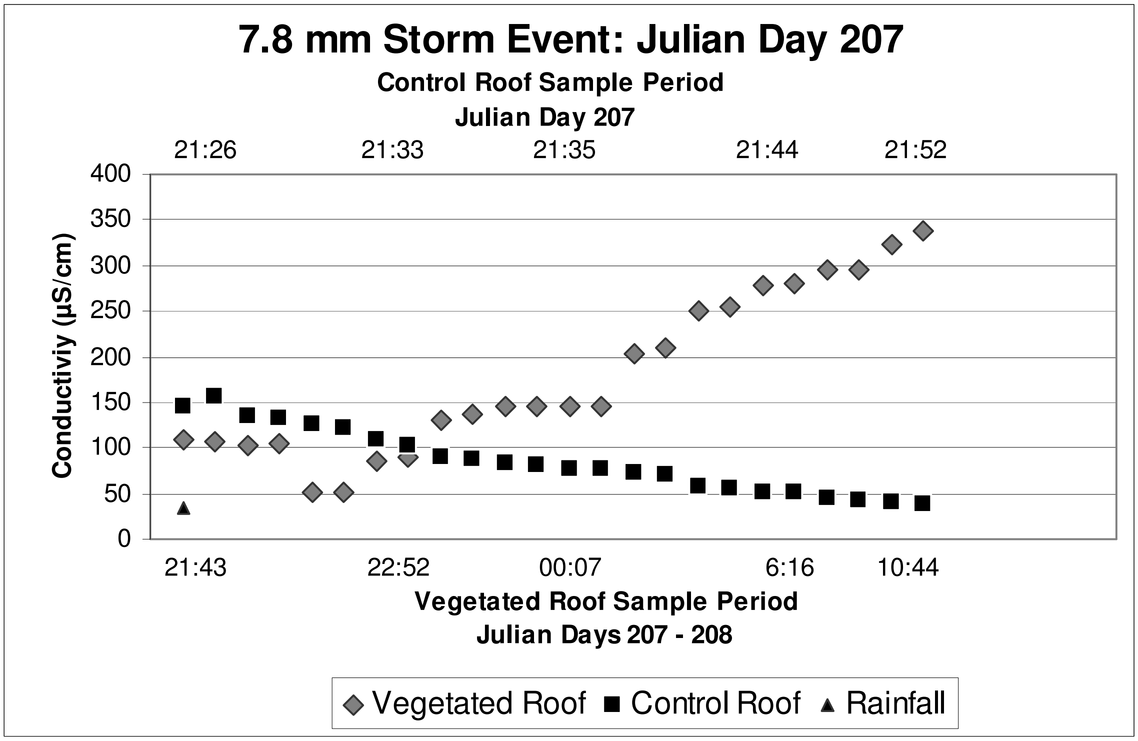


Figure 27: Conductivity in Rainfall and Runoff from the Vegetated and Control Roof

3.6.3: Sample Water Temperature

There was a slight variation in water temperature for rainfall and runoff from the two roof types. The mean temperature of the water samples from the vegetated roof was 21.1 ° C with a range of 18.3 ° C to 22.9 ° C. The control roof had a mean sample temperature of 21.3 ° C with a range of 19.5 ° C to 22.9 ° C. Rainfall's mean sample temperature was 21.2 ° C with a range of 19.6 ° C to 21.9 ° C.

3.6.4: Total Dissolved Solids

The highest concentration of total dissolved solids (TDS) was measured on the vegetated roof during the study period. The mean TDS concentration of vegetated roof was 0.131 mg/L with a range of 0.036 mg/L to 0.235 mg/L. Runoff from the control roof had a mean TDS concentration of 0.035 mg/L with a range of 0.003 mg/L to 0.144 mg/L. The TDS concentration of rainfall had a slightly higher mean of 0.013 mg/L and a range of 0.009 mg/L to 0.024 mg/L. During individual storm events, TDS concentrations in vegetated roof runoff typically increased and control roof runoff concentrations decreased over the sampling period of the storm event (Figure 28).

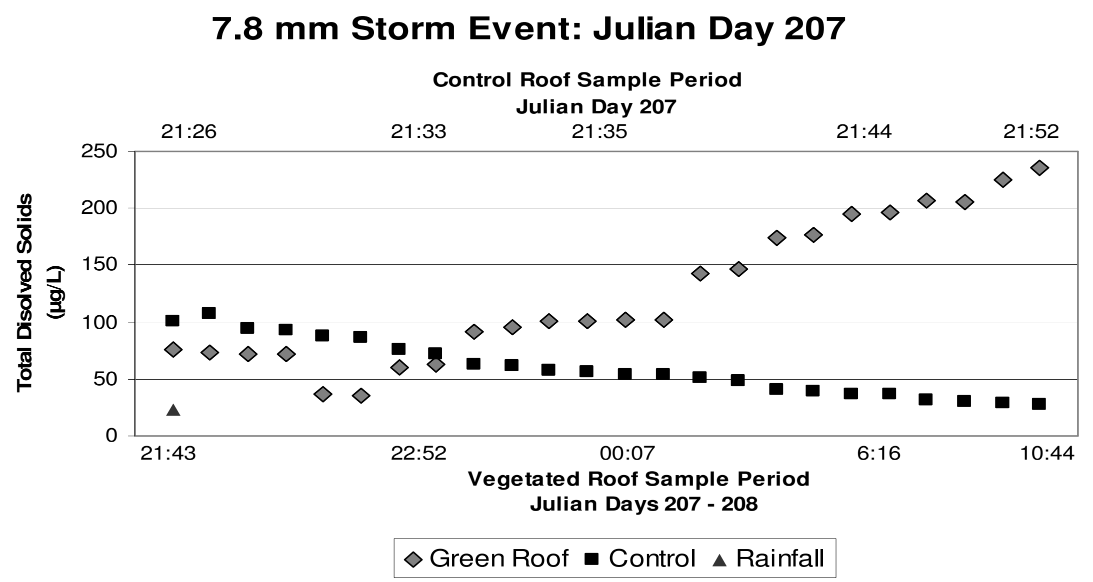


Figure 28: TDS in Rainfall and Runoff from the Vegetated and Control Roof

3.6.5: Suspended Solids

The highest mean suspended solid concentration (SS) was measured in runoff from the control roof (Figure 29). Mean SS concentration in the control roof was 8.3 mg/L with a range of 0.0 mg/L to 66.0 mg/L over the sample period. The vegetated roof had a lower mean SS concentration of 5.6 mg/L with a range of 0.0 mg/L to 15.0 mg/L. Thus, average vegetated roof SS concentration was 32.5 % (2.7 mg/L) less than control roof average SS concentration, however differences in SS concentration are not significant. Rainfall had the lowest mean SS concentration of 2.3 mg/L with a range of 0.0 mg/L to 6.5 mg/L.

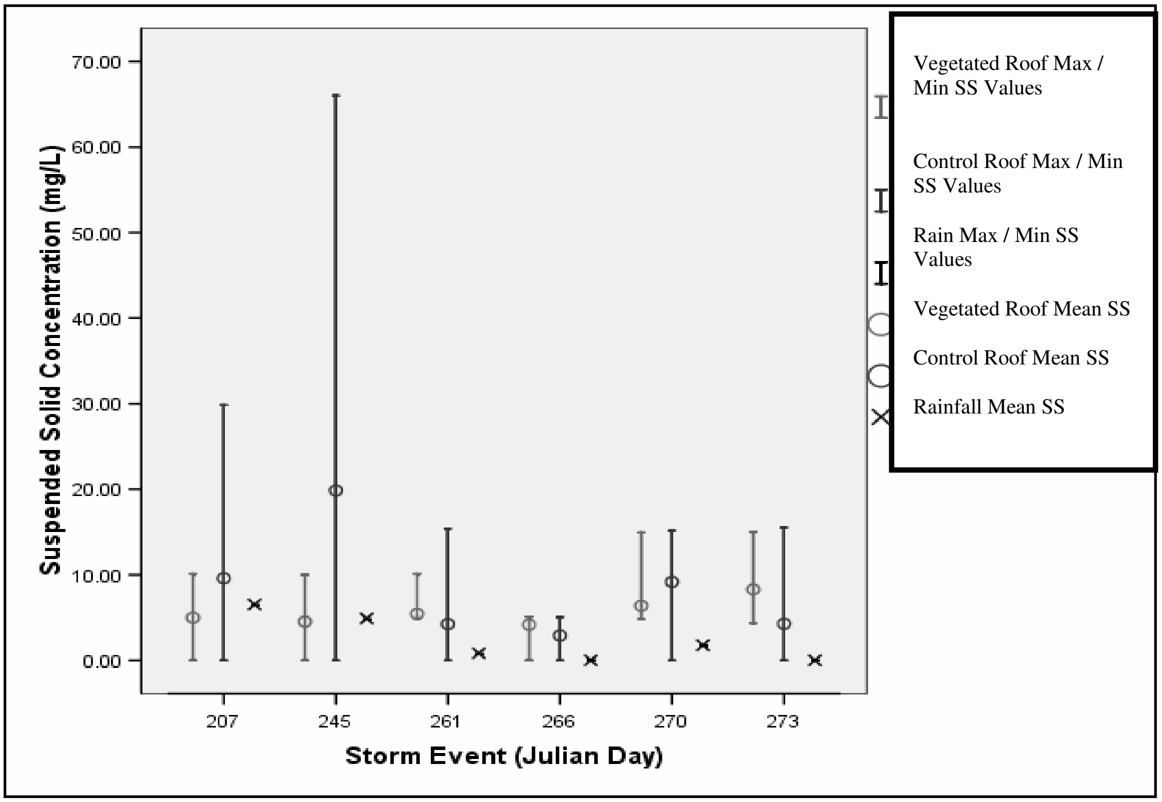


Figure 29: SS Concentrations in Rainfall and Runoff from the Control and Vegetated Roofs

The highest suspended solids concentration was typically measured at the beginning of a storm event. A representative scatter plot graph illustrates typical characteristics of SS concentration from the two roof types during a storm event where initial SS concentrations decrease over the storm event (Figure 30).

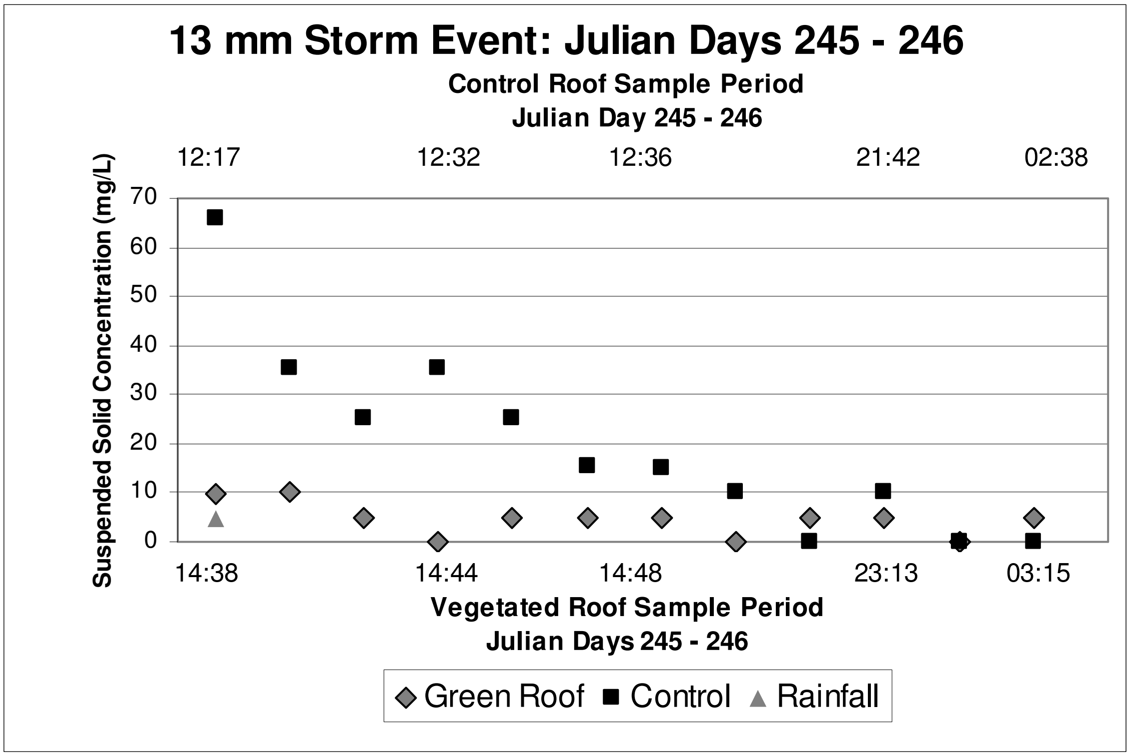


Figure 30: Comparison of Suspended Solid Concentrations in Rainfall and Runoff from the Vegetated and Control Roofs

3.6.6: Total Phosphorus

The vegetated roof was a source of total phosphorus (TP) (Figure 31) (Appendix 2). The mean TP concentration from the vegetated roof was 99.8 µg/L and ranged from 33.8 µg/L to 204.8 µg/L. The mean TP concentration in runoff from the control roof was 15.4 µg/L which ranged from 1.0 µg/L to 102.9 µg/L. The mean rainfall TP concentration was 16.9 µg/L which ranged from 4.5µg/L to 33.3 µg/L. Values < 10 µg/L were in question due to instrumental and experimental error. However, changes in mean concentration in rainfall and control roof runoff due to error would not vary significantly

(± 2 µg). Overall, the mean TP concentration of vegetated roof runoff was over five times greater than that in rainfall and four times greater than that in control roof runoff.

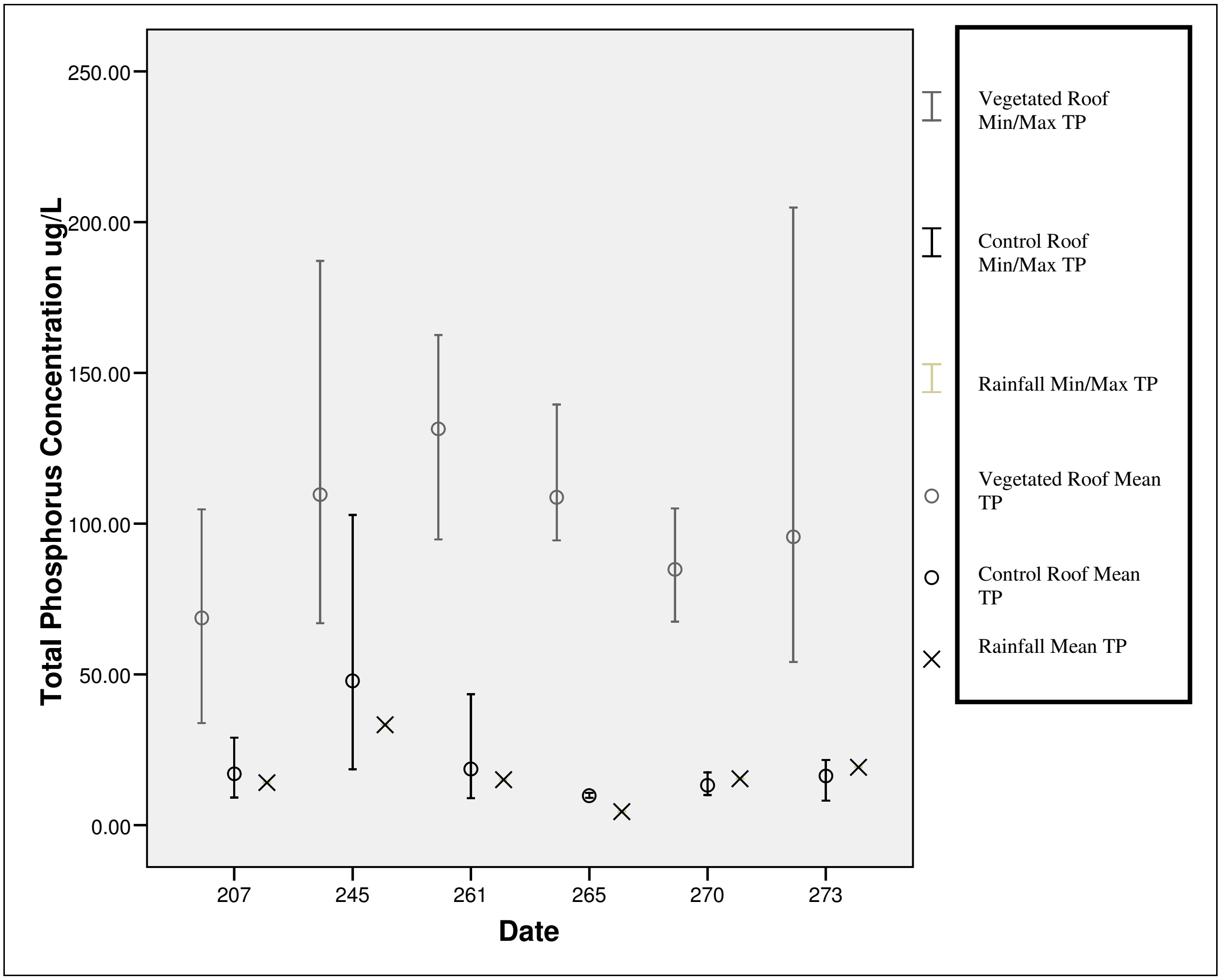


Figure 31: TP Concentration in Rainfall and Runoff from the Vegetated and Control Roofs

During individual storm events, TP concentrations from the vegetated and control roofs varied temporally over the storm event. Concentrations of TP in runoff from the vegetated roof both increased and decreased (Figure 32) over the storm event depending upon the timing and duration of the storm event. During storm events, TP concentrations in runoff from the control roof fluctuated but typically decreased over time.

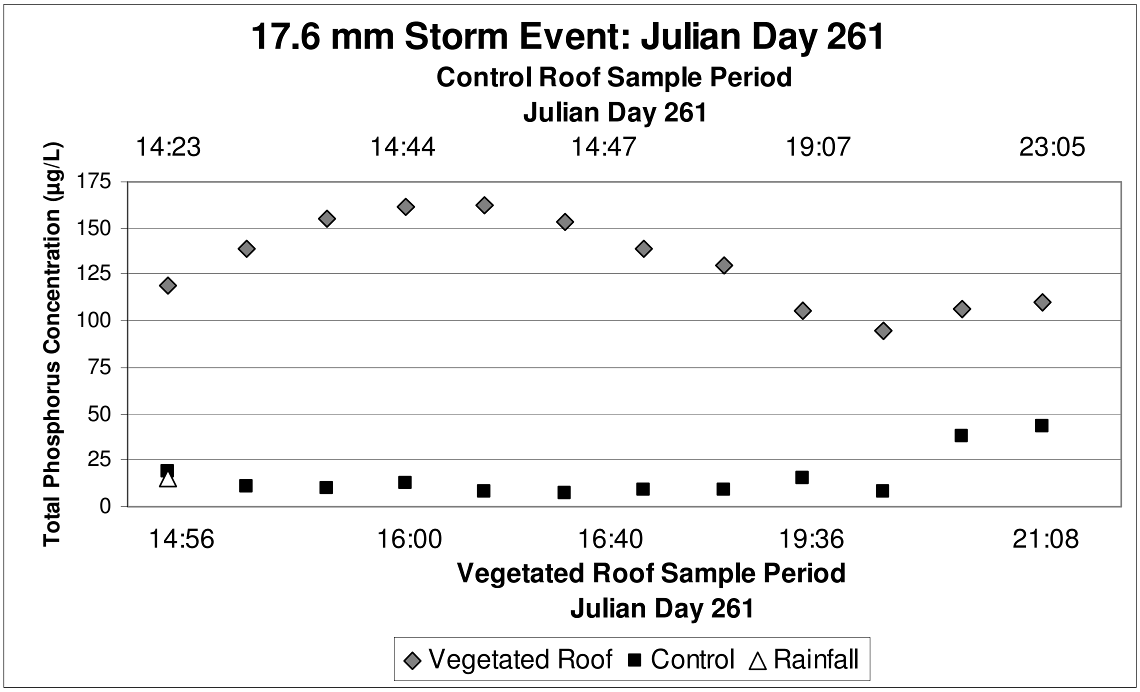


Figure 32: TP Concentrations in Rainfall and Runoff from the Vegetated and Control Roofs on Julian Day 261

3.6.7: Soluble Reactive Phosphorus

The vegetated roof was a source of soluble reactive phosphorus SRP (Figure 33) (Appendix 2). Mean SRP concentration from the vegetated roof runoff was 40.0 µg/L with a range of 7.7 µg/L to 98.0 µg/L. A majority of runoff samples from the control roof had SRP concentration below method detection limit of 1 µg/L. Mean SRP concentration of the control roof was 3.8 µg/L with a range of 1 µg/L to 12.5 µg/L. The concentration of SRP in rainfall was below the detection limit of 1 µg/L with the exception of 1 storm event which was 2 µg/L. Overall, SRP concentrations in runoff from the vegetated roof were ten times greater than that measured in runoff from the control roof and twenty times greater than concentrations measured in rainfall.

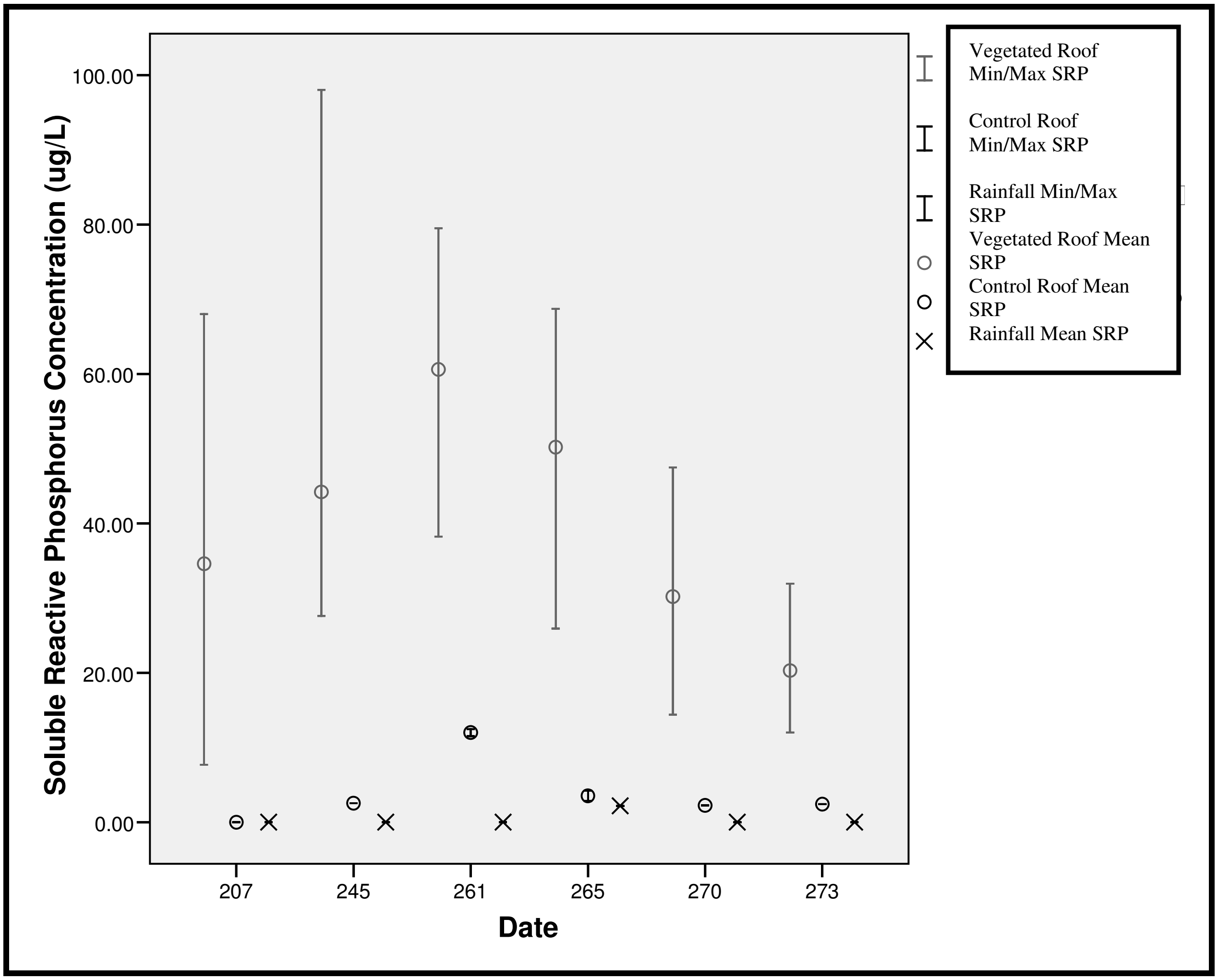


Figure 33: Soluble Reactive Phosphorus Concentrations in Rainfall and Runoff from the Vegetated and Control Roofs

3.6.8: Metals

Four dissolved metal concentrations (Cu, Zn, Cr, Cd) were analyzed in rainfall and runoff from the vegetated and control roof (Appendix 2). Levels of Cu elevated in samples from rainfall and runoff from the vegetated and control roof compared to other metals measured. Mean Cu levels in rainfall was 3.13 mg/L compared to the vegetated roof at 0.94 mg/L and control roof at 0.92 mg/L. The data suggest that the vegetated and control roofs serve as a copper sink (Figure 34). Differences in runoff and rainfall mean

Cu concentrations show that the control roof retained 2.21 mg/L (71 %) and 2.19 mg/L (70 %) for the vegetated roof.

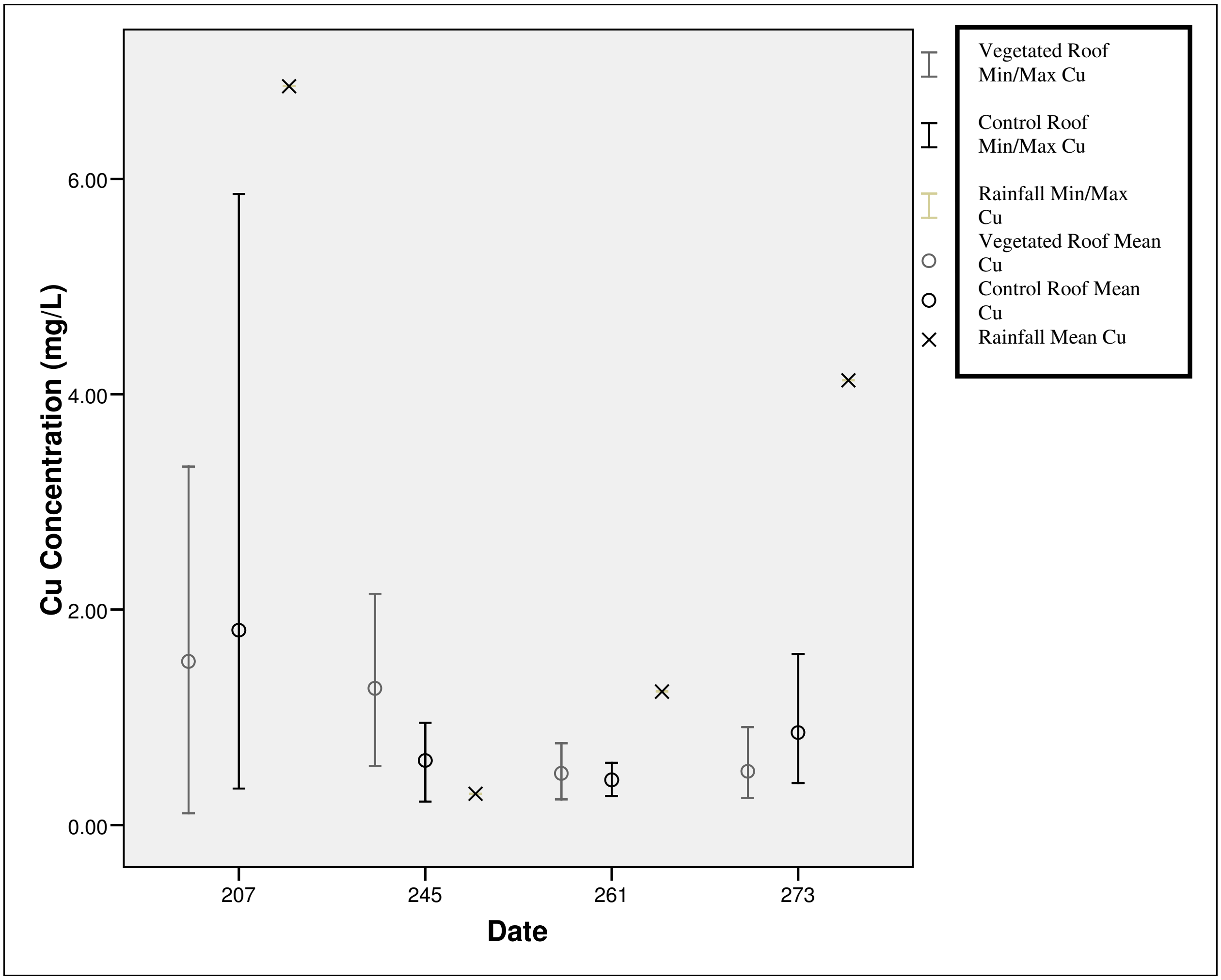


Figure 34: Cu Concentrations in Rainfall and Runoff from the Vegetated and Control Roofs

During individual storm events, copper concentrations fluctuated (Figure 35). A representative scatter plot graph of copper concentration in rainfall and runoff from the control and vegetated roofs shows copper concentrations in runoff vary during the storm event.

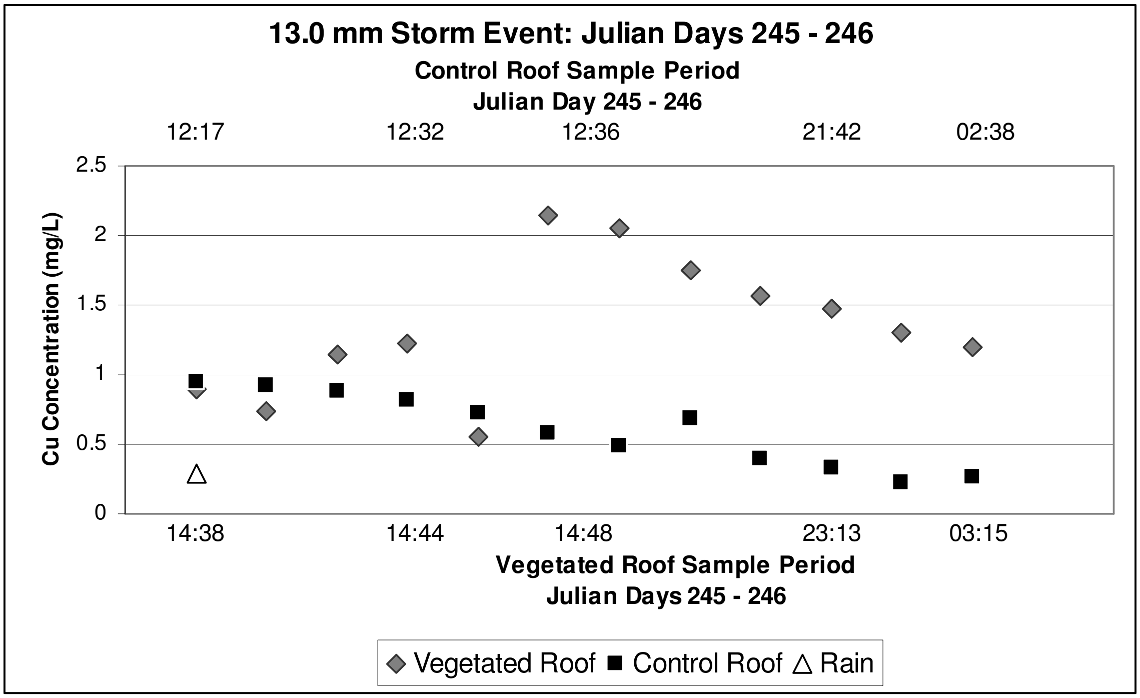


Figure 35: Cu Concentrations in Rainfall and Runoff from the Vegetated and Control Roofs on Julian Days 245 - 246

The highest mean Zinc (Zn) concentration was measured in rainfall (1.29 mg/L) (Figure 36; Appendix 2). Mean Zn levels in rainfall ranged from 0.81 mg/L to 2.25 mg/L. Overall mean Zn concentration in control roof runoff was at 0.42 mg/L with a range of 0.26 mg/L to 0.67 mg/L. The vegetated roof runoff had the lowest overall mean Zn concentration of 0.24 mg/L with a range of 0.09 mg/L to 0.39 mg/L. Differences in rainfall and runoff mean concentrations show that the Zn trap efficiency of the vegetated roof was 81.4 % (1.05 mg/L) and 66.1 % (0.82 mg/L) for the control roof. Thus, the vegetated roof showed an improved trapping efficiency of 15.3 % (0.23 mg/L) compared to the control roof.

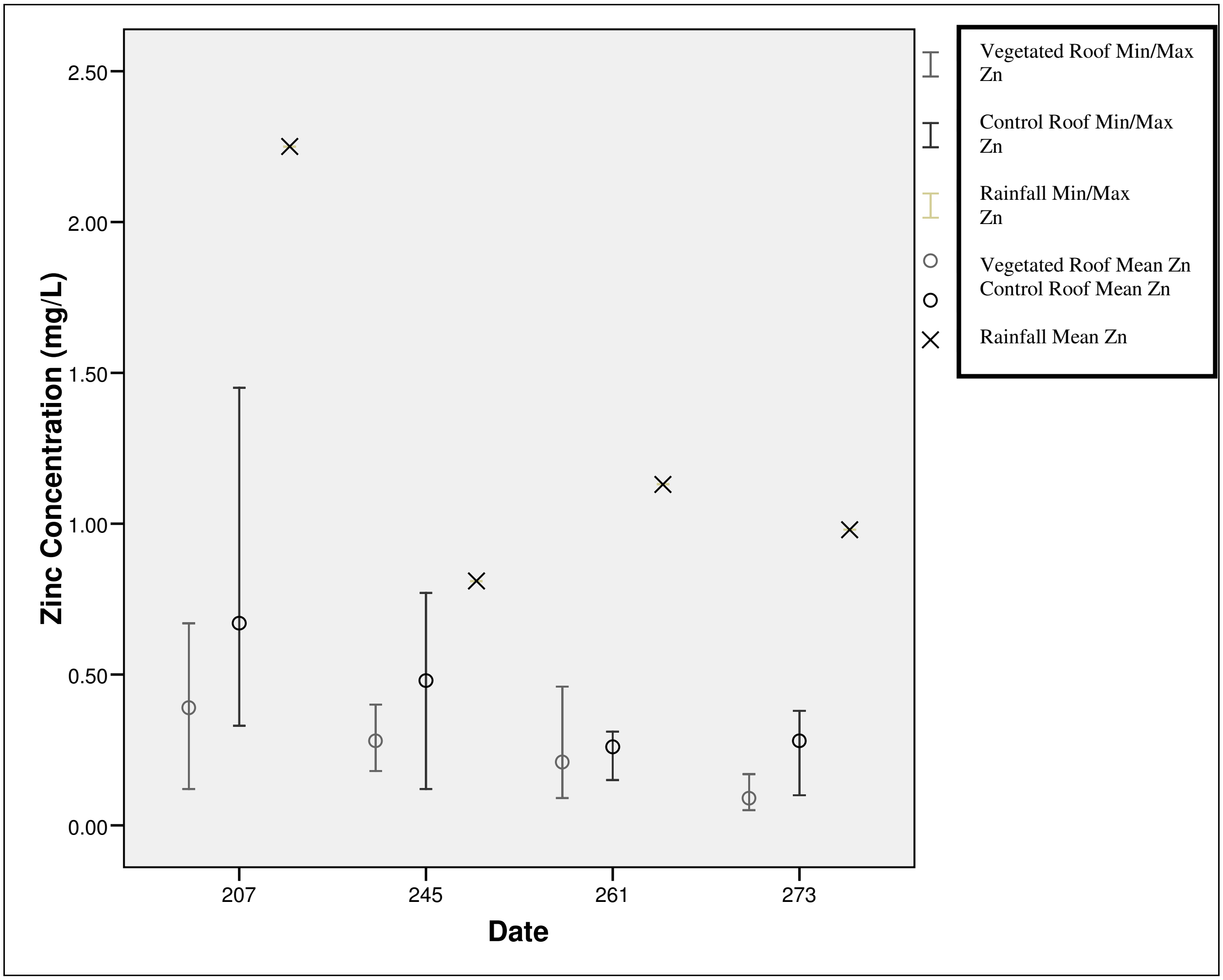


Figure 36: Zn Concentrations in Rainfall and Runoff from the Vegetated and Control Roofs

During individual storm events, the most notable changes in metal concentrations were seen in runoff from the control roof. A representative scatter plot graph (Figure 37) illustrates a decrease in zinc concentration in runoff from the control roof over the duration of the storm event. A decrease in zinc concentration in runoff from the vegetated roof is also apparent, however not to the same extent as is apparent in control roof runoff.

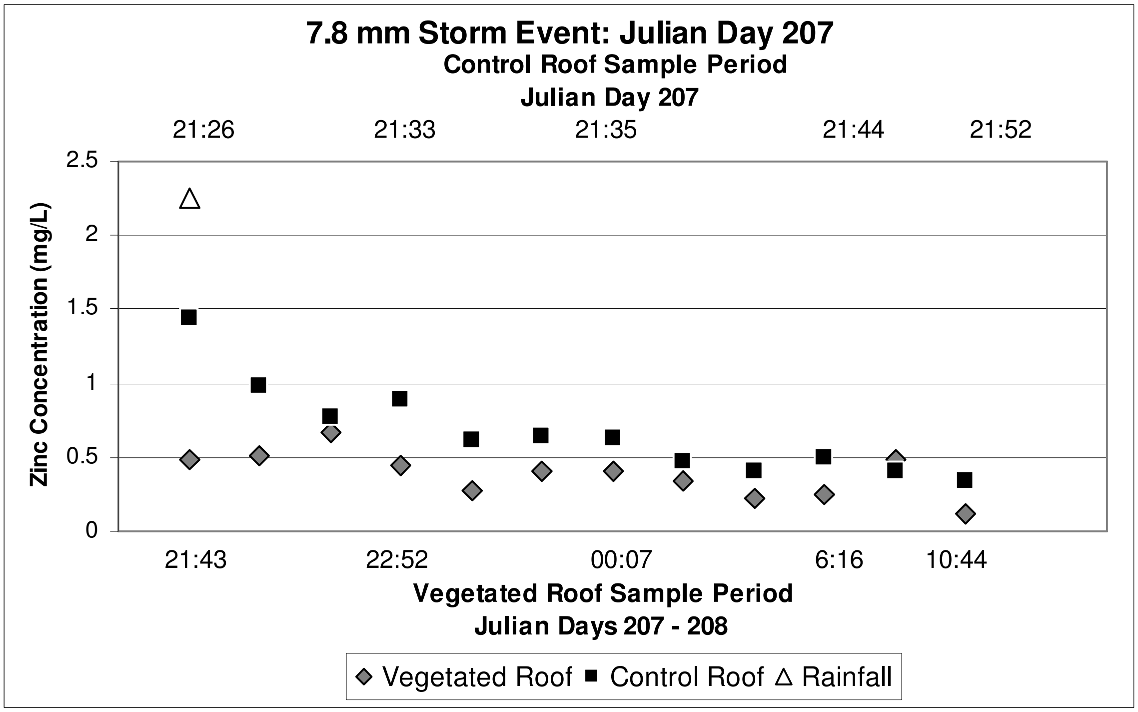


Figure 37: Zn Concentrations in Rainfall and Runoff from the Vegetated and Control Roofs on Julian Day 207

There were no large differences in Cr concentrations in rainfall and runoff from the control and vegetated roofs (Figure 38). Mean Cr concentration in rainfall and runoff from the control roof was 0.11 mg/L and 0.10 mg/L for the vegetated roof runoff. Cr levels ranged in rainfall from 0.06 mg/L to 0.13 mg/L, 0.08 mg/L to 0.13 mg/L for the control roof and 0.04 mg/L to 0.13 mg/L for the vegetated roof. Overall, the vegetated roof showed to be a Cr sink.

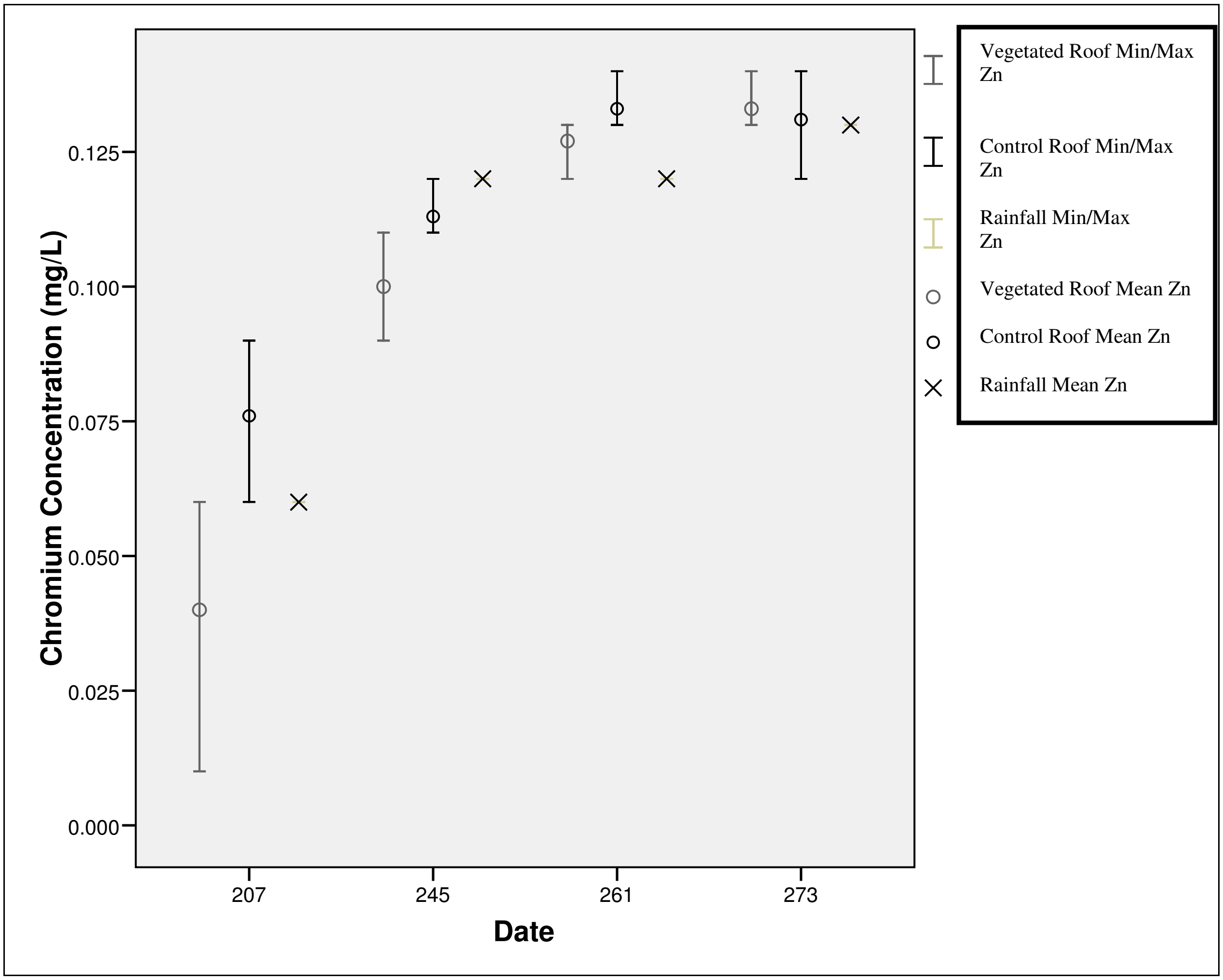


Figure 38: Cr Concentration in Rainfall and Runoff from the Vegetated and Control Roofs

During individual storm events, there were small changes in chromium concentrations over the period of the storm event in runoff from the control and vegetated roofs. A representative scatter plot illustrates chromium concentrations in rainfall and runoff from the two roof types (Figure 39). Chromium concentrations tended not to decrease or increase markedly over the sampling periods of the storm events.

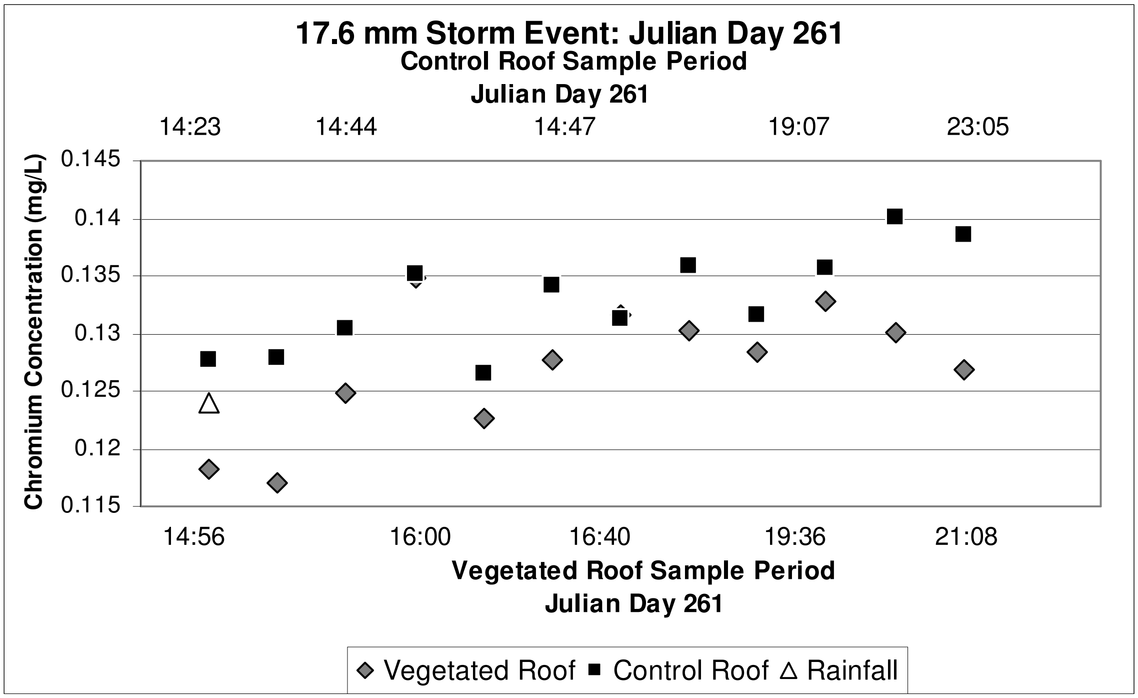


Figure 39: Cr Concentrations in Rainfall and Runoff from the Control and Vegetated Roofs on Julian Day 261

Cadmium levels in rainfall and runoff were lower than Cu, Zn, and Cr and often below detection limit. Rainfall and runoff from the two roof types all had a mean Cd concentration of 0.03 mg/L. Over the sampling period, mean Cd concentrations in rainfall and runoff increased incrementally for each storm event (Figure 40). Mean Cd concentrations in runoff from the vegetated roof ranged from 0.01 mg/L to 0.04 mg/L; runoff from the control roof: 0.02 mg/L to 0.04 mg/L and rainfall: 0.00 mg/L to 0.05 mg/L (Appendix 2).

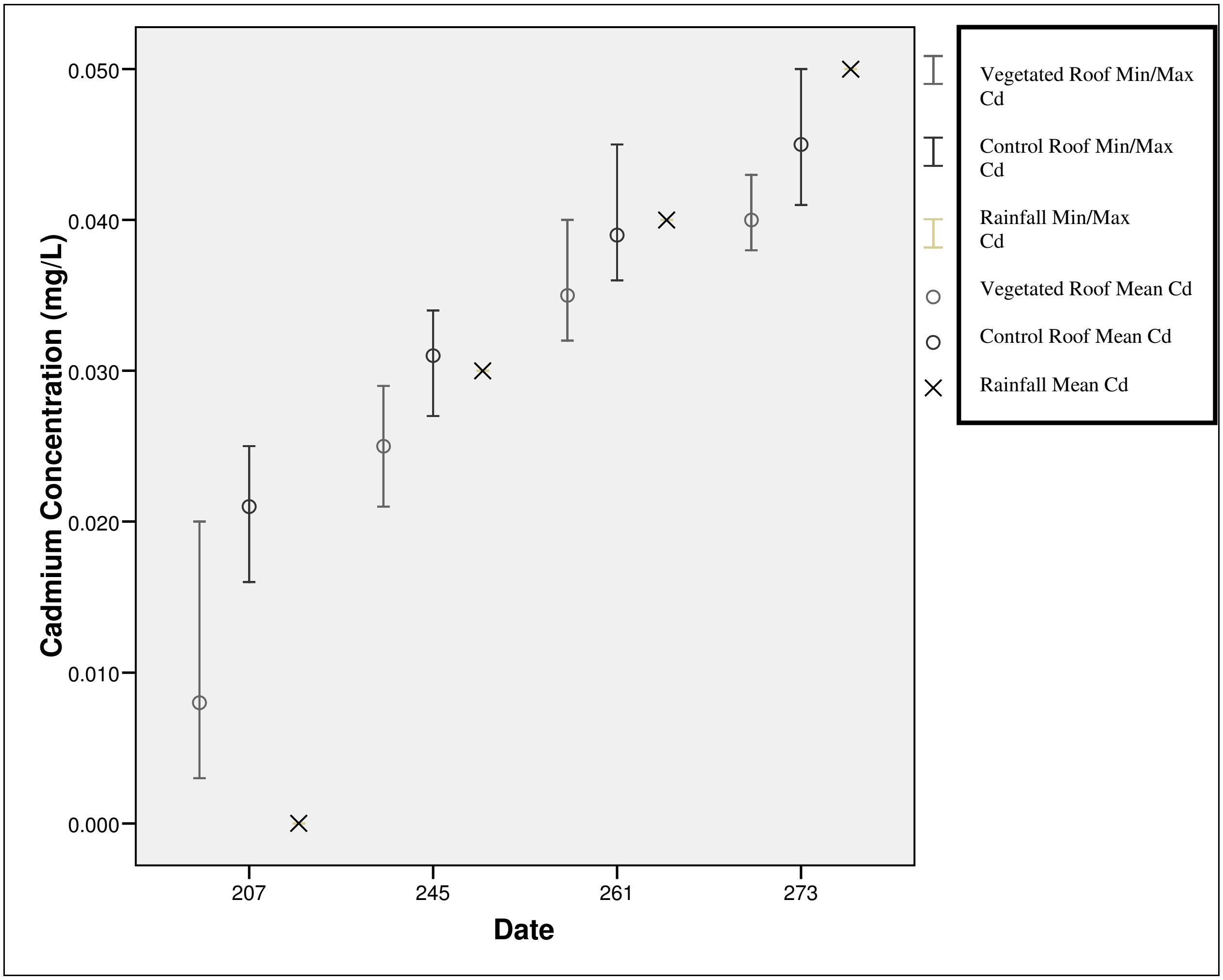


Figure 40: Cd Concentrations in Rainfall and Runoff from the Vegetated and Control Roofs

During individual storm events, the vegetated roof showed greatest changes in cadmium concentration in runoff. A representative scatter plot graph illustrates the changes in concentration from the onset of runoff to the end of sampling (Figure 41). The range in Cd from the control roof did not increase greatly during individual storm events although concentrations did increase.

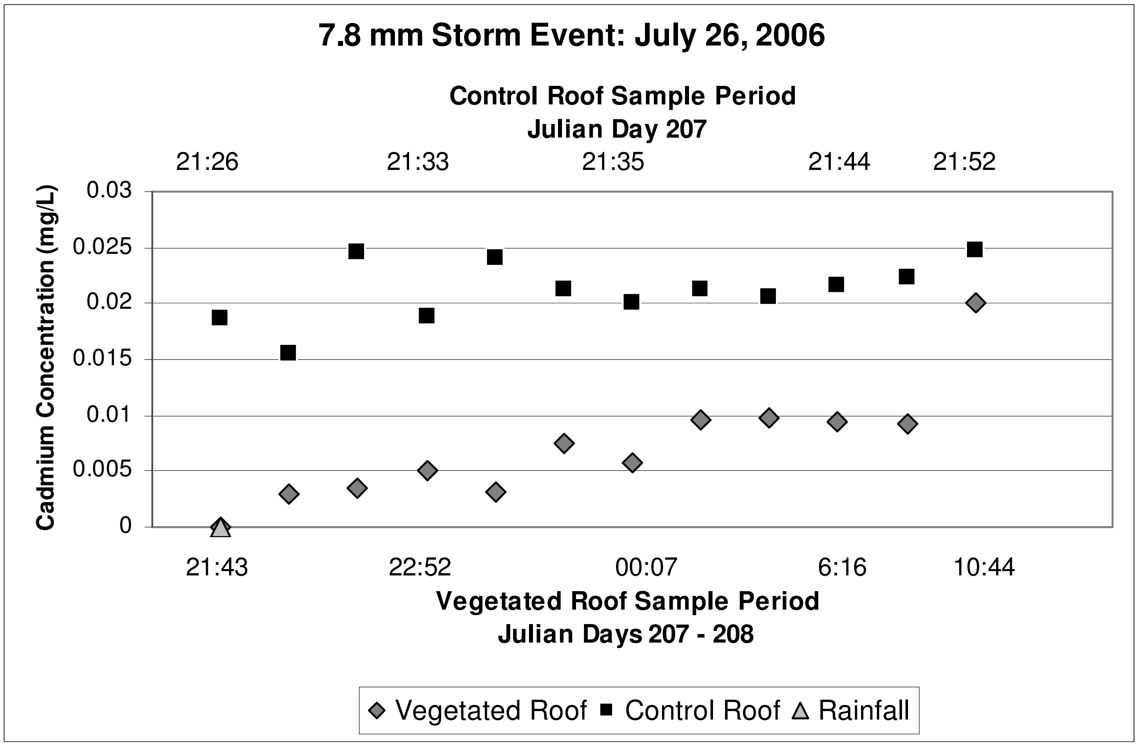


Figure 41: Cd Concentrations in Rainfall and Runoff from the Vegetated and Control Roofs on Julian Days 207 – 208

Chapter 4: Discussion

4.1: Introduction

The benefits of vegetated roofs as a stormwater source control measure are being increasingly reported (VanWoert *et al.,* 2005a; DeNardo *et al.,* 2005; TRCA, 2006; Carter and Rasmussen, 2006) but there is a lack of data on the wet weather performance vegetated roofs in a variety of geographical settings (Getter and Rowe, 2006). In addition, much of the existing wet weather performance data lacks accessibility, replication nor has it been peer reviewed (VanWoert et *al.,* 2005a; Getter and Rowe, 2006). Accordingly, if vegetated roofs are to be considered as a viable source control stormwater management option then a more rigorous review of their benefits and limitations is required before they can be fully utilized by the general public and professional sectors (ie. planners, engineers, architects, policy makers) (Getter and Rowe, 2006). Such information will aid planning, improve stormwater management, assist in policy development, refine construction and performance standards and inform the public and professional sectors on vegetated roof storm water control capability. In the following sections, results from the present study are compared to published literature on wet weather performance of vegetated roofs. Implications of the study for planning and stormwater management are discussed.

4.2 Vegetated Roof Hydrological Performance

4.2.1: Stormwater Retention Rates

Vegetated and control roof absolute stormwater retention rates and magnitudes are compared with data from previous studies to place the present study within the context of the literature (Table 14). This table shows that stormwater

Table 14: Summary of Stormwater Retention Results in Published Literature

Study	Location	Events	Media Depth (mm)	Slope (%)	Vegetated Roof Retention (%)	Hard Surface Roof Retention (%)
Waterloo Vegetated Roof	Waterloo, Ontario	19	30	< 2	47.9 41.4*	4.0
Jennings *et al.* 2003	Kinston & Goldsboro, North Carolina	6	100	3; < 2	Goldsboro: 70.0	-
Monterrusso *et al.,* 2004	East Lansing, Michigan	4	20; 100	2	20 mm – 39.6 100 mm – 58.1	-
Moran *et al.*, 2005	Raleigh & Goldsboro, North Carolina	8	75, 100	< 2; 7	Raleigh: 55.0 Goldsboro: 63.0	-
Liu, 2003; Liu & Baskaran, 2005	Ottawa, Ontario	-	150	2	54.0	-
VanWoert *et al.* 2005a	East Lansing, Michigan	83	30	< 2	60.6*	27.2
Liu & Minor, 2005	Toronto, Ontario	-	75	-	57.0	-
La Berge *et al.,* 2005	Chicago, Illinois	-	-	2.5	68.5	11.0
Bengtsson *et al.,* 2005	Malmo, Sweeden	-	30	2	46.4*	-
DeNardo *et al.,* 2005	Rock Springs, Pennsylvannia	7	89	-	45.0	-
Liu & Connelly, 2005	Vancouver, British Columbia	7	75	-	67.0	-
Carter & Rasmussen, 2006	Athens, Georgia	31	76.2	< 2	78.0	-
TRCA, 2006	Toronto, Ontario	-	140	10.0	65.0*	6.0

* Retention rate of total rainfall

retention rates from the current study are similar to those reported in previous studies (ie.VanWoert *et al.,* 2005a; La Berge *et al.,* 2005; TRCA, 2006). In Waterloo, higher retention rates were observed in the vegetated roof compared to the control roof. Differences in stormwater retention between the two roof types are due to the nature of the vegetated roof's growth medium properties and the presence of water retention fabric. The porous surface of the vegetated roof allows for better water infiltration and storage compared to the hard surface of the control roof (VanWoert *et al.,* 2005a). Water retention by the control roof is due to the drain inlet being elevated over the surface of the roof allowing for some water to pool.

The absolute storm water retention rate of the Waterloo vegetated roof is slightly lower than rates reported in the majority of comparable studies (Table 14) which reported absolute mean or total retention rates 50 % or greater (Jennings *et al.,* 2003; Liu, 2003; Moran *et al.,* 2005; Liu and Minor, 2005; Liu and Connelly, 2005; La Berge *et al.,* 2005;; DeNardo *et al.,* 2005; TRCA, 2006; Mentens *et al.,* 2006; Carter and Rasmussen, 2006). The higher retention rates reported in the literature may be due to the thickness of the vegetated roof growth mediums studied. VanWoert *et al.,* (2005a) noted that increasing growth medium thickness increases storm water retention rates. The thickness of the Waterloo vegetated roof growth medium is 35 mm and a majority of previous studies were conducted on deeper vegetated roof growth mediums ranging from 75 mm to 100 mm. Some studies on thinner growth substrates (≤ 35 mm) have lower retention rates similar to the Waterloo vegetated roof (Table 14). A 20 mm vegetated roof in Michigan had a mean retention rate of 39.6 % (Monterusso *et al.,* 2004) and a 30 mm vegetated roof in Sweden retained 46.4 % of total rainfall (Bengtsson *et al.,* 2005).

There are a number of factors that influence stormwater retention of a vegetated roof. The Waterloo vegetated roof showed an inverse relationship between storm size and stormwater retention ($p<0.05$). Several previous studies show stormwater retention rates decrease as storm sizes increase (LaBerge *et al.,* 2005; VanWoert *et al.,* 2005a; Carter and Rasmussen, 2006). Overall, larger storm sizes have a greater potential to exceed the vegetated roof's water storage capacity.

The wetting history of the vegetated roof is another important factor that influences stormwater retention (Moran *et al.,* 2005). Storm size and the time period between storm events will influence vegetated roof retention rates. A saturated vegetated roof from consecutive rain events will retain less during subsequent rain events (Jennings *et al.,* 2003; Moran *et al.,* 2005;Carter and Rasmussen, 2006) compared to a dry vegetated roof.

Seasonality also influences vegetated roof stormwater retention. Frequent rainfall, low temperatures and lower rates of evapotranspiration during fall and winter months can reduce vegetated roof stormwater retention rates. The results from the Waterloo vegetated roof are comparable to other studies which documented lower retention rates in the fall and winter months (ie. Bengtsson *et al.,* 2005; TRCA, 2006; Carter and Rasmussen, 2006). The negative retention rates (runoff volume exceeds rainfall input) observed on Julian days 292 and 295 (October 19 and October 22, 2006) in Waterloo was due to a previous 28.6 mm rain event on Julian day 290 (October 17) not included in the data set. Water detained (temporarily stored) by the vegetated roof during the storm event on Julian day 290 would later contribute to runoff measured from storm events on Julian days 292 and 295.

4.2.2: Lag time, Runoff Peak Flow and Runoff Flow Time

The Waterloo vegetated roof significantly increased runoff lag time compared to the control roof ($p<0.05$) and the results are comparable to that reported in the literature (Table 15).

Table 15: Roof Rainfall Response Characteristics from the Present and Past Studies

Study	Location	Events	Media Depth	Slope (%)	Vegetated Roof Runoff Lag Time (minutes)	Control Roof Runoff Lag Time (minutes)	Reduction in Peak Flow (%) (relative to control roof)	Mean Runoff Time Extension (relative to control roof) (minutes)
Present Study	Waterloo, ON	19	30 mm	< 2	69.0	14.0	54.0	39.0
Jennings *et al.* 2003	Kinston & Goldsboro, NC	6	100 mm; 100 mm	3; < 2	Kinston 120.0	-	Kinston 70.0	-
Moran *et al.*, 2005	Raleigh & Goldsboro, NC	8	75 mm, 100 mm	< 2	30.0	-	Raleigh: 57.0 Goldsboro: 8	-
VanWoert *et al.* 2005a	Lansing, MI	83	30 mm	< 2	28.3	18.3	-	30.0
Liu & Minor, 2005	Toronto, ON	-	75 mm;	-	20 - 40	-	42.5	-
DeNardo *et al.,* 2005	Rock Springs, PN	7	89 mm		342	-	44.0	-
Liu & Connelly, 2005	Vancouver, BC	7	75 mm	-	72.4	-	-	-
Carter & Rasmussen, 2006	Athens, GA	31	76.2 mm	< 2	34.9	17.0	53.0	-
TRCA, 2006	Toronto, ON	-	140 mm	10.0	29.8	2.9	73.1	-

Variability in lag time values (Table 15) could be due to several reasons. A report by the *Toronto Region Conservation Authority* indicated that there a number of factors affecting lag time such as soil moisture, substrate depth, storm size, rain intensity, air temperature and relative humidity. The study did not provide any conclusive evidence on any one variable but rather concluded it was a combination of factors that could affect vegetated roof lag time. However, rain intensity is one factor that influences the lag time of the Waterloo vegetated and control roof. As rain intensity increased, vegetated and control roof lag time decreased significantly ($p<0.05$). Greater rainfall intensity exceeds vegetated and control roof water storage capacity at a quicker rate and therefore decreases lag time.

The Waterloo vegetated roof also significantly reduced runoff peak flow ($p<0.05$). Results from the Waterloo vegetated roof are comparable to those reported in previous studies (Table 15). The reduction in peak flow is likely due to the saturation and flow of stormwater through the vegetated roof component layers (Bengtsson *et al.,* 2005). In comparison, the hard surface of the control roof did not slow stormwater flow and increased with rain intensity ($p<0.01$).

Overall, the reduced flow rate from the Waterloo vegetated roof increased total runoff flow time and data from this thesis is comparable to results reported by VanWoert *et al.,* (2005a) whom also documented an extended runoff flow time. An increase in vegetated runoff flow time is due to the slowing of rainfall infiltration and flow through the multiple layers of the vegetated roof system.

4.3: Vegetated Roof Water Quality Treatment

Although vegetated roofs have been identified as a feasible technology that could be used to improve stormwater quality by reducing nutrient and metal concentrations (Johnston and Newton, 1996; Peck *et al.,* 1999), there are relatively few studies that have examined the water quality treatment performance of vegetated roofs in Canada. The first studies of vegetated roof water quality were conducted in Germany (VanWoert *et al.,* 2005a; Getter and Rowe, 2006). Subsequent studies report vegetated roofs as a source of phosphorus and show that vegetated roofs are not an effective technology to remove metal from stormwater (Jennings *et al.,* 2003; Monterusso *et al.,* 2004; TRCA, 2006; Berndtsson *et al.,* 2006). In the present study, water quality of runoff from the Waterloo vegetated roof was examined by measuring pH, temperature, conductivity, total dissolved solids, suspended solids, total phosphorus, soluble reactive phosphorus, copper, zinc, chromium and cadmium. In the following sections, water quality results of the Waterloo vegetated roof are presented and discussed in the context of published literature and water quality standards set by Ontario's *Provincial Water Quality Objectives* (PWQO).

4.3.1: pH, Conductivity, Total Dissolved Solids and Suspended Solid Concentrations

The mean pH measured in vegetated roof runoff is significantly higher than that measured in rainfall or control roof runoff ($p<0.05$). The levels recorded are comparable to results in a previous study that reported a higher average pH in vegetated roof runoff (TRCA, 2006) (Table 16). A higher average pH level in vegetated roof runoff is most likely due to the alkalinity of the growth medium (TRCA, 2006) which tends to buffer stormwater runoff.

The mean conductivity measured in runoff from the vegetated roof is significantly greater than that measured in either the rainfall or control roof runoff ($p<0.05$). Results from the present study are similar to results in a previous study (TRCA, 2006) which measured greater conductivity levels in vegetated roof runoff (Table 16). Higher conductivity does not necessarily equate to poor water quality but indicates the presence of a variety of inorganic anion and cation species (Köhler and Schmidt, 2003). TRCA (2006) found vegetated roof Cl concentrations 249.1 % greater than control roof Cl concentration which could lead to greater TDS in vegetated roof runoff.

Table 16: Mean pH, Conductivity, TSS and TDS levels in Rainfall and Runoff from the Vegetated and Control Roofs

Water Quality Properties	**Present Study**			**TRCA (2006)**			**PWQO**
	Control Roof	**Rain**	**Vegetated Roof**	**Control Roof**	**Rain**	**Vegetated Roof**	
Mean pH	**6.1**	**6.3**	**7.8**	**7.3**	**5.9**	**8.1**	**6.5 – 9.5**
Conductivity (µS/cm)	**49.3**	**17.9**	**181.1**	**45.5**	**17.0**	**205.3**	**-**
Total Suspended Solids (SS) (mg/L)	**8.3**	**2.3**	**5.6**	**5.55**	**-**	**1.25**	**-**
Total Dissolved Solids (TDS) (mg/L)	**0.035**	**0.013**	**0.131**	**-**	**-**	**-**	**-**

The mean total dissolved solids (TDS) in vegetated roof runoff is significantly greater than that measured in rainfall and control roof runoff ($p<0.05$). No other previous studies have reported TDS concentrations in vegetated roof runoff (Table 16). A higher TDS concentration is related to higher conductivity levels present from the vegetated roof growth medium and fertilizer application.

Total suspended solids (SS) concentrations measured in vegetated roof runoff are lower than levels measured in control roof runoff, however are not significant. Vegetated roof SS levels are comparable to a previous study by TRCA (2006) which reported an 85.4 % reduction in SS concentration in vegetated roof runoff (Table 16). The lower vegetated roof SS concentration is likely due to the filter cloth layer in the Waterloo vegetated roof system which prevents the loss of organic material from the growth medium.

4.3.2: Total Phosphorus and Soluble Reactive Phosphorus

Total phosphorus and soluble reactive phosphorus concentrations in runoff from the Waterloo vegetated roof are significantly greater than concentrations in either rainfall or control roof runoff ($p<0.05$). Levels measured in the present study exceed the OME PWQO for total phosphorus at 30µg/L. However, concentrations of TP in the control roof are comparable to levels measured in rainfall and well below the limits set by the PWQO. These results are similar to those found in the majority of literature which indicates that vegetated roofs are a source of both total phosphorus and soluble reactive phosphorus (Table 17).

Table 17: Vegetated roof TP and SRP Levels Relative to Levels in Rainfall

Study	**Vegetated roof Total Phosphorus levels**	**Vegetated Roof Soluble Reactive Phosphorus levels**	**Exceed PWQO Guidelines for TP (0.03 mg/L)**
Waterloo vegetated roof	**Higher**	**Higher**	**Yes**
Jennings *et al.,* 2003	**Higher**	**-**	**-**
Köhler and Schmidt, 2003	**Lower**	**-**	**-**
Moran *et al.,* 2005	**Higher**	**-**	-
Berndtsson *et al.,* 2006	**Higher**	**Higher**	-
TRCA, 2006	**Higher**	**Higher**	**Yes**

Sources of phosphorus for the vegetated roof likely come from the growth medium and fertilizer application (Jennings *et al.,* 2003; Berndtsson *et al.*, 2006; TRCA, 2006; Emilsson *et al.,* 2007). Studies concluded (TRCA, 2006; Berndtsson *et al.,* 2006, Emilsson *et al.,* 2007) that the organic content in the growth medium and fertilizer application is the likely source of phosphorus. The Waterloo vegetated roof growth medium consists of 14 % organic material and fertilizers (3.5 % P_2O_2) were applied June 9, 2006 (Xero Flor, 2006). Fertilizers are used in the maintenance of the Waterloo vegetated roof to help establish plant growth and coverage (Berndtsson *et al*., 2006; Emilsson *et al.,* 2007). TRCA (2006), Berndtsson *et al.,* (2006) and Emilsson *et al.,* (2007) recommend the use of controlled release fertilizers to limit nutrient input and to reduce phosphorus leaching.

Older established vegetated roofs with limited nutrient input have shown to retain phosphorus. Köhler and Schmidt (2003) documented phosphorus retention of 67 % by a 15 year old vegetated roof in Germany. In addition, studies indicating vegetated roofs as a source of phosphorus have reported decreases in phosphorus concentrations. TRCA (2006) showed that vegetated roof phosphorus levels dropped 214 % over a one year period. With time, excess phosphorus will leach and concentrations can possibly decrease.

4.3.3: Metal Concentrations in Rainfall and Runoff from the Vegetated and Control Roofs

The Waterloo vegetated roof was not a source of metals, however had levels that exceeded the OME PWQO of 0.05 mg/L. The vegetated and control roof both had smaller mean Cu concentrations than that measured in rainfall, however the very high rainfall Cu concentrations was likely due to cross contamination from the tipping bucket rain gauge. To collect rainfall samples, rainfall flowed through the tipping bucket rain gauge and then into the sample collection bottle. In contrast to the present study's results, TRCA (2006) and Berndtsson *et al.,* (2006) both found higher Cu levels in vegetated and control roof runoff than in rainfall explaining that roof drainage pipes was the likely source (Table 18).

The concentrations of Zn in runoff from the Waterloo vegetated roof are significantly lower than levels measured in rainfall or the control roof runoff ($p < 0.05$). Results from previous studies are comparable and show a vegetated roof reduction in Zn concentrations (Berndtsson *et al.* 2003; TRCA, 2006) (Table 18). Retention of Zn by the vegetated roof is most likely due to the growth medium or possible due to plant uptake. No studies have directly investigated mechanisms of metal cycling in vegetated roof systems. However, a study on plant uptake of metals in China showed *Sedum alfredii* to be a zinc hyperaccumulating plant as it aids in stem and shoot development (Yang *et al.,* 1977).

Table 18: Vegetated roof Metal Concentrations Relative to Metal in Rainfall

Metal	**Present Study**	**Köhler and Schmidt (2003)**	**Berndtsson *et al.,* 2006**	**TRCA, 2006**
Cu	**No difference**	**-**	**Higher**	**Lower**
Exceed Cu PWQO 0.05 mg/L	**Higher**	**-**	**Higher**	**Higher**
Zn	**Lower**	**-**	**Lower**	**Lower**
Exceed Zn PWQO 0.02 mg/L	**Higher**	**-**	**-**	**Lower**
Cr	**No difference**	**-**	**No difference**	**Below Detection Limit**
Exceed Cr PWQO 0.009 mg/L	**Higher**	**-**	**-**	**Below Detection Limit**
Cd	**No difference**	**Lower**	**Below Detection Limit**	**Below Detection Limit**
Exceed Cd PWQO 0.0001 mg/L	**Higher**	**-**	**-**	**Below Detection Limit**

Mean Cr concentration in runoff from the Waterloo vegetated roof is comparable to levels measured in rainfall and the control roof runoff. The mean Cr concentrations in vegetated and control roof runoff exceed the OME PWQO of 0.0089 mg/L. These results are comparable to Berndtsson *et al.* (2006) who also found that vegetated roof Cr levels were also similar to Cr levels in rainfall and control roof runoff (Table 18). Considering there is no significant difference in Cr concentrations between vegetated and control roof runoff and rainfall, the most likely source is atmospheric deposition.

The mean Cd concentration in vegetated roof runoff is not significantly different from concentrations in rainfall and control roof runoff ($p > 0.05$). Mean Cd levels measured in vegetated and control roof runoff did exceed the PWQO standard of 0.0001 mg/L. Other studies report that Cd concentrations are often below the method detection limit (Table 18). However, Köhler and Schmidt (2003) measured an 87.6 % retention of Cd by a 15 year old vegetated roof in Berlin, Germany. Enhanced Cd retention may be possible after several years of vegetated roof operation as excess metals leach from the growth medium. Whether this phenomenon is indicative of all older vegetated roofs is questionable as this study is yet to be replicated.

4.4: Implications for Watershed Planning and Stormwater Management

Various plans and technologies have been adopted to mitigate the impacts of storm water runoff (Marsalek, 2005). However, conventional planning using traditional drainage systems has been ineffective due to costs, nonflexible application and inability to reduce total storm water volume (Chocat, 2001; Marsalek and Chocat, 2002; Bradford and Gharabhagi, 2004). As a result, greater government adoption of sustainable planning techniques (watershed planning), development strategies (ie.LID), and storm water management technologies (ie. vegetated roofs) have evolved over the last 30 years

(Marsalek and Chocat, 2002; Marsalek, 2005). In Ontario, the Provincial government initiated watershed planning in the early 1990's (OMEE, 1993a; 1993b; Khandl, 2005) and identified four parts of a watershed plan: 1) issue identification and data gathering; 2) analysis and planning; 3) implementation and 4) monitoring (PMC, 1997; Khandl, 2005). One of the main purposes of watershed planning has been the long term protection, management and restoration of important watershed features and fair allocation of water resources (OME, 2001, p.31). Watershed plan goals and guidelines encompass the entire watershed down to the lot level. The objectives of a watershed plan are implemented at the lot level with storm water management plans and the application of BMP(s) (OMEE, 1993b; Marsalek and Chocat, 2002; Khandl, 2005). Monitoring of BMP(s) is crucial to gathering wet weather performance data and assessing whether watershed objectives are achievable or need to be updated (Montgomery *et al.,* 1995; Khandl, 2005). The following section evaluates the wet weather performance of an extensive vegetated roof and discusses the implications for storm water management planning and vegetated roof application and design.

4.5: Implications for Stormwater Management Planning and BMP Application

Stormwater management plans seek to mitigate the impact of runoff on the natural and human environment at the lot level (OME, 2003). Application of storm water management plans addresses BMP(s) selection, size, and location and should adequately demonstrate that selected storm water controls will meet the goals of the watershed plan (OMEE, 1993b). The OME *Stormwater Management Planning and Design Manual* (SWMPDM) (2003) assists with BMP implementation and provides an overview of BMP performance. The manual recommends that BMP(s) be applied as a treatment train consisting of lot level, conveyance and end-of-pipe controls (OME, 2003b; Khandl, 2005). However, water quantity and quality treatment is primarily focused upon the use of end-of-pipe controls such as storm water management ponds (OME, 2003b; Bradford and Gharabhagi, 2004). Recent interest in SUDS/LID emphasizes greater use of source/lot level controls that reduce total storm water volume (Marsalek and Chocat, 2002). Yet, little attention is given to SUDS or LID technologies like vegetated roofs within the SWMPDM (Bradford and Gharabhagi, 2004). Lack of information on new storm water technologies makes it difficult to determine the application of vegetated roofs and the combination of BMPs to use with it to meet watershed plan objectives (Marsalek and Chocat, 2002)

Results from the present study and others (VanWoert *et al.,* 2005a; TRCA, 2006; Carter and Ramussen, 2006) has shown that vegetated roofs are a proven source control, able to reduce storm water volume, decrease peak flow and increase runoff lag time. When stormwater management ponds are not feasible in city cores due to cost and land availability (Bradford and Gharabhagi, 2004), application of vegetated roofs is very possible as they can be built on existing rooftops (Jennings *et al.,* 2003). Greatest changes to historical hydrological conditions have been in urban centers where older storm water infrastructure (combined sewers) is often overwhelmed by larger storm events (Graham *et al.,* 2004; Carter and Ramussen, 2006). Implementation of vegetated roofs in these areas can improve storm water management by reducing runoff volumes and peak flows (Jennings *et al.,* 2003; Carter and Ramussen, 2006).

Although BMP performance is described in the SWMPDM (2003), Marsalek and Chocat (2002) describe BMPs as dynamic systems which are affected by multiple variables causing wet weather performance to vary. Results from the present study and others (TRCA, 2006; DeNardo *et al.,* 2005) have shown lower vegetated roof stormwater retention rates during fall and winter months because of cooler temperatures and lower evapotranspiration rates. Application of vegetated roof as a source control should be combined with other stormwater controls in a treatment train to supplement decreased performance in fall and winter months (Bradford and Gharabaghi, 2004). In addition, vegetated roof water quality results also illustrate the changing nature of BMPs. Results from the present study and others (Monterusso *et al.,* 2004; Moran *et al.,* 2005; TRCA, 2006; Berndtsson *et al.,* 2007) show that vegetated roofs are a source of phosphorus. It has been well documented that phosphorus is a limiting factor of algal growth within bodies of water (Tubea, B. *et al.,* 1981; Havens, K.E. *et al.,* 1999; Pietilainen and Niinioja, 2001). Marsalek and Chocat (2002) describe phosphorus leaching as a "secondary impact" due to organic content in the vegetated roof growth medium and fertilizer application. BMP secondary impacts are often not considered during stormwater management planning (Marsalek and Chocat, 2002) and can be lessened with remedial measures such as modifying maintenance procedures such as limiting fertilizer input or using aggregate based growth mediums (Berndtsson *et al.,* 2006; Emilsson *et al.,* 2007).

Chapter 5: Conclusions and Recommendations

The main purpose of the study was to evaluate the wet weather performance of an extensive vegetated roof in southern Ontario. The results of the study provide a better understanding of vegetated roofs as a stormwater source control. In addition, performance results can aid the development of green roof policy, help establish performance standards, aid vegetated roof design and increase vegetated roof awareness among public and professional sectors. Based upon an analysis of the present study, the following conclusions and recommendations can be given.

5.1: Meteorological Results

1) A total of 31 rain events were monitored during the 5 month study period from June, 2006 to October, 2006
2) Rain events size ranged from 0.6 mm to 48.4 mm
3) Total monthly rainfall depths for May, July, September and October were above long term averages (1970 – 2000)
4) Temperatures on the roof of Waterloo City Hall fluctuate to a greater degree than ground level temperatures. Absolute daily maximum and minimum temperatures ranged from 60.9˚C / 2.9 ˚C on the vegetated roof compared to 31.1 ˚C / 6.0 ˚C at the University of Waterloo Weather Station.

5.2: Vegetated Roof Wet Weather Performance – Hydrological Results

1) The vegetated roof is an effective source control increasing absolute total stormwater volume retention by 37 % over a hard surface roof (control roof). The vegetated roof retained an absolute total stormwater volume of 41.5% over the 5

month study period and had an absolute mean stormwater retention rate of 47.6 %. The control roof retained an absolute total stormwater volume of 3.3 % and had an absolute mean retention rate of 4.7 %.

2) The vegetated roof had an absolute mean storage capacity at 3.5 mm and the control roof's absolute mean storage capacity was 0.3 mm.
3) Increasing storm size and seasonality influenced vegetated roof stormwater retention. Increasing storm size reduced vegetated roof stormwater retention. Cooler temperatures and lower evapotranspiration rates in the fall months reduced stormwater retention rates.
4) Analysis of individual rain events showed that the vegetated and control roofs demonstrated common rain response characteristics. The vegetated roof increased lag time, reduced peak flow and extended runoff flow time compared to the control roof. However, rain response characteristics were also subject meteorological conditions. Increased storm intensity decreased lag time for both roof types and increased control roof peak flow. With increased storm size, control roof peak flow increased and runoff flow time was extended for both the vegetated and control roofs.

5.3: Vegetated Roof Wet Weather Performance – Water Quality Results

1) The pH range of the vegetated roof runoff was 6.8 to 8.4 with a mean of 7.8; 4.0 to 7.2 for control roof runoff with a mean of 6.1 and 5.3 to 7.3 for rainfall with a mean of 6.3. The neutral pH level of vegetated roof runoff was likely due to the dolomite present in the growth medium which acts as a buffer.

2) Conductivity levels for the vegetated roof ranged from 51.6 µS/cm to 338.0 µS/cm with a mean of 181.1 µS/cm, 4.7 µS/cm to 198.5 µS/cm for control roof runoff with a mean 48.9 µS/cm and 13.0 µS/cm to 33.6 µS/cm for rainfall with a mean of 17.9 µS/cm. Greater conductivity levels measured in vegetated roof runoff is like due to the inorganic material in the growing medium
3) Sample temperatures of vegetated roof runoff ranged from 18.3˚C to 22.9˚C, 19.5 ˚C to 22.9 ˚C for control roof runoff and 19.6˚C to 21.9˚C for rainfall.
4) Total dissolved solids in vegetated roof runoff were significantly greater than TDS measured in control roof runoff. TDS levels in vegetated roof runoff ranged from 0.036 mg/L to 0.235 mg/L with a mean of 0.131 mg/l and 0.003 mg/L to 0.144 mg/L with a mean 0.035 mg/L for the control roof. Higher TDS in vegetated roof runoff is indicative of greater concentrations of inorganic compounds which could be due leaching or fertilizer application.
5) Suspended solid concentrations in vegetated roof runoff were relative to concentrations in control roof runoff. Mean SS concentration for the vegetated roof ranged from 0.0 mg/L to 15.0 mg/L with a mean of 5.6 mg/L and for control roof runoff 0.0 mg/L to 66.0 mg/L with a mean of 8.3 mg/L.
6) The vegetated roof was a source of total phosphorus and soluble reactive phosphorus. Phosphorus loss from the vegetated roof exceeded PWQO limits. TP concentrations for the vegetated roof ranged from 33.8 µg/L to 204.8 µg/L with a mean of 99.8 µg/L, for the control roof TP concentrations ranged from 1.0 µg/L to 102.9 µg/L with a mean of 15.4 µg/L and for rainfall, TP concentrations ranged from 4.5 µg/L to 33.3 µg/L and a mean of 16.9 µg/L. SRP concentrations

in vegetated roof runoff ranged from 7.7 µg/L to 98.0 µg/L with a mean of 40.0 µg/L and 1.0µg/L to 12.5 µg/L for the control roof with a mean of 3.8 µg/L. Sources of phosphorus were most likely the organic matter in the vegetated roof growth medium and the application of fertilizer.

7) The vegetated roof was not a source of metals. Mean Cu concentration from the vegetated roof was 0.94 mg/L, 0.92 mg/L for the control roof runoff and 3.13 mg/L from rainfall. High Cu concentrations in rainfall is likely due cross contamination from tipping bucket rain gauge as rain samples collected drained through the tipping bucket rain gauge and into the sample collection bottle
8) Chromium concentrations varied little between rainfall and the vegetated and control roof. Cr concentrations ranged from 0.04 mg/L to 0.13 mg/L with a mean of 0.10 mg/L for the vegetated roof, 0.08 mg/L to 0.13 mg/L with a mean of 0.11 mg/L for control roof runoff and 0.06 mg/L to 0.13 mg/L with a mean of 0.11 mg/L for rainfall. Sources of Cr is likely due to atmospheric deposition
9) Cadmium concentrations did not vary between rainfall and runoff from the vegetated and control roofs. Mean Cd concentration of 0.03 mg/L was measured in rainfall and runoff from both the vegetated and control roofs. Sources of Cd is likely from atmospheric deposition
10) Zn metal concentrations in vegetated roof runoff were significantly lower than Zn concentrations in control roof runoff and rainfall. Zn concentrations in vegetated roof runoff ranged from 0.09 mg/L to 0.39 mg/L with a mean of 0.24 mg/L, 0.26 mg/L to 0.67 mg/L with a mean of 0.42 mg/L for control roof runoff and 0.81 mg/L to 2.25 mg/L with a mean of 1.29 mg/L. Lower Zn levels in vegetated roof

runoff could be due *Sedum alfredii* present in the vegetated roof system which has been shown to be a zinc hyper-accumulating plant.

5.4: Implications for Planning and Management

Monitoring of vegetated roofs is important in ensuring goals and objectives of the watershed plan and stormwater management plan are being met or need to be updated (Montgomery *et al.,* 1995). The vegetated roof is effective at reducing total stormwater volume however it is a dynamic system with wet weather performance influenced by varying meteorological conditions. Application of vegetated roofs should be structured within the BMP treatment train to optimize wet weather performance. In addition, secondary impacts like nutrient leaching should be planned for and may be mitigated by changing maintenance procedures and selecting a growth medium with lower organic content.

5.5: Recommendations for Future Research

Analysis of results from the present study has raised a number of questions concerning the influence of vegetated roofs on stormwater quality. Further long term research is needed to investigate the impact of vegetated roofs on stormwater quality. The following recommendations for future study are based on results from this research and findings in the literature.

1) Few studies have researched older (> 5 years) vegetated roof systems. A more detailed study investigating older vegetated roof systems and their influence on stormwater quality is needed.

2) Studies have shown phosphorus loss from vegetated roof systems decrease over time. However, no studies have showed a reduction in phosphorus loss lead to phosphorus retention. Thus, long term studies are needed to monitor phosphorus loss from vegetated roof systems over several growing seasons and determine ways to minimize or control phosphorus leaching from the vegetated roof system.
3) There is a need for studies to investigate varying concentrations of organic content in growth mediums and their influence on vegetated roof nutrient loss.
4) There is a need to use monitoring data to develop quantitative tools for use in the design of stormwater controls.

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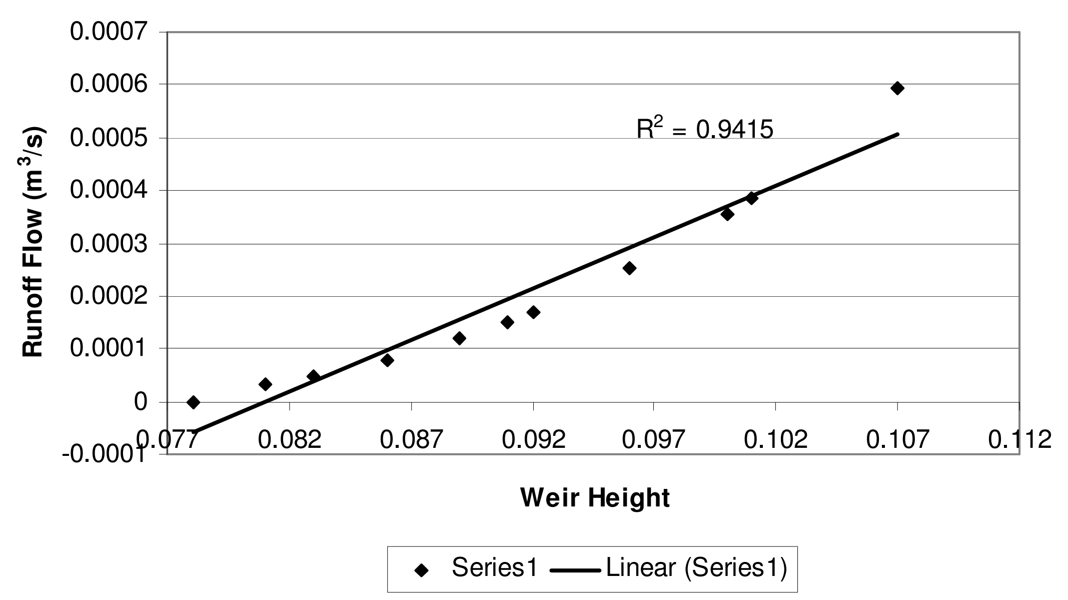
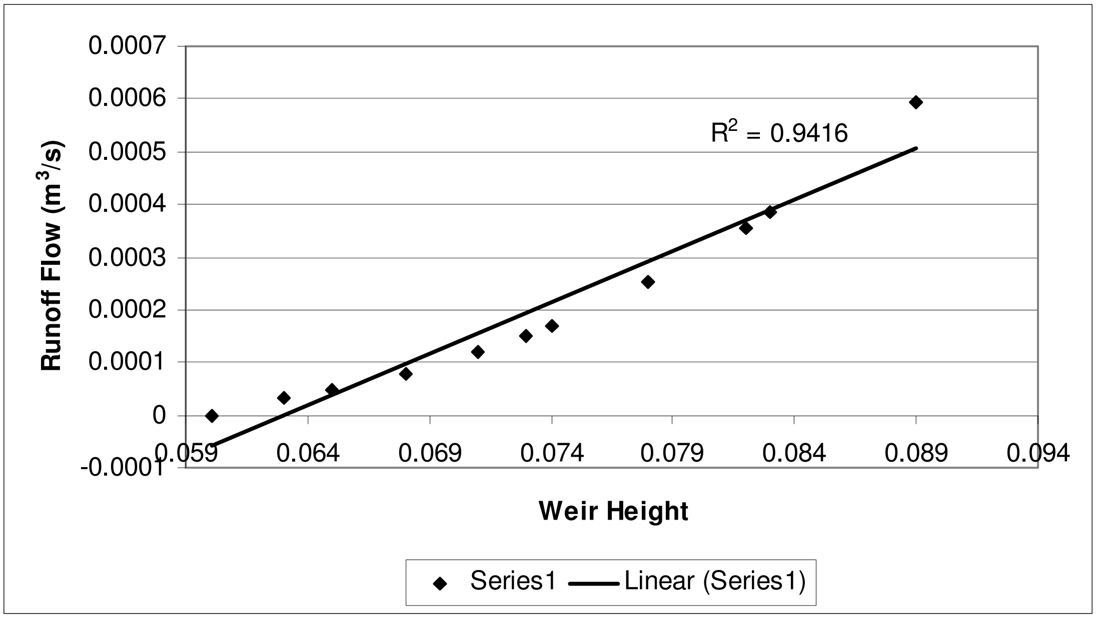
Appendix 1
Weir Height and Runoff Flow Points

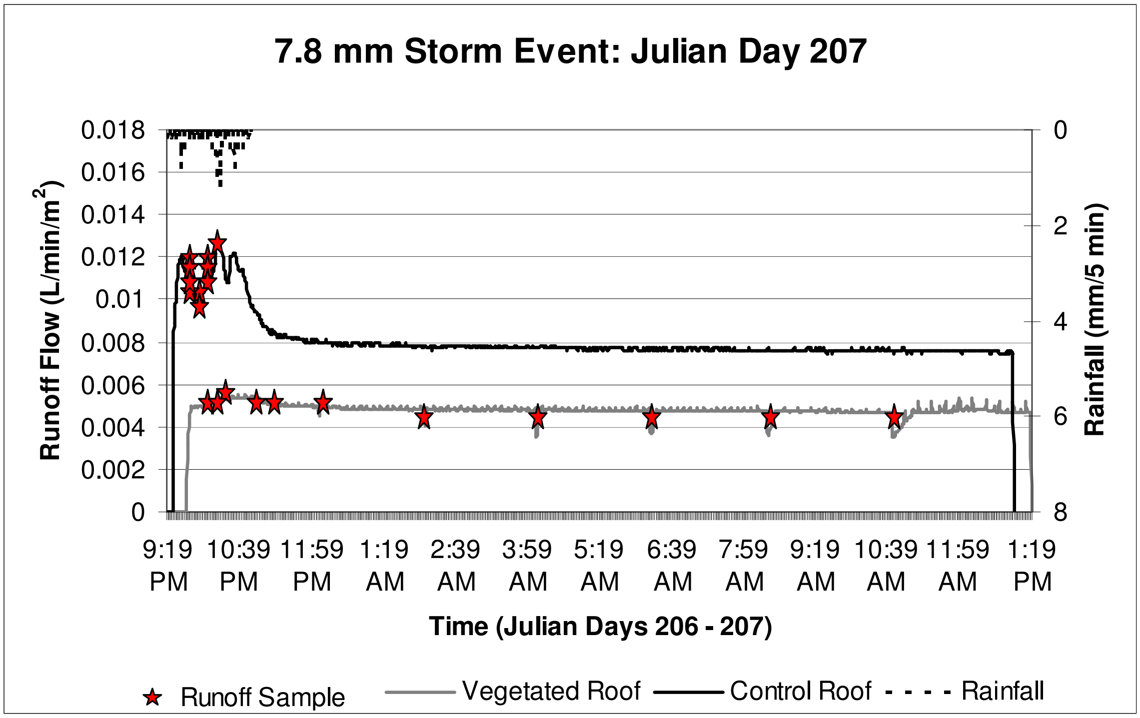
Vegetated Roof Weir Height (m)	Vegetated Roof Runoff Flow (L/s)	Control Roof Weir Height (m)	Control Roof Runoff Flow (L/s)
0.078	0.000	0.060	0.000
0.081	0.033	0.063	0.033
0.083	0.049	0.065	0.049
0.086	0.079	0.068	0.079
0.089	0.119	0.071	0.119
0.091	0.151	0.073	0.151
0.092	0.169	0.074	0.169
0.096	0.252	0.078	0.252
0.100	0.357	0.082	0.357
0.101	0.386	0.083	0.386
0.107	0.593	0.089	0.593



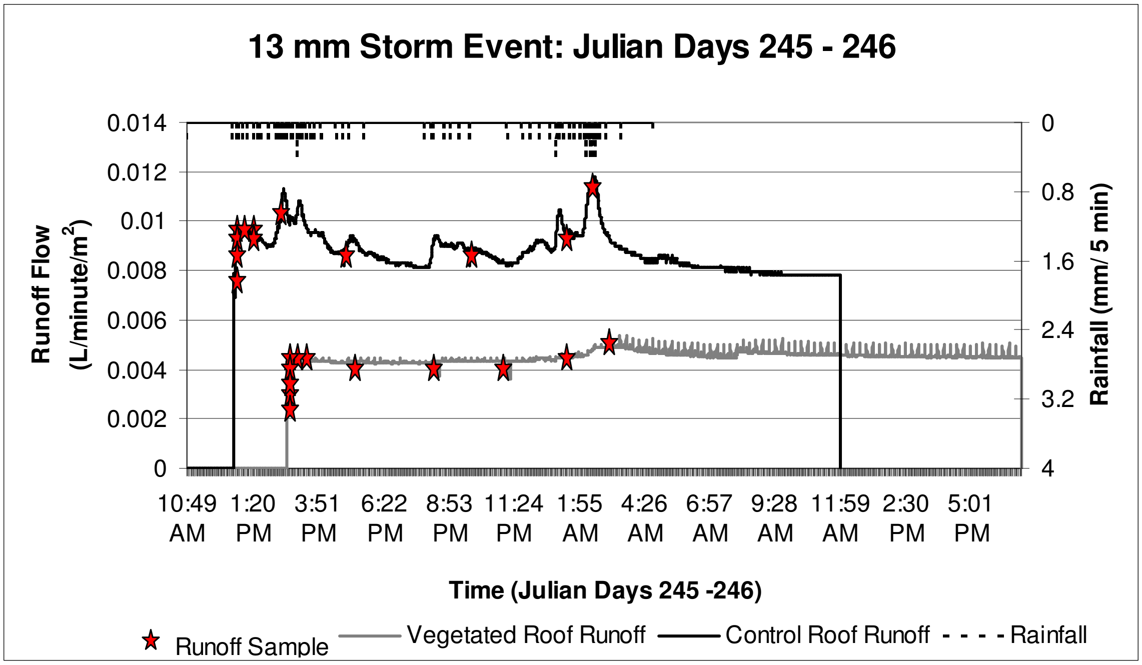
Vegetated Roof Rating Curve



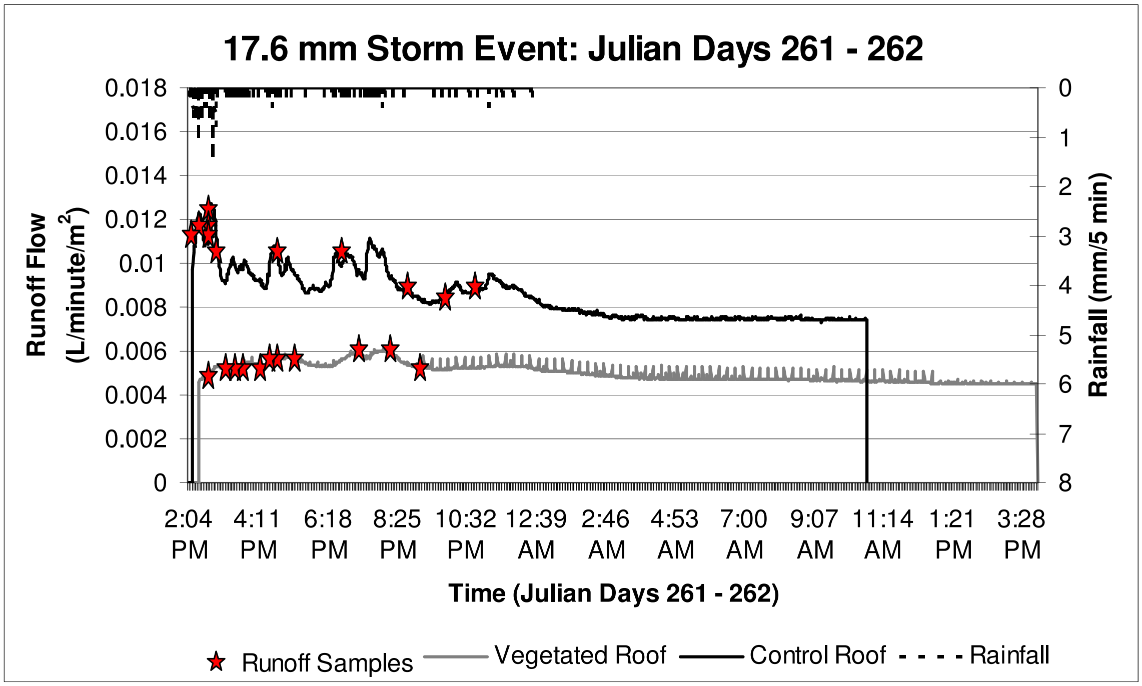
Control Roof Rating Curve



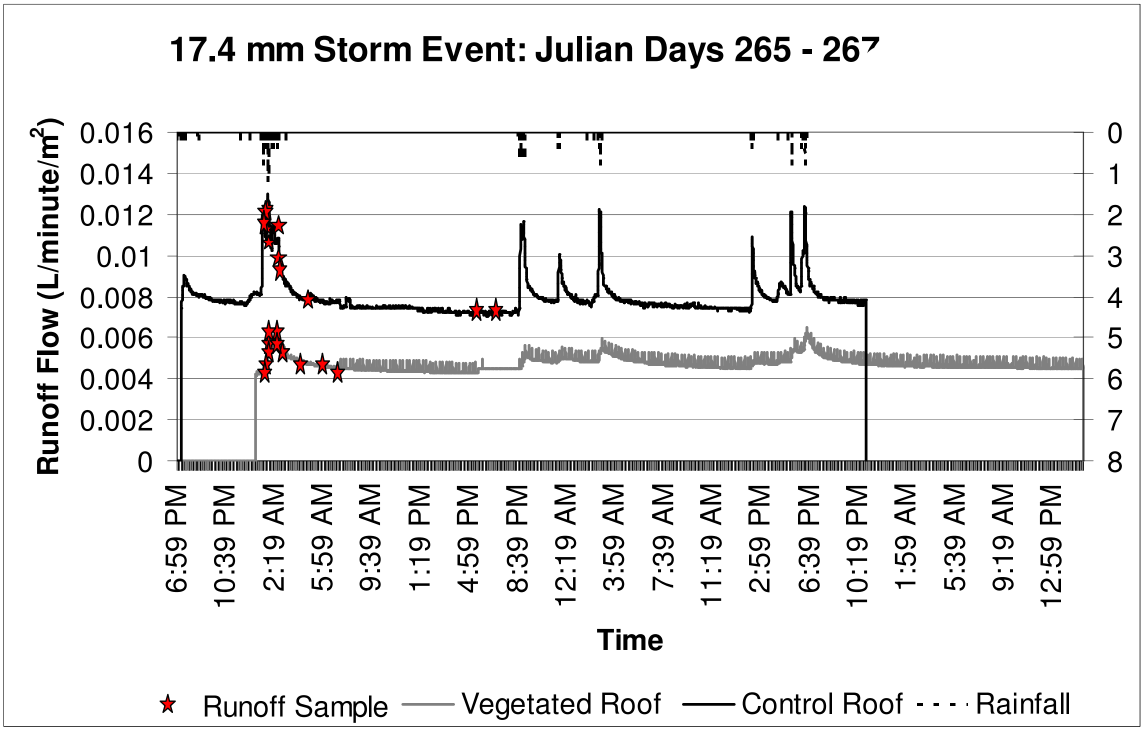
Runoff Sample Times from a Storm Event on Julian Day 206 – 207



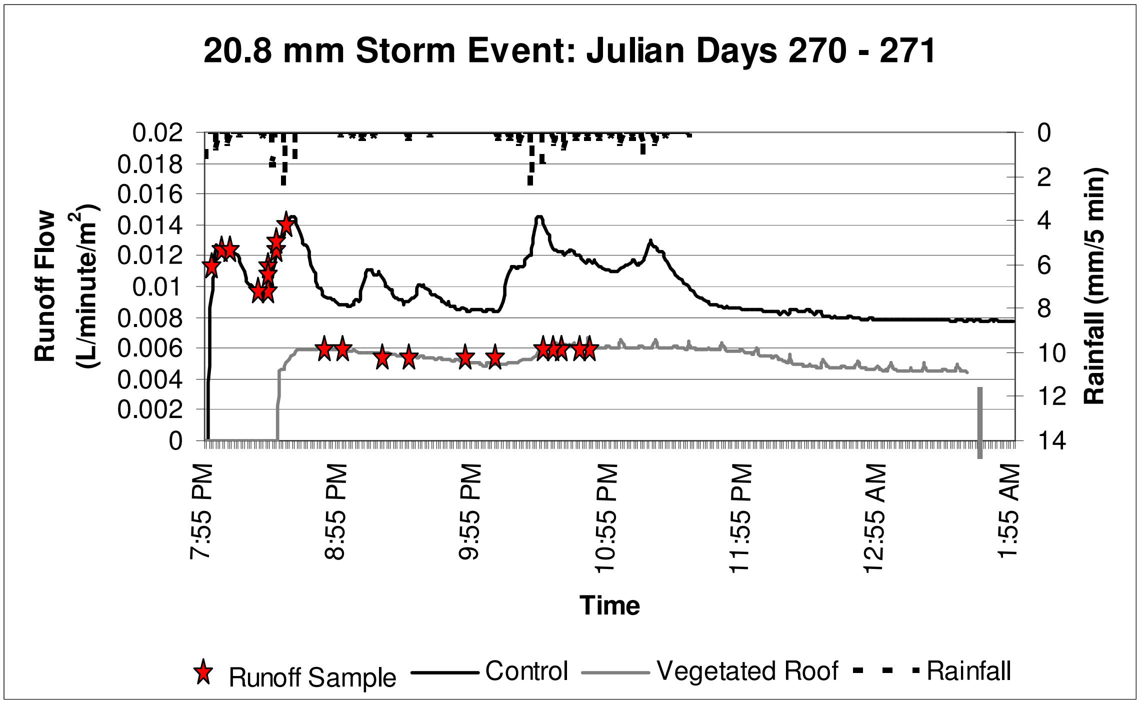
Runoff Sample Times from a Storm Event on Julian Days 245 - 246



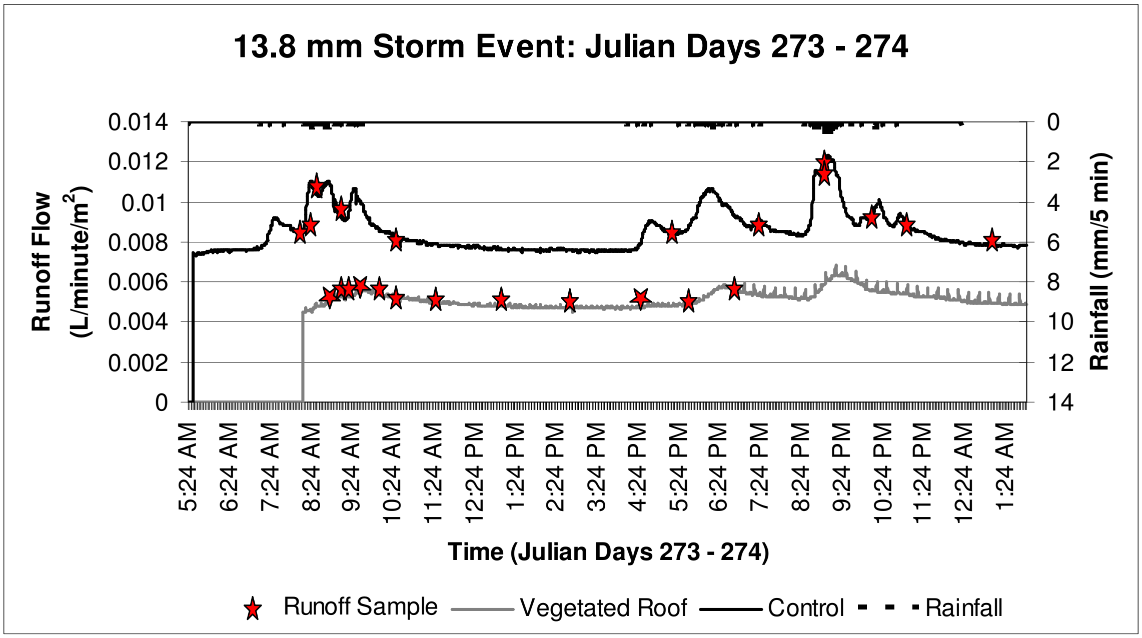
Runoff Sample Times from a Storm Event on Julian Days 261 – 262



Runoff Sample Times from a Storm Event on Julian Days 265 – 267



Runoff Sample Times from a Storm Event on Julian Days 270 – 271



Runoff Sample Times from a Storm Event on Julian Days 273 - 274

Appendix 2

Vegetated Roof Daily Potential ET Rates

Date	ET (mm/day)	Date	ET (mm/day)	Date	ET (mm/day)	Date	ET (mm/day)	Date	ET (mm/day)
Jun.1/06	1.3	Jul.1/06	3.8	Aug.1/06	3.3	Sept.1/06	2.5	Oct.1/06	1.0
Jun.2/06	1.2	Jul.2/06	2.8	Aug.2/06	2.0	Sept.2/06	0.0	Oct.2/06	1.6
Jun.3/06	0.5	Jul.3/06	3.5	Aug.3/06	0.0	Sept.3/06	0.0	Oct.3/06	1.2
Jun.4/06	3.3	Jul.4/06	3.3	Aug.4/06	3.3	Sept.4/06	1.1	Oct.4/06	0.0
Jun.5/06	4.0	Jul.5/06	2.3	Aug.5/06	4.2	Sept.5/06	1.1	Oct.5/06	1.9
Jun.6/06	5.0	Jul.6/06	3.6	Aug.6/06	3.1	Sept.6/06	1.9	Oct.6/06	2.3
Jun.7/06	4.6	Jul.7/06	5.3	Aug.7/06	2.9	Sept.7/06	2.5	Oct.7/06	2.3
Jun.8/06	3.3	Jul.8/06	5.6	Aug.8/06	4.5	Sept.8/06	2.2	Oct.8/06	2.1
Jun.9/06	0.0	Jul.9/06	3.9	Aug.9/06	4.1	Sept.9/06	0.2	Oct.9/06	0.8
Jun.10/06	5.1	Jul.10/06	0.7	Aug.10/06	3.8	Sept.10/06	2.7	Oct.10/06	1.4
Jun.11/06	3.2	Jul.11/06	2.8	Aug.11/06	5.8	Sept.11/06	1.6	Oct.11/06	0.0
Jun.12/06	2.7	Jul.12/06	0.0	Aug.12/06	5.2	Sept.12/06	0.0	Oct.12/06	0.5
Jun.13/06	3.6	Jul.13/06	4.4	Aug.13/06	5.2	Sept.13/06	0.4	Oct.13/06	0.0
Jun.14/06	6.7	Jul.14/06	3.8	Aug.14/06	0.5	Sept.14/06	0.0	Oct.14/06	0.2
Jun.15/06	6.3	Jul.15/06	4.0	Aug.15/06	3.0	Sept.15/06	0.7	Oct.15/06	1.5
Jun.16/06	6.2	Jul.16/06	4.3	Aug.16/06	4.1	Sept.16/06	1.0	Oct.16/06	1.1
Jun.17/06	6.2	Jul.17/06	4.4	Aug.17/06	3.1	Sept.17/06	1.5	Oct.17/06	0.0
Jun.18/06	2.8	Jul.18/06	5.1	Aug.18/06	3.8	Sept.18/06	0.0	Oct.18/06	1.0
Jun. 19/06	2.7	Jul.19/06	4.2	Aug.19/06	0.7	Sept.19/06	0.7	Oct.19/06	0.0
Jun.20/06	5.2	Jul.20/06	1.1	Aug.20/06	0.0	Sept.20/06	0.7	Oct. 20/06	0.0
Jun.21/06	1.4	Jul.21/06	3.3	Aug.21/06	4.4	Sept.21/06	1.7	Oct. 21/06	1.0
Jun.22/06	3.6	Jul.22/06	0.3	Aug.22/06	3.8	Sept.22/06	0.1	Oct. 22/06	0.0
Jun.23/06	4.9	Jul.23/06	2.0	Aug.23/06	3.5	Sept.23/06	0.0		
Jun.24/06	5.4	Jul.24/06	3.7	Aug.24/06	1.0	Sept.24/06	0.0		
Jun.25/06	5.2	Jul.25/06	1.7	Aug.25/06	0.0	Sept.25/06	1.0		
Jun.26/06	0.5	Jul.26/06	0.7	Aug.26/06	0.0	Sept.26/06	1.9		
Jun.27/06	1.1	Jul.27/06	1.9	Aug.27/06	0.1	Sept.27/06	0.5		
Jun.28/06	3.4	Jul.28/06	2.6	Aug.28/06	1.3	Sept.28/06	0.0		
Jun.29/06	1.4	Jul.29/06	2.4	Aug.29/06	1.6	Sept.29/06	1.3		
Jun.30/06	3.3	Jul.30/06	2.0	Aug.30/06	3.1	Sept.30/06	0.0		
		Jul.31/06	3.5	Aug.31/06	3.3				

Control Roof Daily Potential ET Rates

Date	ET (mm/day)	Date	ET (mm/day)	Date	ET (mm/day)	Date	ET (mm/day)	Date	ET (mm/day)
Jun.1/06	2.5	Jul.1/06	6.0	Aug.1/06	5.9	Sept.1/06	3.8	Oct.1/06	1.8
Jun.2/06	2.0	Jul.2/06	5.0	Aug.2/06	4.1	Sept.2/06	0.0	Oct.2/06	2.6
Jun.3/06	1.5	Jul.3/06	5.7	Aug.3/06	0.0	Sept.3/06	0.0	Oct.3/06	2.2
Jun.4/06	5.2	Jul.4/06	5.4	Aug.4/06	5.5	Sept.4/06	1.9	Oct.4/06	0.0
Jun.5/06	6.0	Jul.5/06	4.1	Aug.5/06	6.8	Sept.5/06	1.6	Oct.5/06	2.9
Jun.6/06	7.8	Jul.6/06	5.6	Aug.6/06	5.3	Sept.6/06	3.0	Oct.6/06	3.5
Jun.7/06	7.0	Jul.7/06	8.1	Aug.7/06	4.8	Sept.7/06	3.9	Oct.7/06	3.4
Jun.8/06	5.0	Jul.8/06	8.3	Aug.8/06	6.9	Sept.8/06	3.5	Oct.8/06	3.2
Jun.9/06	0.3	Jul.9/06	5.9	Aug.9/06	6.7	Sept.9/06	0.7	Oct.9/06	1.3
Jun.10/06	7.3	Jul.10/06	2.1	Aug.10/06	5.7	Sept.10/06	4.0	Oct.10/06	2.2
Jun.11/06	5.2	Jul.11/06	4.9	Aug.11/06	8.4	Sept.11/06	2.7	Oct.11/06	0.0
Jun.12/06	4.8	Jul.12/06	0.0	Aug.12/06	7.9	Sept.12/06	0.0	Oct.12/06	1.1
Jun.13/06	5.5	Jul.13/06	7.3	Aug.13/06	7.9	Sept.13/06	1.0	Oct.13/06	0.1
Jun.14/06	9.6	Jul.14/06	6.2	Aug.14/06	1.0	Sept.14/06	0.0	Oct.14/06	0.6
Jun.15/06	8.9	Jul.15/06	6.7	Aug.15/06	4.9	Sept.15/06	1.3	Oct.15/06	2.2
Jun.16/06	8.4	Jul.16/06	6.6	Aug.16/06	6.6	Sept.16/06	1.6	Oct.16/06	1.6
Jun.17/06	8.8	Jul.17/06	6.8	Aug.17/06	5.1	Sept.17/06	2.7	Oct.17/06	0.0
Jun.18/06	4.8	Jul.18/06	7.9	Aug.18/06	6.1	Sept.18/06	0.0	Oct.18/06	0.0
Jun. 19/06	4.5	Jul.19/06	6.7	Aug.19/06	1.3	Sept.19/06	1.4	Oct.19/06	0.0
Jun.20/06	7.5	Jul.20/06	2.0	Aug.20/06	0.5	Sept.20/06	1.5	Oct. 20/06	0.0
Jun.21/06	2.4	Jul.21/06	5.4	Aug.21/06	6.8	Sept.21/06	2.6	Oct. 21/06	0.4
Jun.22/06	5.4	Jul.22/06	0.9	Aug.22/06	5.8	Sept.22/06	0.5	Oct. 22/06	0.0
Jun.23/06	7.1	Jul.23/06	3.4	Aug.23/06	5.2	Sept.23/06	0.3		
Jun.24/06	8.3	Jul.24/06	6.0	Aug.24/06	2.0	Sept.24/06	0.0		
Jun.25/06	7.9	Jul.25/06	3.4	Aug.25/06	0.0	Sept.25/06	1.8		
Jun.26/06	1.4	Jul.26/06	2.1	Aug.26/06	1.0	Sept.26/06	2.9		
Jun.27/06	2.3	Jul.27/06	3.6	Aug.27/06	0.9	Sept.27/06	1.3		
Jun.28/06	5.5	Jul.28/06	5.0	Aug.28/06	2.4	Sept.28/06	0.1		
Jun.29/06	3.1	Jul.29/06	4.4	Aug.29/06	2.9	Sept.29/06	2.1		
Jun.30/06	5.5	Jul.30/06	3.5	Aug.30/06	5.0	Sept.30/06	0.0		
		Jul.31/06	6.0	Aug.31/06	5.4				

Total Phosphorus Concentrations in Rainfall and Runoff Samples from the Vegetated & Control Roofs

Storm Event	**Vegetated Roof**	**(µg/L)**					
Julian Day	**Number of Samples**	**Minimum**	**Maximum**	**Mean**	**Median**	**Std. Deviation**	**Std. Error**
207	12	33.8	104.7	68.7	65.8	21.3	6.2
245	12	67.0	187.1	109.6	98.9	39.0	11.3
261	12	94.7	162.5	131.4	134.4	23.9	6.9
266	12	94.4	139.5	108.7	104.9	14.4	4.1
270	12	67.5	105.0	84.8	84.7	9.7	2.8
273	12	54.1	204.8	95.6	80.8	46.1	13.3
Average		68.6	150.6	99.8		25.7	7.4
Storm Event	**Control Roof**	**(µg/L)**					
Julian Day	**Number of Samples**	**Minimum**	**Maximum**	**Mean**	**Median**	**Std. Deviation**	**Std. Error**
207	11	6.3	29.0	12.3	9.3	8.2	2.4
245	12	3.3	102.9	36.9	33.0	30.3	8.8
261	12	7.0	43.4	15.8	10.6	12.1	3.5
266	9	1.0	10.7	4.3	4.7	4.0	1.2
270	12	2.4	17.5	9.5	8.7	4.7	1.4
273	9	2.7	21.6	8.5	6.4	8.0	2.3
Average		**6.3**	**37.5**	**15.4**		**11.2**	**3.2**
Storm Event	**Rainfall**	**(µg/L)**					
Julian Day	**Number of Samples**	**Minimum**	**Maximum**	**Mean**	**Median**	**Std. Deviation**	**Std. Error**
207	1	14.4	14.4	14.4	-	-	-
245	1	33.3	33.3	33.3	-	-	-
261	1	15.3	15.3	15.3	-	-	-
266	1	5.0	5.0	5.0	-	-	-
270	1	15.6	15.6	15.6	-	-	-
273	1	19.3	19.3	19.3	-	-	-
Average		**16.9**	**16.9**	**16.9**			

Soluble Reactive Phosphorus Concentrations in Rainfall & Runoff Samples from the Vegetated & Control Roofs

Storm Event	**Vegetated Roof**	**(µg/L)**					
Julian Day	**# of valid Samples**	**Minimum**	**Maximum**	**Mean**	**Median**	**Std. Deviation**	**Std. Error**
207	12	7.7	68.0	34.6	34.9	20.3	5.9
245	12	27.6	98.0	44.2	37.0	21.1	6.1
261	12	38.2	79.5	60.6	67.0	13.5	3.9
266	12	25.9	68.7	50.2	54.7	12.3	3.5
270	12	14.4	47.5	30.2	29.7	10.6	3.1
273	12	12.0	31.9	20.3	20.0	6.5	1.9
Average		**20.9**	**65.6**	**40.0**		**14.1**	**4.1**
Storm Event	**Control Roof**	**(µg/L)**					
Julian Day	**# of valid Samples**	**Minimum**	**Maximum**	**Mean**	**Median**	**Std. Deviation**	**Std. Error**
207	0	n/a	n/a	n/a	-	n/a	n/a
245	1	2.6	2.6	2.6	-	n/a	n/a
261	2	11.5	12.5	12.0	12.0	0.7	0.5
266	2	2.9	4.2	3.5	3.0	1.0	0.7
270	1	2.3	2.3	2.3	-	n/a	n/a
273	1	2.4	2.4	2.4	-	n/a	n/a
Average		**4.3**	**4.8**	**4.6**		**0.8**	**0.6**
Storm Event	**Rainfall**	**(µg/L)**					
Julian Day	**# of valid Samples**	**Minimum**	**Maximum**	**Mean**	**Median**	**Std. Deviation**	**Std. Error**
207	0	-	-	-	-	-	-
245	0	-	-	-	-	-	-
261	0	-	-	-	-	-	-
266	1	2.1	2.3	2.2	2.2	-	-
270	0	-	-	-	-	-	-
273	0	-	-	-	-	-	-
Average		-	-	-	-	-	-

Suspended Solid Concentrations

Storm Event	**Vegetated Roof**	**(mg/L)**					
Julian Day	**# of valid Samples**	**Minimum**	**Maximum**	**Mean**	**Median**	**Std. Deviation**	**Std. Error**
207	12	0.0	10.1	5.0	4.9	3.7	1.1
245	12	0.0	10.0	4.5	4.9	3.3	1.0
261	12	4.9	10.1	5.4	5.0	1.5	0.4
266	12	0.0	5.1	4.2	5.0	2.0	0.6
270	12	4.9	14.9	6.4	5.0	3.3	1.0
273	12	4.4	15.0	8.3	9.9	3.3	1.0
Average		**2.4**	**10.9**	**5.6**		**2.8**	**0.8**
Storm Event	**Control Roof**	**(mg/L)**					
Julian Day	**# of valid Samples**	**Minimum**	**Maximum**	**Mean**	**Median**	**Std. Deviation**	**Std. Error**
207	12	0.0	29.9	9.6	9.9	7.5	2.2
245	12	0.0	66.0	19.9	15.3	19.3	5.6
261	12	0.0	15.4	4.2	5.0	4.8	1.4
266	12	0.0	5.1	2.9	4.9	2.6	0.7
270	12	0.0	15.2	9.2	10.0	5.2	1.5
273	12	0.0	15.5	4.3	5.0	4.9	1.4
Average		**0.0**	**24.5**	**8.3**		**7.4**	**2.1**
Storm Event	**Rainfall**	**(mg/L)**					
Julian Day	**# of valid Samples**	**Minimum**	**Maximum**	**Mean**	**Median**	**Std. Deviation**	**Std. Error**
207	1	6.5	6.5	6.5	-	-	-
245	1	4.9	4.9	4.9	-	-	-
261	1	0.8	0.8	0.8	-	-	-
266	1	0.0	0.0	0.0	-	-	-
270	1	1.8	1.8	1.8	-	-	-
273	1	0.0	0.0	0.0	-	-	-
Average		**2.3**	**2.3**	**2.3**	-	-	-

Copper Concentrations in Rainfall and Runoff from the Vegetated and Control Roofs

Sample Source	Storm Julian Day	N Statistic	Range Statistic (mg/L)	Minimum Statistic (mg/L)	Maximum Statistic (mg/L)	Mean Statistic (mg/L)	Std. Error	Std. Deviation Statistic	Variance Statistic
Vegetated	207	12	3.22	0.11	3.33	1.52	0.30	1.05	1.11
Roof	245	12	1.6	0.55	2.15	1.27	0.14	0.46	0.21
	261	12	0.52	0.24	0.76	0.48	0.05	0.17	0.03
	273	12	0.67	0.25	0.91	0.50	0.05	0.18	0.03
	Average	**12**	**1.50**	**0.29**	**1.79**	**0.94**	**0.14**	**0.46**	**0.35**
Control	207	12	5.52	0.34	5.86	1.81	0.51	1.75	3.06
Roof	245	12	0.73	0.22	0.95	0.60	0.08	0.26	0.07
	261	12	0.32	0.27	0.58	0.42	0.04	0.12	0.02
	273	12	1.19	0.39	1.59	0.86	0.12	0.42	0.18
	Average	**12**	**1.94**	**0.31**	**2.25**	**0.92**	**0.18**	**0.64**	**0.83**
Rainfall**	207	1		6.86	6.86	6.86			
	245	1		0.29	0.29	0.29			
	261	1		1.24	1.24	1.24			
	273	1		4.13	4.13	1.56			
	Average	**1**		**3.13**	**3.13**	**3.13**			

** Composite Sample

Zinc Concentrations in Rainfall and Runoff from the Vegetated and Control Roofs

Sample Source	Storm Julian Day	N Statistic	Range Statistic (mg/L)	Minimum Statistic (mg/L)	Maximum Statistic (mg/L)	Mean Statistic (mg/L)	Std. Error	Std. Deviation Statistic	Variance Statistic
Vegetated	207	12	0.55	0.12	9.45	0.39	0.04	0.15	0.02
Roof	245	12	0.22	0.18	0.29	0.28	0.02	0.07	0.00
	261	12	0.36	0.09	1.24	0.21	0.03	0.09	0.01
	273	12	0.11	0.05	4.16	0.09	0.01	0.04	0.00
	Average	**12**	**0.31**	**0.11**	**3.78**	**0.24**	**0.03**	**0.09**	**0.01**
Control	207	12	1.11	0.33	0.67	0.67	0.09	0.32	0.10
Roof	245	12	0.65	0.12	0.40	0.48	0.07	0.25	0.06
	261	12	0.16	0.15	0.46	0.26	0.02	0.06	0.00
	273	12	0.28	0.10	0.17	0.28	0.03	0.09	0.01
	Average	**12**	**0.55**	**0.18**	**0.42**	**0.42**	**0.05**	**0.18**	**0.04**
Rainfall**	207	1	0	2.25	2.25	2.25			
	245	1	0	0.81	0.81	0.81			
	261	1	0	1.13	1.13	1.13			
	273	1	0	0.98	0.98	0.98			
	Average	**1**	**0**	**1.29**	**1.29**	**1.29**			

** Composite Samples

Chromium Concentrations in Rainfall and Runoff from the Vegetated and Control Roofs

Sample Source	Storm Julian Day	N Statistic	Range Statistic (mg/L)	Minimum Statistic (mg/L)	Maximum Statistic (mg/L)	Mean Statistic (mg/L)	Std. Error	Std. Deviation Statistic	Variance Statistic
Vegetated	207	11	0.05	0.01	0.06	0.04	0.005	0.016	0.00025
Roof	245	12	0.02	0.09	0.11	0.10	0.002	0.007	0.00005
	261	12	0.02	0.12	0.13	0.13	0.002	0.006	0.00003
	273	12	0.01	0.13	0.14	0.13	0.001	0.005	0.00002
	Average	**12**	**0.03**	**0.09**	**0.11**	**0.10**	**0.002**	**0.008**	**0.00009**
Control	207	12	0.03	0.06	0.09	0.08	0.003	0.009	0.00008
Roof	245	12	0.01	0.11	0.12	0.11	0.001	0.004	0.00002
	261	12	0.01	0.13	0.14	0.13	0.001	0.004	0.00002
	273	12	0.01	0.12	0.14	0.13	0.001	0.004	0.00002
	Average	**12**	**0.02**	**0.11**	**0.12**	**0.11**	**0.002**	**0.005**	**0.00003**
Rainfall**	207	1	0	0.06	0.06	0.06			
	245	1	0	0.12	0.12	0.12			
	261	1	0	0.12	0.12	0.12			
	273	1	0	0.13	0.13	0.13			
	Average	**1**	**0**	**0.11**	**0.11**	**0.11**			

** Composite Sample

Cadmium Concentration in Rainfall and Runoff from the Vegetated and Control Roofs

Sample Source	Storm Julian Day	N Statistic	Range Statistic (mg/L)	Minimum Statistic (mg/L)	Maximum Statistic (mg/L)	Mean Statistic (mg/L)	Std. Error	Std. Deviation Statistic	Variance Statistic
Vegetated	207	11	0.02	0.00	0.02	0.01	0.0015	0.0048	0.000023
Roof	245	12	0.01	0.02	0.03	0.03	0.0007	0.0024	0.000006
	261	12	0.01	0.03	0.04	0.04	0.0007	0.0026	0.000007
	273	12	0.01	0.04	0.04	0.04	0.0005	0.0019	0.000003
	Average	**12**	**0.01**	**0.02**	**0.03**	**0.03**	**0.001**	**0.003**	**0.000010**
Control	207	12	0.009	0.02	0.02	0.02	0.0008	0.003	0.000007
Roof	245	12	0.008	0.03	0.03	0.03	0.0008	0.003	0.000007
	261	12	0.009	0.04	0.05	0.04	0.0008	0.003	0.000007
	273	12	0.008	0.04	0.05	0.04	0.0007	0.002	0.000006
	Average	**12**	**0.009**	**0.03**	**0.04**	**0.03**	**0.0008**	**0.003**	**0.000007**
Rainfall**	207	1	0	0	0	0			
	245	1	0	0.03	0.03	0.03			
	261	1	0	0.04	0.04	0.04			
	273	1	0	0.05	0.05	0.05			
	Average	**1**	**0**	**0.03**	**0.03**	**0.03**			

**Composite Sample