FINAL

Green Roof Performance Study

Seattle Public Utilities

Seattle Public Utilities

June 2012

Prepared by

Cardno TEC
Cardno TEC, Inc.
2825 Eastlake Avenue East, Suite 300
Seattle, Washington 98102

This publication, methodology, and associated monitoring activities were funded in part through a King Conservation District Member Jurisdiction & WRIA Forum Grant.

EXECUTIVE SUMMARY

Over the past ten years, Seattle Public Utilities (SPU) has considered green roofs one of its promising sustainable strategies for stormwater management within Seattle's (City) highly urban areas. Given this, numerous questions have been posed regarding the benefit of green roofs as a stormwater management strategy in Seattle's climate. For example, how effective are green roofs at reducing overall runoff volume and peak flow rates given our climate's low-intensity rainfall patterns? And specifically, during the rainy season (November through March), can green roofs effectively reduce stormwater runoff volumes and peak flows entering into the City's combined sewer system? To answer such questions, SPU managers identified the need to better understand how green roofs perform for stormwater control in the Seattle region. In turn, the City could further develop stormwater codes and appropriately focus incentive programs based on the stormwater benefit received through increasing green roof coverage across the City.

In 2005, SPU initiated discussions to answer such questions. At that time, there were very few green roofs on public or commercial buildings in Seattle. In addition, regional research quickly revealed that green roof performance data for Seattle, as well as the Pacific Northwest region, was limited. Thus, SPU, in conjunction with the City of Seattle's Office of Sustainability and Environment (OSE) embarked on the Green Roof Performance Study (GRPS). This study focused on developing a high-quality, continuous data set that can be used to understand the hydrologic performance of green roofs within Seattle.

The first study objective was to identify monitoring guidelines to ensure consistent data collection for all hydrologic parameters of interest across all green roof monitoring sites. Both SPU and OSE worked closely with Cardno TEC, Inc. (Cardno TEC [formerly Taylor Associates, Inc.])[1] to develop design guidelines for monitoring the performance of green roofs. The monitoring guidelines (Taylor Assoc. 2006) recommend a mass balance approach to measure the hydrologic (water quantity) performance of green roofs. In support of this approach, data parameters monitored included flow (runoff), irrigation input, and weather parameters including rainfall, air temperature, relative humidity, solar radiation, and wind. In addition to hydrologic parameters, the monitoring guidelines called for collecting flow-weighted storm event composite samples to characterize the water quality of green roof runoff.

While writing the green roof monitoring guidelines, site selection was initiated through a rapid assessment process. Proposed monitoring sites were visited and site plans reviewed to determine the most feasible sites to collect cost-effective, quality data to meet the overall study goal. At the completion of the rapid assessments, five buildings were selected [Seattle Parks and Recreation's Ross Playfield (Park) Shelterhouse, Woodland Park Zoo's Zoomazium (Zoomazium), Seattle Public Library's Ballard Branch (Ballard Library), City of Seattle's Fire Station 10 (FS10), and City of Seattle's Emergency Operations Center (EOC)]. Plans for adding a sixth building (Seattle Center's 5th Avenue N. Parking Garage) were abandoned due to funding limitations. Upon selection, each site's conceptual monitoring design (also developed

[1] The Green Roof Performance Study was completed by Taylor Associates, Inc., which became the Water Resources Division of Cardno TEC, Inc., in October 2011.

during the rapid assessment process) was then realized by the Cardno TEC project team through collaboration with each site's building owner, mechanical and electrical engineers, and architects and landscape architects.

Data collection for the first of the five buildings began at the Zoomazium in early 2007. The monitoring system began testing in February 2007 and was officially brought on-line the following month. Two more green roof monitoring sites came on-line late in 2007 (Ballard Library in May 2007, Ross Park Shelterhouse in October 2007) and the fourth and fifth (FS10 and EOC) in May 2008. A total of five separate green roofs and two conventional (control) roofs were monitored across the five buildings. The monitored conventional roofs were located on the Ross Park Shelterhouse and EOC building.

At the start of the study, the objective was to collect three years of data for each monitoring site and perform quality assurance and quality control (QA/QC) for each data set. In late 2008, project tasks had to be reprioritized based on changes in available project funding. At the end of the study, the following data collection and QA/QC was completed:

- A continuous, three-year data set was collected and QA/QC'd for three green roofs across three buildings; the Zoomazium, FS10, and EOC.
- A continuous, three-year data set was collected for one conventional roof at the EOC. (Note: Due to budget constraints, this study included QA/QC for only two quarters of the conventional roof flow data set.)
- Continuous, one-year data sets were collected for two green roofs and one conventional roof across two buildings; Ballard Library (one green roof) and Ross Park Shelterhouse (one green roof and one conventional roof).
- Data QA/QC was completed for three months of the 12-month Ross Park Shelterhouse data set.
- Data QA/QC was completed for three months of the 12-month Ballard Library data set.

Thus, the data analysis results presented in this report includes data collected and QA/QC'd for the Zoomazium (one green roof), FS10 (one green roof), and EOC (one green roof and one conventional roof) monitoring sites. The SPU green roof modeling effort is currently in progress and expected to be complete later in 2012. Therefore, modeling results are currently not available for this report.

Study Results

The data analyses performed as part of this study provides a basic understanding of the hydrologic performance of the monitored green roofs in terms of runoff volume reduction and peak flow reduction. The methods for quantitative analyses are described and the results of those analyses are presented herein. A qualitative analysis discussion on (1) the significance of increased runoff travel time (lag time) and (2) the effects of antecedent moisture and rainfall event patterns on green roof runoff is also presented.

Selected event rainfall and corresponding unit area peak runoff data from the EOC conventional roof were used to evaluate the effectiveness of the green roofs in reducing peak runoff rates. The median estimated peak flow reduction percentages are 53.3% (SD±7.8), 28.6% (SD±9.1) and 15.0% (SD±28.4), for the EOC, FS10, and Zoomazium green roofs, respectively. Runoff volume reduction on each of the greens roofs was evaluated on the quarterly basis and for selected events. This analysis was completed by calculating runoff volume as a percentage of rainfall volume over each of the green roof areas. The percentage of rainfall volume represented in the runoff volume varies between the green roofs. Generally, for all three green roofs, the runoff percentages increase during the wetter seasons approaching 100% and decrease during the dryer seasons to approximately 30% or lower.

Each of the roofs produces a rainfall-runoff response reflective of their unique physical, hydrologic, and hydraulic characteristics and processes. The differences in performance are attributable to several variables including:

- differences in size, shape, and slope on the roofs,
- antecedent soil moisture conditions,
- magnitude and distribution of rainfall events,
- vegetative conditions, and
- runoff travel path.

The effectiveness of green roofs for stormwater runoff control in the Seattle climate is mixed. The capacity of these systems to provide long term (seasonal) runoff volume reduction varies significantly depending on the season. During extended rainy periods, runoff volume control provided by these green roofs is limited due to the relatively thin soil profile, reduced evapotranspiration and the direct connection of the underlying drainage layer to the roof drain system.

Effectiveness in peak flow reduction, however, can be significant even during extended rainy periods due to the increased runoff travel time compared to that of a conventional roof. Also, substantial recovery (drying out) of the soil profile even during the wet season can occur over a dry period of only a few hours. Therefore, peak runoff rate reduction for intermittent rainfall events is significant year around.

The study findings presented reflect the stated purpose in the project scope of work. Additional future work that could be performed using and building on these findings include:

- Producing hydrologic model calibrations for each of the green roof data sets.
- Applying calibrated green roof hydrologic models in evaluating the usefulness of green roof systems in reducing basin specific confined sewer overflow occurrences.
- Using data and models to optimize green roof design parameters including size, shape, slope, soil depth, and drainage layer medium.
- Investigating the use of automated irrigation triggered by real time soil moisture monitoring.

- Comparing findings of this study with those of other similar studies performed in similar or different climates.
- Integrating the findings of this study with those of other studies focusing on other benefits, such as reducing urban heat sources, effects of increasing urban habit, or the effects of green roofs on energy efficiency related to operation of HVAC systems. This could provide for a holistic evaluation of the benefits of green roofs.

TABLE OF CONTENTS

List of Tables

List of Figures

Appendices

(*electronic only*)

ABBREVIATIONS AND ACRONYMS

AKART	all known and reasonable technology
CSO	combined sewer overflow
DQER	Data Quality Evaluation Report
EOC	Emergency Operations Center
EPA	Environmental Protection Agency
FS10	Fire Station 10
gpm	gallons per minute
GRPS	Green Roof Performance Study
HDPE	high density polyethylene
HVAC	heating, ventilation, and air conditioning
IP	internet protocol
LID	low-impact development
MEP	maximum extent practicable
MGS	MGS Flood
NPDES	National Pollutant Discharge Elimination System
OSE	City of Seattle Office of Sustainability and Environment
PCHB	Pollution Control Hearings Board
PVC	polyvinyl chloride
QA	quality assurance
QC	quality control
RL	reporting limit
SCPG	Seattle Center 5th Avenue N. Parking Garage
sf	square feet
SGRM	Seattle Green Roof Model
SPU	Seattle Public Utilities
SWMM	Storm Water Management Model
WWHM	Western Washington Hydrology Model

1.0 INTRODUCTION

Green roofs—sometimes called living roofs or eco-roofs—are rooftops covered by growing media and vegetation. The benefits of such roofs are numerous and include stormwater retention, rain water filtration, reductions in building energy costs, increased air quality, improvement of architectural and landscape aesthetics, and increased biodiversity and habitat, among other benefits (Dunnett and Kingsbury 2004, Earth Pledge Foundation 2005, Moran et al. 2004, NRCC 2002, and Peck and Goucher 2005). For stormwater benefits, many European and North American cities have documented a performance for reducing and attenuating stormwater runoff volume (Herman 2003, Hutchinson et al. 2003, Mentens et al. 2003, Mentens et al. 2005, and Moran 2004). In the Pacific Northwest region, there have been several green roof monitoring projects (Connelly 2011, Hutchinson et al. 2003, Johnston et al. 2004, Spolek 2005, Taylor and Gangnes 2004). However, prior to 2005, only one study (Taylor and Gangnes 2004, Taylor et al. 2005) was specific to the Seattle climate. Prompted by limited green roof performance data, Seattle Public Utilities (SPU) embarked on a long-term study of green roofs, the Green Roof Performance Study (GRPS).

The Green Roof Performance Study was initiated in 2005 to support development of City of Seattle green roof policies, codes, and incentive programs. The city's goal being to develop stormwater management policies and incentive programs based on the stormwater benefits expected for the Seattle climate. To achieve this, SPU is using a regional hydrology model to predict performance. However, a model's ability to predict green roof runoff in Seattle is in-part dependent on region-specific data. Thus, the main goal of the GRPS was to collect a long-term, continuous data set for model calibration. This report documents the six and half year effort to collect this data; from the conceptual phase, through site selection and data collection, and ending with preliminary data analysis and results. The SPU green roof modeling effort is currently in progress, and thus, modeling results are not presented in this report.

1.1 BACKGROUND

The Puget Sound faces chronic pollutant loading to its receiving waters from stormwater runoff. Degraded urban and suburban streams, lakes, and marine ecosystems need a long term management plan for sustainability. Alternative approaches to conventional conveyance and treatment are being implemented as part of evolving stormwater management practices and required by federal permits. In 2008, the Pollution Control Hearings Board (PCHB) determined that the "Phase I [NPDES] Permit must be modified to require the use of LID [low-impact development] where feasible, as it is necessary to meet the MEP [maximum extent practicable] and AKART [all known and reasonable technology] standards of federal and state law, respectively" (PCHB 2008). Low-impact development mitigates the effects of development and stormwater at a parcel and sub-parcel scale by attempting to mimic pre development hydrologic conditions. Combined with conventional methods LID provides municipalities with multiple methods for sustainable stormwater management. One such LID or Green Stormwater Infrastructure is a green roof.

Green roofs have been embraced by SPU as one of many Green Stormwater Infrastructure resources (SPU 2012). In 2005 when the GRPS initiated, data on the benefit of green roofs in reducing stormwater runoff was increasing. However, performance results for stormwater treatment and flow attenuation in the Seattle climactic region was limited (Wachter et al. 2007). In response, SPU and the City's Office of Sustainability and Environment (OSE) formed an interagency collaboration, which grew to include numerous public and private partners and stakeholders (Table 1-2, page 1-6).

To effectively move forward with green roof policy and code development, the City recognizes the need to quantify the benefit of green roofs in reducing and attenuating stormwater runoff. Currently engineers use hydrologic models to size detention ponds and vaults to meet standards within the Stormwater Management Manual for Western Washington. The available models for western Washington (WWHM, MGS Flood, SWMM) have access to very little continuous runoff data for green roofs, which is essential for calibrating how hydrologic models predict performance. In addition, green roofs currently have a runoff model representation of till landscaped area or till pasture depending on soil/media depth. This representation may change if current western Washington models can be calibrated with climate specific runoff data. A region-specific calibration would result in an improved management tool for predicting green roof runoff for the Seattle climate.

1.2 PHASE I AND II OVERVIEW

The main goal of the GRPS is to improve western Washington model predictions for green roof hydrologic performance. And more specifically for the City of Seattle, to improve model predictions of green roof performance for stormwater volume and flow control within the city's combined sewer overflow (CSO) basins. This goal led to numerous objectives (tasks) for the study, with the first being to develop green roof monitoring guidelines for the Cascadia region. The first phase of the project also included site selection, monitoring system design and installation, and initiation of data collection. Phase II involved completing data collection and data quality assurance and quality control (QA/QC), preliminary data analysis and reporting. At the end of Phase II, the designated continuous, hydrologic data sets are QC'd and ready for the SPU modeling team to initiate model calibration.

1.2.1 Green Roof Monitoring Guidelines

In the fall of 2005, SPU and OSE collaboratively began work on the first phase (Phase I) of the GRPS. The first objective was to develop guidelines for monitoring green roof performance. The guidelines (Taylor Assoc. 2006) establish a consistent monitoring approach for green roof studies with the intent to develop comparable data sets for green roof performance studies (by private and public stakeholders) in the region.

This first task supports the greater study effort of collecting weather, green roof runoff, and conventional roof runoff data from multiple sites across Seattle. This data set is being used by SPU to calibrate a green roof algorithm for a western Washington continuous hydrology model. Calibrating a continuous simulation model requires a continuous data set ideally with multiple consecutive dry and wet season cycles.

Due to the model calibration requirements for a continuous and high-quality data set, the monitoring guidelines are the foundation behind the GRPS. The guidelines recommend consistent data collection approaches for identified green roof hydrologic and water quality parameters. To complete the guidelines document, SPU and OSE worked closely with Cardno TEC, Inc. (Cardno TEC [formerly Taylor Associates, Inc.[2]]) to define recommendations and monitoring-specific content. The guidelines include:

- A common basis for monitoring of green roof hydrologic and water quality performance.
- An overview of reported monitoring efforts and results for green roofs in the northwest region.
- Recommendations for a minimum set of climatic parameters (e.g., wind, rainfall, temperature) and specific physiographic characteristics (e.g., soil permeability, roof slope) needed for evaluating factors that contribute to roof performance.
- Recommendations for the equipment, monitoring system layout and minimum parameters necessary to evaluate green roof performance relative to stormwater volume and flow control, and runoff water quality.
- Recommendations for selecting a "control" roof for comparison to a green roof (treated roof).
- Quality Assurance/Quality Control procedures necessary to assure high quality data.
- Timeline and project overview.

1.2.2 Seattle Green Roof Model Calibration

Seattle Public Utilities has developed a green roof hydrologic model named the Seattle Green Roof Model (SGRM) (She and Pang 2010), which uses the U.S. Environmental Protection Agency (EPA) SWMM5 for the final simulation result (SPU 2012). For this green roof model, the hydrologic process is modeled in three modules: the evapotranspiration module, the infiltration module, and the flow routing module.

For model calibration, a set of significant storm events is selected as input to the model to simulate a runoff response. Model parameters are then adjusted within a realistic range for each parameter with the objective to produce simulated (modeled) hydrographs matching the measured green roof runoff data (GRPS data). Through this calibration process, a set of hydrologic runoff parameters is defined for the SGRM based on measured green roof runoff specific to the climate of Seattle.

1.2.3 Rapid assessment phase and site selection

Once a standardized plan was established for regional monitoring, the next step was evaluating potential green roof locations for the feasibility of monitoring. Optimal post construction monitoring locations were difficult to find due to access limitations and the cost associated with retrofitting facilities for monitoring. Because building drainage systems are not designed with flow and water quality monitoring in mind, runoff is generally comingled with sections of the

[2] The Green Roof Performance Study was completed by Taylor Associates, Inc., which became the Water Resources Division of Cardno TEC, Inc., in October 2011.

conventional roof. This often requires expensive retrofits to separate and monitor green roof or conventional roof runoff separately.

In late 2005, SPU requested that Cardno TEC began to investigate numerous Seattle buildings as potential GRPS monitoring sites. The project team's task involved investigating buildings identified by SPU for feasibility of cost-effective monitoring (that is, can the site be monitored at a reasonable cost while meeting the study's data quality objectives). All proposed buildings were either:

- An existing structure with a green roof already installed.
- An existing structure with potential for a green roof retrofit.
- Under construction with plans for a green roof.
- In the design phase with a green roof proposed.

Four buildings were initially prioritized for rapid assessments. The buildings included City Hall, Justice Center, Zoomazium, and Seattle Public Library's Ballard Branch (Table 1-1). For each building's rapid assessment, the team was to determine and define the following:

- Overall feasibility to monitor.
- Logistical challenges with monitoring the roof runoff (conventional or green roof).
- Qualitative assessment of expense to monitor.
- If ultimate data quality would meet the study's data quality objectives.
- Potential to include a control (conventional) roof in the building's monitoring design.

Throughout the rapid assessment phase, numerous memorandums were prepared to provide a summary of the current investigation effort. These memorandums (Appendix B) include:

- A list of the potential monitoring sites assessed.
- Details of the activities completed for the investigation.
- A listing of pros and cons for selecting the building as a GRPS monitoring site.
- Recommendations for site selection.

Over the course of the study, numerous buildings were investigated for inclusion with ultimately six buildings selected for monitoring (Table 1-2). Of the six buildings selected for monitoring, five were actually monitored. Those buildings and the green roof characteristics are provided in the methods chapter (Table 2-1). The Seattle Center 5th Avenue N. Parking Garage (SCPG) was the only building selected for monitoring where the monitoring system design was not finalized and installed. Thus, data collection at this site was never initiated. Work on the SCPG was discontinued in fall 2008 due to a reduction in project funding.

Table 1-1 Buildings Included in the Rapid Assessment and Selected for Monitoring

Proposed Buildings	Site Visits Completed for Rapid Assessment to Determine Monitoring Feasibility	Buildings Selected for Monitoring under the GRPS
Ballard Branch, Seattle Public Library	Ballard Branch, Seattle Public Library	Ballard Branch, Seattle Public Library
Zoomazium, Woodland Park Zoo	Zoomazium, Woodland Park Zoo	Zoomazium, Woodland Park Zoo
Emergency Operations Center, Seattle Fleets and Facility		Emergency Operations Center Seattle Fleets and Facility
Fire Station 10, Seattle Fleets and Facility		Fire Station 10, Seattle Fleets and Facility
Ross Park Shelterhouse Seattle Parks and Recreation		Ross Park Shelterhouse, Seattle Parks and Recreation
Justice Center, City of Seattle	Justice Center, City of Seattle	
City Hall, City of Seattle	City Hall, City of Seattle	
Seattle Fleets and Facility warehouses on Charles Street and Airport Way S. *Sites proposed for green roof retrofit (roll-out)*	Seattle Fleets and Facility warehouses on Charles Street and Airport Way S.	
Seattle Center 5th Ave. N Parking Garage	Seattle Center 5th Ave. N Parking Garage	Seattle Center 5th Ave. N Parking Garage *Not monitored.*

Table 1-2 Green Roof Performance Study Sites and Monitoring Timelines

Building	Data Collection Timeline	Building Owner	Funding/Stakeholders
Fire Station 10 Emergency Operations Center (2 separate buildings)	March 2008 – June 2011	Seattle Fleets and Facilities	Seattle Public Utilities
			Department of Development and Planning
			Seattle Fleets and Facilities
			King Conservation District
Seattle Public Library Ballard Branch	May 2007 – June 2008	Seattle Public Library	Seattle Public Utilities
			Seattle Public Library
			University of Washington
			King Conservation District
Ross Park Shelterhouse	October 2007 – October 2008	Seattle Parks and Recreation	Seattle Public Utilities
			Office of Sustainability and Environment
			Seattle Parks and Recreation
			King Conservation District
Zoomazium	February 2007 – March 2010	Woodland Park Zoo	Seattle Public Utilities
			Woodland Park Zoo
			Seattle Parks and Recreation
			King Conservation District
Seattle Center 5th Ave. N Parking Garage	Data collection not initiated.	Seattle Center (building owner) Bill & Melinda Gates Foundation (green roof owner)	Seattle Public Utilities
			Seneca Group LLC
			Seattle Center
			Bill & Melinda Gates Foundation

1.2.4 Decisions Made over the Project Timeline

Over the six year project timeline (July 2005 – March 2012), numerous decisions were made resulting in changes to how data was collected or data QA/QC was completed. Project decisions to change project direction or postpone activities were primarily made by SPU in the context of the City's study priorities relative to changes in available funding. Table 1-3 outlines the major activities and changes for each site across the entire data collection timeline.

Table 1-3 Project Timeline and SPU Project Decisions

Timeline	Activity/Task	Description/Decisions
July 2005	Round Table with PNW green roof stakeholders to discuss green roof data needs. Organized by OSE.	Recognition of need to design monitoring study. Need to further define study objectives and data collection methods.
Sept 2005	Rapid assessment process was initiated.	SPU to select green roof monitoring sites that: - Are feasible monitoring sites and meet the data collection objectives for the study. - Create public education opportunities to support the Mayor's Green Building Initiative.
Nov-Dec 2005	Rapid assessment of Airport Way S. and Seattle Fleets Facilities warehouses.	Warehouse sites were proposed for monitoring a conventional roof pre- and post-green roof treatment (that is, retrofit with a rollout green roof).
April 2006	Seattle Green Roof Guidelines completed.	See Section 1.2.1 for a description of guidelines content.
Feb 2007	Data collection begins at Zoomazium (Woodland Park Zoo).	Data collection for the first green roof (Zoomazium) began in early 2007, with two additional green roofs targeted to come on-line later in 2007. Target to collect 3-years of continuous hydrologic data.
March 2007	Water quality at the Zoomazium initiated. First water quality sample collected at Zoomazium.	Due to a reduction in funding, a decision was made to substantially reduce the water quality component of the green roof project and focus primarily on assessing hydrologic performance. Thus, only two storm events were sampled at the Zoomazium site. The results objective was redefined to determine presence/absence for identified parameters.
May 2007	Data collection begins at Ballard Branch (Seattle Public Library).	Data collection for the second green roof begins with target to collect 3-years of continuous hydrologic data.
Oct 2007	Data collection begins at Ross Park Shelterhouse.	Data collection for the third building (one green roof and one conventional roof at this site.
Nov 2007	Second water quality sample collected at Zoomazium.	Two storm events were sampled at the Zoomazium site. Results determine presence/absence for identified parameters.
Feb 2008	Rapid assessment process completed.	A fifth building was added to the GRPS monitoring site list, the Seattle Center Parking Garage with a 1.5 acre green roof. As of March 2012, this building has the largest green roof in Seattle and one of the largest in the PNW.
May 2008	Data collection begins at Fire Station 10 and Emergency Operations Center (Seattle Fleets & Facilities).	Data collection initiated for the final two buildings. The EOC building has one green roof and one conventional roof monitored at this site. FS10 has one green roof.
June 2008	Decision to stop monitoring design for Seattle Center Parking Garage.	With Sellen, pursue funding from Gates Foundation for water quality sampling. Due to lack of SPU funding, work to support monitoring of SCPG is temporarily put on-hold.

Timeline	Activity/Task	Description/Decisions
June 2008	Ross Park Shelterhouse data QA/QC process postponed.	Post-pone the Ross Park Shelterhouse data QA/QC effort due to an unplanned reduction in project funding. Only 3 months of data QC'd and one DQER completed.
August 2008	Ballard Library data QA/QC process postponed.	Post-pone the Ballard Library data QA/QC effort due to an unplanned reduction in project funding. Only 3 months of data QC'd and one DQER completed.
Sept 2008	Zoomazium data QA/QC process postponed.	Post-pone the Zoomazium data QA/QC effort due to an unplanned reduction in project funding.
Oct 2008	Design process for SCPG monitoring system postponed.	Post-pone the SCPG design process due to an unplanned reduction in project funding.
Dec 2008	GRPS project reduced to data collection for only the Zoomazium, FS10 and EOC buildings.	Reduce all efforts down to data collection only at three buildings due to an unplanned reduction in project funding.
Dec 2008	Monitoring of HVAC flows onto conventional roof.	Based on limited funding, decision to not monitor HVAC flow onto conventional roof. Determined inputs would be negligible when compared to total roof runoff.
Nov 2009	FS10/EOC data QA/QC initiated.	FS10/EOC initial data QA/QC funded by Seattle DPD until King Conservation District grant for Phase II is awarded.
March 2010	Data collection for Zoomazium is terminated early.	Data collection was to continue through June 2010. Magmeter malfunctioned and could not measure high flows after March 2010. Due to lack of funding, SPU decided not replace/repair the magmeter and ended the data collection period.
June 2010	Contract to support Phase II initiated.	Phase II funded solely with King Conservation District grant.
May 2011	Data collection ends at Fire Station 10 and Emergency Operations Center.	Data collection for the GRPS Phase I and II is complete.
Oct 2011	Zoomazium data QA/QC process reinitiated.	Upon review of the remaining GRPS Phase II budget and tasks to be completed, the SPU and Cardno TEC project managers determined that an additional task can be added to the current contract, completion of the Zoomazium data QA/QC effort.
Nov 2011	FS10/EOC data QA/QC complete.	Last DQER and QC'd data files for FS10 and EOC Center delivered to SPU.
Dec 2011	Zoomazium data QA/QC complete.	Last DQER and QC'd data files for Zoomazium delivered to SPU. The end of the data QA/QC process closes the GRPS data collection for Phase I and II of the study.
Jan 2012	SPU team begins model calibration with the GRPS data sets.	FS10, EOC and Zoomazium raw and QC'd data sets provided to SPU for model calibration.

Notes:
FS10 Fire Station 10
EOC Emergency Operations Center
DQER Data Quality Evaluation Report
DPD Department of Planning and Development
PNW Pacific Northwest

2.0 DATA COLLECTION METHODS

The following sections summarize the data collection methods for each selected monitoring site. Buildings include the Woodland Park Zoo's Zoomazium, Seattle Public Libraries' Ballard Branch, Seattle Fleets and Facilities' FS10 and EOC, and Seattle Parks and Recreation's Ross Playfield (Park) Shelterhouse. A summary of the green roofs characteristics is provided in Table 2-1. For the SCPG, data collection was never initiated. However, the monitoring system design phase was in progress when SPU decided to post-pone monitoring for this site. A description of this work is provided in Section 2.5.

2.1 ZOOMAZIUM

The Zoo's Zoomazium building is located to the north of the Zoo's western entrance on Greenwood Ave North in Seattle, Washington. The eastward facing green roof covers approximately 8,000 square feet (sf) and drains to one galvanized gutter that runs the length of the roof (Figure 2-1). Rainwater runoff percolates through the soil media and is collected in the gutter and dispersed onto a lower conventional roof. As runoff spreads across the roof it eventually spills over the edge of the roof into landscaped planting beds against the footing of the building. The slope is on a 225 foot radius curve, which is flat on the upper western side and transitions to a 3:12 pitch on the eastern side. The soil and vegetative composition of the green roof can be found in the implementation plan (Appendix A) and

Table 2-1. For this site, monitoring of flow and meteorological data began in February 2007 and continued through March 2010.[3]

The monitoring system was designed to measure onsite weather conditions and the full flow range estimated for runoff from the Zoomazium green roof. As with all the roofs monitored through this study, the low (trickle) flows from a green roof can be difficult to accurately measure. This required that sensors and flow meters be controlled by two dataloggers programmed to measure and record data. One recorded the rate of runoff, weather conditions, and irrigation while the second recorded the soil temperature and moisture. Flow monitoring equipment was installed on a lower conventional roof of the Zoomazium building near the gutter downspout. The weather monitoring sensors where installed on a mast directly above the flow monitoring equipment. A diagram of the monitoring stations and location for instrument installations can be found in the Zoomazium implementation plan (Appendix A).

[3] Zoomazium data collection was planned to continue through June 2010. However, the site's high-flow magmeter malfunctioned and could not measure high flows after March 2010. Due to lack of funding for equipment, SPU decided not replace or repair the magmeter and ended the data collection period.

Table 2-1 Summary of Green Roof Characteristics for the Seattle Green Roof Performance Study Sites

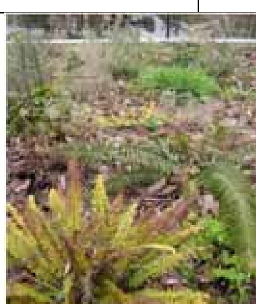
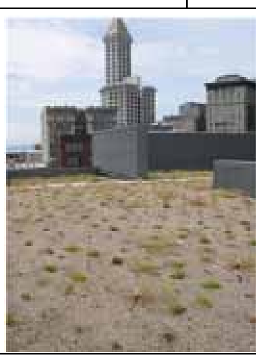
Building	Green Roof Area (~ft^2)	Slope	Soil Depth and Composition	Vegetation Type	
Zoomazium 	8,000	Variable from 0:12 to 3:12 on 225' radius curve	6 inches 65% mineral (pumice) 10% coarse sand 25% aged organics 5% fertilizers & amendments	Gaultheria shallon, Polystichum munitum Arctostaphylos uva-ursi Allium cernum	Sysyinchrium douglassii Fragaria chiloensis Lupinus polyphyllus
Ballard Library 	20,000	Variable from 2.5:12 to 0.5:12 on North and from 1:12 to 0.5:12 on South concave profile	4-5 inches 45% mineral 15% coarse sand 40% approved aged organic fertilizers and amendments-as specified	Achillea tomentosa America maritime Carex inops (pensylvanica) Eriphyllum lanatum Festuca rubra Festuca idahoensis Phlox subulata	Saxifrage cepitosa Sedum oreganum Sedum album Sedum spurium Sisyrinchium idahoensis Thymus serphyllum Triteleia hyacintha
Ross Park Shelterhouse 	876	1:16	6 inches American Hydrotech Lite-Top 40	Blechnum spicant Fragaria chiloensis Oxalis oregano Polystichum munitum Tiarella trifoliata unifoliata Callierigonella Dicranum	Drepandocladtus uncinatus Polytrichum Pogonatum Racomitrium canescens Eurhynchium Rhytidiadelphus loreus
FS10 EOC 	Two roofs FS10 6,400 EOC 7,475	1:24 for both roofs	2" drainage layer Roofmeadow® Type A Granular Drainage Media 4" growth layer Roofmeadow® Type M3 Growth Media	Sedum album micranthum Chloroticum Sedum slbum sp. Sedum spurium Whiteform Delosperma aberdeenesne Abbey White Silene waldsteinii Minuartia laricofolia	Sedum floriferum Weihenstephaner Gold Sedum sexangulare Delosperma nubigenum Baustoland Sedum sichotense Potentilla verna Draba azoides

Figure 2-1 Green Roof on the Zoomazium at the Woodland Park Zoo

Weather and flow measurements were collected and averaged over a five minute period, then stored to the memory of the corresponding datalogger. Access to the Zoo network was arranged so that data could be downloaded with a simple Ethernet connection; however, due to security firewall complications data was later collected by manual download. Raw data was backed up to an analog tape and kept as a physical backup at the Cardno TEC office. To save on equipment costs and improve data quality, the three existing gutter drains were consolidated into a drain in the center. Cardno TEC worked with the Zoomazium architect, Mithūn, and determined that the runoff from the entire roof could be directed into the center downspout. Riser pipes (Figure 2-2) were installed in the remaining drains allowing them to bypass, should the system become blocked.

Figure 2-2 Downspout Risers Installed in the Roof Gutter

2.1.1 Flow Monitoring

Initially, it proved problematic to accurately monitor the full range of flows from the Zoomazium green roof. Thus, a two-stage flow monitoring system was designed to accurately measure the wide range of flow rates that was estimated to runoff. Two designs were considered for the flow monitoring system. The first design included a HS Flume and tipping bucket combination, but required extensive roof modification. The second design included a tipping bucket flow meter and electromagnetic flow meter to measure the higher flows. Both design options had comparable capabilities, however, installation of a flume would have required modifications to the roof and subsequent increased monitoring costs.

The magmeter (Figure 2-3) installed to measure higher flow rates has diminishing accuracy as flow rates drop beneath 1.5 gallons per minute (gpm) which is why a tipping bucket (Figure 2-4) was added to the monitoring system. The tipping bucket is designed by the manufacturer to measure flow rates up to 2.0 gpm. However, prior to installation while testing and calibrating the instrument, Cardno TEC staff noted the tipping bucket did not tip at the expected rate as the flow approached 2.0 gpm. A decision was made to develop a calibration curve by recording the number of tips per minute at several different flow rates. This allowed for the development of a tips/minute to flow rate relationship. The tipping bucket calibration curve developed by Cardno TEC is included in the implementation plan (Appendix A). The installed monitoring station measured runoff as it passed through the magmeter, into the tipping bucket and onto the conventional roof.

Figure 2-3 Three Inch Unimag DP03ECTERPAA Dual Sensor Electromagnetic Flow Meter

Figure 2-4 Unidata 6506H Tipping Bucket Flow Meter

2.1.2 Weather Monitoring

A weather station that monitors wind speed, air temperature, relative humidity, and solar radiation was installed on the Zoomazium roof. The data collected, which are assumed to represent hydrologic input (rainfall) and output (evapotranspiration) conditions on the green roof, provide a basis for calibrating these processes within the hydrologic model. Each sensor was mounted to a mast secured to a center roof beam above the flow monitoring station (Figure 2-5). A rain gauge was placed on the conventional roof in a location that minimized interference from nearby trees or the elevated green roof. It was mounted to a plywood platform that both anchored and allowed it to be leveled during maintenance visits. Rain gauge tips were individually recorded by a datalogger and stored to memory. The rain and irrigation totals were used to calculate all moisture inputs to the green roof. Wires from each sensor were connected to the corresponding datalogger. Any unintentional effects from maintenance (that is, false rain gauge tips) were noted on the field sheet and later removed or corrected from the dataset.

Figure 2-5 Weather Station Containing Wind Speed, Air Temperature, Relative Humidity and Solar Radiation Sensors

2.1.3 Irrigation Monitoring

A permanent irrigation system was not a part of the original green roof design, but due to plant mortality irrigation became necessary during the dry summer months. Rotary sprinklers were attached to two hoses that ran from two bibs on the wall above the conventional roof. In 2009, a roof retrofit was completed with an automated sprinkler system that eliminated the need for maintenance workers to manually irrigate the green roof. The permanent irrigation system involved installing actuated valves and polyvinyl chloride (PVC) pipe for each of the rotary sprinkler heads providing some flexibility in timing and the volume delivered. To measure the irrigation, input turbine flow meters were connected to each wall connection. The combined meters recorded the total irrigation volume delivered to the green roof by sending an electric signal through a wire to the datalogger. During the winter months the meters were drained and encased in a Styrofoam insulated cover to protect internal parts from freezing.

2.1.4 Soil Moisture Content

Soil moisture and soil temperature data were collected as supplemental measurements. There were five soil moisture probes paired with five soil temperature sensors installed on the green roof. The sensors were installed in an "X" pattern, one at each of the 4 corners and one in the center. It is thought that this should represent the varying roof slope and shade conditions from nearby trees. Budget constraints did not allow the soil moisture content probes to be calibrated to the specific roof soil media type. Subsequently the data should not be used for soil porosity water storage estimates or other engineering calculations.

2.1.5 Water Quality Monitoring

Water quality samples were collected to determine presence or absence of specific parameters (i.e., metals, nutrients, suspended sediments). Two rain events (March 22, 2007, November 26, 2007) were sampled using an automated sampler to collect flow-weighted stormwater samples.

Samples were collected from the Zoomazium's one gutter through Teflon-lined tubing into four glass bottles. These samples were analyzed to determine presence/absence for specific pollutants. The Zoomazium water quality sampling plan and a complete list of analytes can be found in Appendix F.

For the composite sample, subsample frequency was flow-weighted per the runoff flow rate measured by the monitoring station. The auto-sampler was triggered to collect an aliquot (subsample) after a specified runoff volume flowed from the green roof. This ensured representative samples were collected over the rising and falling limb of the runoff hydrograph. Because water quality sampling was not included as a main objective for the study, all water quality sampling equipment was installed on a temporary basis and removed once sampling for each storm event was completed. All quality control samples were collected during a single event.

2.2 BALLARD LIBRARY

The Seattle Public Libraries' Ballard Branch (Figure 2-6) was the second roof to come on-line for the study and is located in Seattle's Ballard neighborhood at 5614 22nd Avenue Northwest. The library opened May 14, 2005, as part of the "Libraries for All" building program and was designed by Bohlin Cywinski Jackson and built by PCL Construction Services, Inc. Approximately 18,000 plants were used on the Ballard Library green roof, which covers approximately 20,000 sf. Three pairs of downspouts located in the center of the concave roof, capture runoff and redirect it to the combined sewer system. Solar panels were installed on the northern edge of the roof taking advantage of an unobstructed southern exposure. Monitoring for the Ballard Library green roof was initiated in May 2007 and completed in June 2008.

Figure 2-6 Green Roof on the Seattle Public Library Ballard Branch

Source: American Hydrotech

The monitoring system was controlled by a datalogger programmed to measure roof runoff, weather parameters, soil moisture, and irrigation. All parameters were logged every five minutes and downloaded to a base station computer every 24 hours via modem. The modem was assigned a static internet protocol (IP) address and connected to a cellular antenna allowing remote communication. Lack of access to an isolated rain leader pipe restricted the type and variety of flow monitoring equipment available and is often the case with post construction monitoring. To overcome the intrinsic site complications, Cardno TEC developed custom flow monitoring devices, which were inserted into the roof drains. In collaboration with the University of Washington, the inserts where taken to the Harris Hydraulics Laboratory to develop a stage-discharge relationship and calibration curve (Appendix A). This allowed for water level measurements in the roof drains to be converted to a flow rate.

2.2.1 Flow Monitoring

As stated above, the inaccessibility of the rain leader pipes, limited the options for a successful monitoring approach. Other studies have used a flume (Hutchinson et al. 2003) to monitor the flow; however, this has the potential to backup water onto the roof. A flume could measure the full flow range but is inaccurate at the very low end (0.1 gpm or less). An inability to accurately measure these low flows can result in a tendency to overestimate retention and underestimate runoff. To cover the wide range of flow rates, Cardno TEC developed inserts for the primary and overflow drains. The combination of the bypass and primary inserts provided measurement from approximately 0 to 160 gpm. The primary flow devices were constructed from PVC and contained a series of orifices that increased in size along the longitudinal axis of the insert (Figure 2-7). Roof runoff flowed into the insert, out the orifices, and down the drainpipe.

The bypass insert was constructed of PVC and to maintain drain capacity (in case of severe rain or a plugged primary drain) had a slightly larger diameter than the drain pipe. Three V-notch weirs were cut into a four-inch PVC pipe (Figure 2-8) to create a consistent flow control surface. Pressure transducers were then installed within the primary drain and behind the bypass inserts and calibrated to measure water level at the invert of the lowest orifice and v-notch weir.

Figure 2-7 Installation of the Primary Flow Device in the Roof Drain

Figure 2-8 Installation of the V-notch Weirs for Monitoring Bypass Flows in the Roof Drain

2.2.2 Weather Monitoring

A weather station was installed on the roof that monitored wind speed, air temperature, relative humidity, solar radiation, and rainfall. The architect requested that sensors be installed in areas of the roof that minimize interference with the intended design aesthetic. This required placing each sensor in a different location, so as to not be visible from the observation deck. Per the manufacturers instruction each sensor was given special care when installed to minimize potential influences from nearby structures. All sensors were hardwired to the datalogger, which logged each reading at a 5 minute interval. The rain gauge tipping bucket was placed on the roof of the viewing room and mounted to a platform. The platform was designed so that the tipping bucket rain gauge could be leveled across three separate points. If necessary this was done during bi-monthly maintenance visits. Any unintentional effects from maintenance activities (that is, false rain gauge tips.) were noted on the field sheet and later removed or corrected within the dataset.

2.2.3 Soil Moisture Content

Soil moisture data were collected as supplemental measurements. Four soil moisture sensors were installed on the green roof in a line running north-south to represent the varying roof slope and aspect. The two metal electrodes on the probe were inserted on an angle and with care to not puncture the roof membrane (Figure 2-9). Communication wires from the sensing bodies were run underneath the soil media surface and hardwired to the datalogger. Specifications for all sensors are in the implementation plan (Appendix A).

Figure 2-9 Installation of Soil Moisture Content Probe

2.2.4 Irrigation Monitoring

Moisture inputs from irrigation were measured with an in-line turbine flow meter. This meter recorded the volume delivered to the roof through hand watering and sprinklers. The face of the meter has an output wire that was connected directly to the datalogger. A pulse was sent to the datalogger every time a gallon was measured. During the wet season the irrigation was typically shut off. The meter was housed in a plastic irrigation enclosure beneath the soil media, which insulated it from freezing during the winter months.

2.3 ROSS PARK SHELTERHOUSE

The Ross Park Shelterhouse (Figure 2-10) was the third building to come on-line for the GRPS. The building is situated in the northwest corner of the Ross Playground at 4320 4th Avenue

Northwest in Seattle's Fremont-Ballard neighborhood. The facility is owned and maintained by Seattle Parks and Recreation and was renovated in 2006 with funding from the Pro Parks Levy. The building design was created by Mithūn.

The Ross Park Shelterhouse has two separate roof sections that are parallel but at different elevations. The conventional roof (Figure 2-11) is 470 sf of flat membrane that drains to a pair of scuppers on the north side of the building. It covers the public bathrooms and is lower in elevation than the green roof by approximately five feet. The green roof (Figure 2-12) covers the eastern public use portion of the building and is approximately 876 sf. Runoff is collected in a pair of slotted drains on the north end of the green roof, where a drain pipe conveys roof runoff to the monitoring station. Soil and vegetation characteristics for the green roof are listed in the implementation plan (Appendix A) and in Table 2-1. Data collection for the Ross Park site was initiated on October 1, 2007, and continued for 12 months ending on September 20, 2008.

Figure 2-10 Shelterhouse at the Ross Playground

Figure 2-11 Conventional Roof Located on the West Roof of the Shelterhouse

Figure 2-12 Green Roof located on the East Roof of the Shelterhouse

The monitoring site at the Ross Park Shelterhouse was incorporated into the building redesign, which simplified the monitoring system and eliminated the need to retrofit the structure like some of the other monitoring locations. Cables from flow monitoring sensors were routed through conduit to an enclosure mounted on the wall of the maintenance room in the northwest corner of the building. All cables were hardwired to the datalogger where a program dictated the interval and frequency of measurements. Weather and flow measurements were collected and averaged over a five minute interval. Averaged values were then stored to memory within the datalogger. Parameter-specific measurements and logging intervals are provided in the implementation plan (Appendix A). The datalogger was downloaded to a base station computer at the Cardno TEC office every 24 hours via modem and cellular antenna. The modem was assigned a static IP address from the cellular carrier that allowed consistent communication.

2.3.1 Flow Monitoring

Runoff from the green and conventional roofs were collected in isolated drains and routed to a fabricated steel enclosure on the northern exterior wall (Figure 2-13). Within this enclosure, runoff from each roof was collected in a high density polyethylene (HDPE) tank, which was fabricated with a center partition wall to keep the flow from each roof isolated. To minimize fouling and system blockages, drain grates were installed in the tank to filter out debris. From the HDPE tank, flow is routed through a 3-inch PVC pipe to a tipping bucket flow meter. Two tipping buckets measured low flow rates (less than 1.8 gpm) then drained into stainless steel collection trays (Figure 2-14). These trays then drained to the approach section of a 0.4-ft HS-flume. A pressure transducer converted the changing level in the flume to a corresponding flow rate.

Per the manufacturer, the tipping bucket was designed to accurately measure flow rates up to 2.0 gpm; however, the same variance in accuracy at the upper design rate was found. Cardno TEC developed a rating curve by recording the number of tips per minute at several flow rates to develop a rating curve based on the observed tips-per-minute to flow rate relationship. The tipping bucket rating curve can be found in the implementation plan (Appendix A). To protect the pressure transducer during periods of sustained freezing temperatures, heating elements were placed in the flume sumps. The heating elements were turned on prior to a predicted period of freezing temperatures and then turned off when temperatures rose above freezing.

Figure 2-13 Photo Ross Park Shelterhouse Flow Monitoring Box, Located on the North Side of the Building

Figure 2-14 Two-Stage Flow Monitoring System (Tipping Bucket Coupled With HS-Flume)

2.3.2 Weather Monitoring

A weather station was installed on the conventional roof that monitored wind speed, air temperature, relative humidity, and solar radiation. A rain gauge recorded precipitation and was secured to a concrete block on the northern end of the green roof to minimize the effects from nearby trees on rainfall measurement. The rain gauge was mounted on three points that allowed for leveling during maintenance visits. The remaining meteorological sensors were located on a mast mounted in the northwest corner of the conventional roof. Each sensor was wired to the datalogger, which recorded parameters every five minutes. Any unintentional effects from maintenance activities (that is, false rain gauge tips.) were noted on the field sheet and later removed or corrected within the dataset.

2.3.3 Soil Moisture Content

An estimate of soil moisture was measured at two locations on the green roof. To estimate this secondary parameter, soil moisture sensors were installed on the upper and lower slope of the green roof. Soil moisture is measured using a water content reflectometer (refer to Figure 2-9). Seattle Public Utilities initially intended to measure soil moisture as a secondary parameter; however, as the study progressed analysis of this parameter (and thus, measurement) was dropped from the parameter list. Specifications for all sensors can be found in the implementation plan (Appendix A).

2.3.4 Irrigation Monitoring

Moisture inputs from irrigation were measured with a Multijet turbine flow meter (Figure 2-15). Every gallon applied to the roof triggered an electrical pulse that was recorded by the datalogger. The meter was installed on the green roof upstream of the drip lines and typically only recorded flow during the dry season. During extended periods of freezing, it was necessary to bleed the lines so that the flow meters internal components were not damaged.

Figure 2-15 Multijet Meter Installed for Measurement of Irrigation Water Delivered to the Ross Park Shelterhouse green roof

2.4 FIRE STATION 10 AND EMERGENCY OPERATIONS CENTER

City of Seattle's Fire Station 10 (FS10) and Emergency Operations Center (EOC) were the last two buildings to come on-line for the GRPS. The two-building complex is located at the intersection of 4th Avenue South and South Washington Street. The Seattle architectural firm Weinstein A|U Architects and Urban Designers, LLC., designed the new facility with associate architects Ross Drulis Cusenbury of Sonoma, California. This facility includes three separate rooftops that were monitored, the FS10 green roof, EOC green roof, and EOC conventional roof. The respective roof areas for each roof are:

- EOC green roof, 7,480 sf,
- FS10 green roof, 6,400 sf, and
- EOC conventional roof, 4,550 sf.

The EOC green roof is located to the east of and two stories higher in elevation than the FS10 green roof (Figure 2-16). The EOC green roof slopes to the west except for a small southern portion that slopes eastward. Soil and vegetation characteristic for this green roof can be found in the implementation plan (Appendix A). The monitored portion of the conventional roof is a membrane covered in ballast and is located on the north end of the EOC building. Data collection for all three roofs at the FS10/EOC complex was initiated on April 18, 2008 and continued through June 30, 2011.

Figure 2-16 View of the Fire Station 10 Green Roof from the Emergency Operations Center Rooftop

The monitoring system was a network of dataloggers and sensors installed in three locations. Communication wires physically connect all three dataloggers, allowing data to be transferred between locations. One datalogger was installed on the EOC green roof and recorded irrigation applied to the roof. A second datalogger was installed on the FS10 green roof and recorded irrigation to the roof and weather conditions for entire complex. The third and fourth dataloggers were installed at the flow monitoring station. One datalogger recorded flow measurements for the two green roofs while the other recorded flow for the conventional roof. The implementation plan in Appendix A contains a site schematic showing a general diagram of the two roofs, locations of the dataloggers, and monitoring equipment.

In general, parameters were measured then averaged or totalized, and recorded by the datalogger every five minutes. The dataloggers were remotely downloaded to a base station computer at the Cardno TEC office once every 24 hours via a modem and cellular antenna. Raw data was backed up daily to an offsite server.

2.4.1 Flow Monitoring

The flow monitoring station was located on northwest exterior wall of the second story of the EOC building, adjacent to the diesel generator. Runoff from the three roofs was collected in slotted drains and routed to individual rain leader pipes. Rainwater drains were deliberately plumbed to keep roof runoff isolated until it reached the monitoring station. At which point the three pipes (one from each roof) run in parallel through three independent monitoring systems. Runoff from each roof flows through a 2” Unimag magmeter to a Unidata tipping bucket (Figure 2-17). Runoff from both green roofs was captured in a HDPE tank, which recombined green roof runoff into a single rain water leader pipe. Conventional roof runoff was drained separately. Each of the three pipes had a bypass at the upstream end of the monitoring station that discharged to the plastic tank. Should a clog or malfunction occur, all flow was diverted around the monitoring equipment and into the tank.

Figure 2-17 FS10 / EOC Flow Monitoring Station Located on the West Side of the EOC Building

The two-stage flow monitoring system allowed for accurate measurement of both low and high flows from the green and conventional roofs. Lower flow rates (less than 1.8 gpm) were measured by the tipping bucket while the magmeter measured flows from 1.8 gpm to a maximum rate of 160 gpm. Consistent with other monitored sites, initial bench testing found that the tipping bucket manufacturer's estimated range was inaccurate. The new curves were developed based on an observed tips-per-minute to flow rate relationship. The tipping bucket rating curves developed by Cardno TEC are included in the implementation plan (Appendix A).

A heating, ventilation, and air conditioning (HVAC) system is located on the conventional roof and contributes inputs to this roof. It was proposed to monitor HVAC flows onto the conventional roof; however, due to reductions in project funding a decision was made to not install and maintain a monitoring system specific to the HVAC system. This decision was also supported by the estimation that HVAC inputs would be negligible when compared to total roof runoff.

2.4.2 Weather Monitoring

A weather station that monitored wind speed, air temperature, relative humidity, solar radiation, and precipitation was installed on the FS10 green roof. Meteorological data represents specific weather conditions for this site and are not intended to represent weather conditions beyond the FS10/EOC complex. The tipping bucket rain gauge was secured to a platform in the center of the FS10 green roof to minimize the effect of tall structures (Figure 2-18). The remaining sensors were fastened to a mast approximately 6 feet above roof level. The mast was then secured to the corner of the protective metal fencing surrounding roof vents. Precautions were made to keep sensors away from any building vents that may affect temperature or relative humidity measurements.

All sensors where maintained per the manufacturers guidance, which included replacement of recommended parts. Routine maintenance of the weather station included cleaning and leveling when appropriate. When a sensor was removed for maintenance, a spare was installed in its place to maintain a consistent data record. In the event that the tipping bucket rain gauge stopped working, rain gauge 20 on the SPU online Intelliserve network was used as a substitute. Any unintentional effects from maintenance activities (that is, false rain gauge tips.) were noted on the field sheet and later removed or corrected within the dataset.

Figure 2-18 Meteorological Sensors (Weather Station) Installed on the FS10 Green Roof

2.4.3 Irrigation Monitoring

To accurately account for all inputs to the roof, inline turbine flow meters were connected to the irrigation system. One meter was installed on the EOC green roof and the other on the FS10 green roof. Each had a pulse output wire that was directly measured by a datalogger on each roof. Each gallon applied to the roof resulted in a single electrical pulse sent to the datalogger. The irrigation meters required no active maintenance only visual inspection during the bi-monthly site visits. Typically freezing temperatures can damage the internal components of turbine flow meters if water is not purged during the winter months. However, both meters were buried beneath the soil surface in a plastic enclosure, where heat from the building insulated them from freezing conditions.

2.5 SEATTLE CITY CENTER PARKING GARAGE

The monitoring effort at the SCPG was completed through the concept design phase; however, due to budget shortfalls the monitoring system design was never finalized nor installed. The SCPG green roof (Figure 2-19) covers nearly 1.5 acres and is located at the intersection of Harrison Street and 5th Avenue North. The structure was built through collaboration between the Bill & Melinda Gates Foundation and the Seattle Center. The parking facility was funded by the Seattle Center with funding for the green roof provided by The Bill & Melinda Gates Foundation. The roof is predominantly north facing with the southern quarter sloping to the south. The green roof design and plantings list can be found in Appendix D. Preliminary designs began in Nov 2007 and ended with partial equipment procurement in December 2008.

The monitoring design included measurement of weather parameters, irrigation, and two flow monitoring locations. It was determined that multiple locations would be necessary to model the effects of comingled flow between the conventional and green roof runoff. Irrigation was also independently measured. The flow monitoring and weather stations communicated through radio transmitters with the primary flow monitoring station. Each site was designed with a datalogger and necessary peripheral components (that is, radio antenna and transmitter) for remote communication. Data was to be transmitted to the main flow monitoring station for daily download via Code Division Multiple Access (CDMA) modem and cellular antenna. Irrigation was to be measured using an electromagnetic flow meter installed in a maintenance closet on Level P2 (for specific locations see Appendices C and D). The design concept was completed and modifications to the plumbing and electrical systems were approved by Sellen (General Contractor); however, funding for the project was eliminated before the implementation phase.

Figure 2-19 Seattle City Center Parking Garage Green Roof

2.5.1 Flow Monitoring

Each facility presents a unique set of challenges to overcome. In this case it was not feasible to independently monitor runoff from the green roof because the green roof was not isolated from sections of the conventional roof. This required a second location to monitor contributions from a sub-section of the conventional roof. Measured flow rates from the conventional roof sub-section would then be used to model total contributions from the conventional roof. The conventional roof runoff total could then be subtracted from the total (green + conventional) runoff measured. The main flow monitoring station was designed to be installed on Level P2 against the east wall (Figure 2-20). The main station monitored flow in three stages; including a tipping bucket flow meter and two mag-meters. Runoff would pass through a 6-inch magmeter, a 2-inch magmeter and a tipping bucket flow meter (Appendices C and D). The combination of the three devices can measure rates from 0 to 1200 gpm, which is the max calculated flow rate for a 2-inch per hour storm.

The second flow monitoring system (Figure 2-21) would measure flow from a sub-section of the conventional roof. A “transition time” flow meter was to be clamped to the outside of a 1-inch PVC pipe on Level P2 near column C12. An output wire from the flow meter would connect directly to a datalogger. The datalogger would then record flow and communicate with the main flow monitoring station through a wireless spread spectrum modem.

Figure 2-20 Location of the SCPG Main Flow Monitoring Station on Level P2

Figure 2-21 Second SCPG Flow Monitoring Location

2.5.2 Weather Monitoring

The weather station was designed to measure wind, solar radiation, air temperature, relative humidity, and precipitation. It was agreed upon that it would be installed in the center of the green roof on an elevated mast. The rain gauge was to be mounted on a platform that allowed for leveling and in a location that minimized any interference from surrounding objects. Sensors would connect via wires directly to a datalogger mounted to the wall above the irrigation control cabinet and south of the roof access door. The datalogger would collect and average measurements over the desired interval then transmit the data via spread spectrum radio to the main monitoring station. For more details see Appendices C and D.

2.5.3 Irrigation Monitoring

To accurately account for irrigation, a deduct meter with a pulse switch installation on water service (irrigation) to the green roof was to be installed in the janitors closet on level P2. The output wire would be connected directly to a datalogger, which in turn would transmit any flow to the main monitoring station via a wireless spread spectrum modem. Only routine maintenance would be necessary at this location.

Figure 2-22 Suggested Location of the SCPG Telemetry Enclosure

3.0 DATA QUALITY CONTROL AND QUARTERLY REPORTING

Data collected as part of this project were subjected to a rigorous review and QA/QC process. Through the QA/QC process a final data set was produced. The final data set was included in quarterly Data Quality Evaluation Reports (DQER's) as required by the King Conservation District grant agreement.

The data QA/QC process involved several steps to screen, verify, and modify (as necessary) individual data points. Data were screened on a weekly basis throughout the monitoring period to ensure monitoring equipment was functioning properly. During the weekly review, flow data were compared to rainfall data to verify the rainfall-runoff response was reasonable, consistent, and reliable. When erratic or questionable data were observed, field visits were made to trouble shoot and resolve suspected issues.

In addition to the weekly data review, during the monitoring period a detailed QA/QC check was performed on each quarterly data set. The first step in the quarterly data QA/QC process was to adjust tipping bucket measurements based on updated tipping bucket calibrations. Periodic calibrations were performed on the flow meter tipping buckets to identify measurement drift and provide a basis for data adjustment. Representative equations were developed for each calibration and used to adjust the data points within the affected period. Two calibrations were used to bracket the appropriate portions of the data and a time-linear interpolation between the two calibrations was applied to each data point. In this way, the slow drift in the tipping bucket readings and the transition between calibrations was accounted for and a smooth data set was produced.

The quarterly data QA/QC process involved screening all of the data sets for data gaps and questionable or unreliable data. Unreliable flow data were identified through a comparison with rainfall data. In some cases, unreliable data were replaced with interpolation between reliable data points. This was done where brief periods of questionable data were identified and generally not during peak flow events. Where a significant number of consecutive questionable data points were identified, or when these questionable data occurred at or near the expected peak of a runoff event the data were removed and those time steps were flagged with the appropriate SPU Hydstra codes[4].

As described in the Data Collections Methods section (Section 2), each of the flow monitoring stations included flow data for a magmeter and tipping bucket. The data loggers were programed to select the appropriate data point for each time step based on magnitude thresholds. Data points close in magnitude to this transition threshold were sometimes interpolated by the logger. The response of the two measuring devices was not always identical

[4] Hydstra (Kisters Pioneering Technologies) is data management software, which SPU uses to manage large amounts of time-series water resources data. Hydstra uses codes to allow the user to store quality information with each data point. SPU provided a list of Hydstra codes to the project team for use when completing QA/QC. Thus, each time-series data point that has been QA/QC'd is stored with a Hydstra code defining data quality.

particularly on steep rising or falling limbs for runoff events. For this reason, the transition between the data for the two devices often required a smoothing interpolation.

The QA/QC process was also applied to the weather data set. In general, very few corrections were required for the weather data. Typical corrections to weather data involved removing isolated, unexplained spikes or dips in the temperature and relative humidity data, and correcting solar radiation data points that erroneously indicated sunlight before sunrise or after sunset.

Final quarterly data sets were produced with Hydstra codes for each data point. A Hydstra code of 7 indicates a verified, useable data point. For all data points that were assigned a Hydstra code other than 7, an explanatory comment was provided so that future user of the data may understand how and why the data were modified.

4.0 ZOOMAZIUM WATER QUALITY RESULTS

During 2007, two storm events were sampled at the Zoomazium location (March 22, 2007 and November 26, 2007) and flow-weighted composite samples were collected. Across all GRPS study sites, only these two storm events were sampled because the study's water quality data collection effort was reduced due to limited funding. Given there were only two green roof runoff sampling events, the objective was to determine presence/absence for the defined parameter list (SPU 2007, Appendix F). Presence of a specific water quality parameter was determined relative to the analytical laboratory reporting limit (RL)[5]. If a parameter was not detected at a concentration greater than the RL, it was determined absent.

A summary of detected parameters for the two sampled events are presented in Table 4-1. Full storm summaries, including non-detects, for each event are provided in Appendix F. The storm summaries include a description of sampling activities, an event hydrograph, and analytical results.

Soil depth, soil composition and vegetation for the Zoomazium green roof are provided in Table 2-1 and the implementation plan (Appendix A). It should also be noted that all green roof runoff is captured and conveyed off the green roof via one galvanized gutter. This gutter runs the length of the roof's eastern edge (Figure 2-1 and Figure 2-2).

[5] Reporting Limit is defined as the lowest value at which quantitative detection of a given analyte is reported. The RL is based on the lowest concentration used to calibrate the analytical instrument. (Analytical Resources, Inc., 2012)

Table 4-1 Zoomazium Green Roof 2007 Water Quality Detects

Compound	Units	RL	03-22-07 Event	11-27-07 Event
Nutrients				
Total Phosphorus	mg-P/L	0.004	0.628	0.415
Ortho-Phosphorus	mg-P/L	0.004	0.488	0.182
Total Kjeldahl Nitrogen	mg-N/L	1.20	3.15	3.52
N-Ammonia	mg-N/L	0.010	0.087	0.084
N-Nitrate	mg-N/L	0.010	<RL	0.347
Nitrate + Nitrite	mg-N/L	0.010	<RL	0.347
Metals				
Arsenic - Total	μg/L	0.2	3.9	3.1
Arsenic - Dissolved	μg/L	0.2	4.0	2.8
Cadmium - Total	μg/L	0.2	0.3	3
Cadmium - Dissolved	μg/L	0.2	0.3	0.2
Chromium - Total	μg/L	0.5	2.4	3.8
Chromium - Dissolved	μg/L	0.5	2.5	3.6
Copper -Total	μg/L	0.5	21.5	59.1
Copper - Dissolved	μg/L	0.5	21.6	40.1
Lead - Total	μg/L	1	<RL	3
Lead - Dissolved	μg/L	1	<RL	2
Zinc - Total	μg/L	4	690	1500
Zinc - Dissolved	μg/L	4	700	930
Non-Metals				
Fecal Coliform	CFU/100ml	1	422	606
Diesel Range Hydrocarbons	mg/L	0.25	<RL	1
Motor Oil	mg/L	0.50	<RL	0.54
pH	std units	0.1	6.97	6.54
Calcium	mg/L	0.05	10.6	14.6
Magnesium	mg/L	0.05	1.981	3.1
Hardness	mg/L	< 0.3	34.8	49.1
4-Methylphenol	μg/L	0.10	<RL	14
Benzoic Acid	μg/L	1.0	<RL	3.8
bis(2-Ethylhexyl)phthalate	μg/L	0.2	0.34	0.73
Butylbenzylphthalate	μg/L	0.10	0.16	<RL
Phenanthrene	μg/L	0.10	<RL	0.31
Phenol	μg/L	0.1	<RL	4.9

5.0 DATA ANALYSES AND HYDROLOGIC PERFORMANCE DISCUSSION

5.1 GENERAL

The data analyses performed as part of this study provide a basic understanding of the hydrologic performance of the green roofs in terms of runoff volume reduction and peak flow reduction. The methods for quantitative analyses and the result of those analyses are presented in this chapter. Additional, supportive, qualitative analyses discussion and summary conclusions are also presented.

5.2 PEAK RUNOFF RATE REDUCTION ANALYSIS

Instantaneous peak flow data during rainfall events were used to evaluate the effectiveness of the green roofs in reducing peak runoff rates. Antecedent soil moisture conditions leading into rainfall events can have a significant effect on the green roof effectiveness in reducing peak runoff rates. For this reason events for this peak flow analysis were selected based on the criteria of having approximately two hours of continuous rainfall leading up to the peak rainfall event. This is assumed to produce near saturated soil conditions.

For the EOC and FS10 green roofs, peak runoff attenuation values were calculated by converting instantaneous peak runoff rates for both green roofs and the conventional roof to flow per unit area values. The percent reduction in peak runoff rate for each selected storm event and for both the EOC and FS10 green roofs were calculated using:

$$Q_{\%reduction} = (Q_{conv} – Q_{gr})/Q_{conv}$$

Where:

$Q_{\%reduction}$ = percent reduction in peak runoff rate,
Q_{conv} = unit area runoff from conventional roof, and
Q_{gr} = unit area runoff from green roof

Using this methodology, flow per unit area values were calculated for 47 significant events in 2008, 2009, and 2010.

As presented in Figure 5-1 and Table 5-1 the results show significant effectiveness of the green roofs in reducing peak runoff rates. Summary peak runoff reduction data are presented in Table 5-2.

Figure 5-1 Percent Peak Run-off Reduction for Selected Events

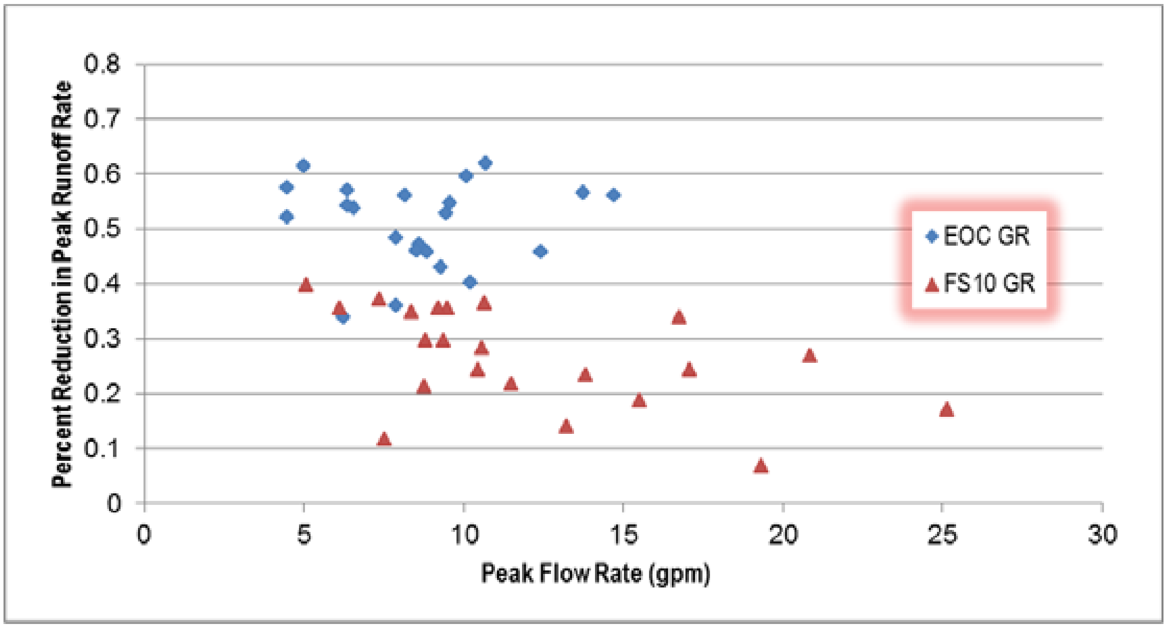


Table 5-1 Peak Runoff Reduction for Selected Events

Event Date	Peak Rainfall Intensity [1]	EOC Green Roof		FS10 Green Roof	
		Peak Runoff Rate (gpm)	Percent Reduction in Peak Runoff Rate	Peak Runoff Rate (gpm)	Percent Reduction in Peak Runoff Rate
11/4/2008	0.02	8.6	47%	9.5	36%
11/6/2008	0.02	8.8	46%	11.5	22%
1/7/2009	0.02	9.3	43%	10.6	28%
3/15/2009	0.02	5.0	61%	7.4	37%
4/2/2009	0.03	8.2	56%	10.7	36%
4/12/2009	0.02	4.5	52%	5.1	40%
5/5/2009	0.05	14.7	56%	25.1	17%
10/16/2009	0.05	10.7	62%	16.8	34%
10/26/2009	0.06	13.8	57%	20.9	27%
11/7/2009	0.02	10.2	40%	13.2	14%
11/10/2009	0.02	4.5	58%	6.1	35%
11/16/2009	0.02	8.5	46%	9.2	36%
11/19/2009	0.02	7.9	36%	8.8	21%
11/22/2009	0.03	9.4	53%	13.8	24%
11/26/2009	0.04	10.1	60%	17.1	24%
1/4/2010	0.02	6.3	57%	9.4	30%
1/8/2010	0.02	6.6	54%	8.4	35%
1/11/2010	0.02	7.9	48%	10.4	24%
1/15/2010	0.02	6.4	54%	8.8	30%
3/12/2010	0.01	6.2	34%	7.5	12%
10/9/2010	0.03	9.6	55%	15.5	19%
12/11/2010	0.04	12.4	46%	19.3	7%

Notes:
[1] Peak rainfall intensity units are total per 5-minute time step.

Table 5-2 EOC and FS10 Green Roof Peak Runoff Reduction Summary

		EOC Green Roof	FS10 Green Roof
% Peak Flow Reduction	Range	35% - 65%	7% - 40%
	Median	53.3%	28.6%
	StDev	7.8%	9.1%

The scatter plot of peak runoff rate reduction values for the EOC and FS10 green roof data is possible because the rainfall for the green roofs and the conventional roofs are identical (same site) allowing for a side-by-side evaluation. Because the EOC and FS10 rainfall events (timing and shape) are not directly transferable to the Zoomazium site (as confirmed through direct comparison of the rainfall data from the two sites), direct comparison of Zoomazium green roof and EOC conventional roof rainfall-runoff response was not possible.

For the peak flow reduction analysis on the Zoomazium green roof, data from the EOC conventional roof was used to develop a line-of-best-fit by plotting maximum 5-minute rainfall totals against a corresponding instantaneous peak unit area runoff rate from the conventional roof. An equation was then generated for the line-of-best-fit. Using the equation and actual Zoomazium rainfall data, theoretical peak flow values were generated and used as the basis for evaluating peak flow attenuation on the Zoomazium green roof. Figure 5-2 shows the plotted data, the line-of-best-fit, and the representative equation. The theoretical reductions in Zoomazium peak runoff rate for selected events (calculated using the equation developed from the conventional roof runoff data) are presented in Figure 5-3 and Table 5-3. Summary peak runoff reduction data presented in Table 5-4 indicate a relatively wide range in peak flow reduction effectiveness.

The range in peak runoff rate reduction and the occurrence of negative calculated values is partially related to the less precise methodology used for the Zoomazium runoff data analyses. The greater range may reflect a more dynamic rainfall-runoff relationship for the Zoomazium green roof, in comparison to the FS10 and EOC green roofs, due to the roof's physical characteristics (variation in slope). However, given an identical event rainfall distribution, negative values generated in the Zoomazium analysis should not be interpreted to indicate an absolute increase in runoff rate from this green roof in comparison to a conventional roof. The differences in green roof runoff control performance are discussed in greater detail in Section 5.4.3.

Figure 5-2 Instantaneous Unit Area Conventional Roof Peak Runoff vs. Rainfall Intensity

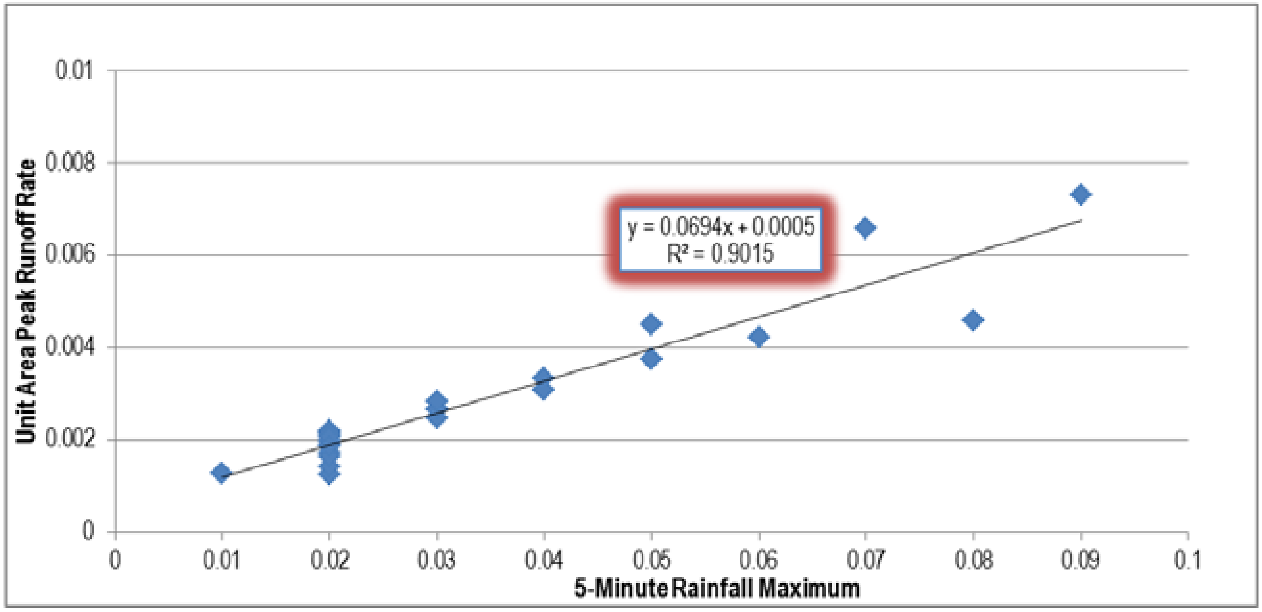


Figure 5-3 Percent Peak Runoff Reduction for Selected Zoomazium Events

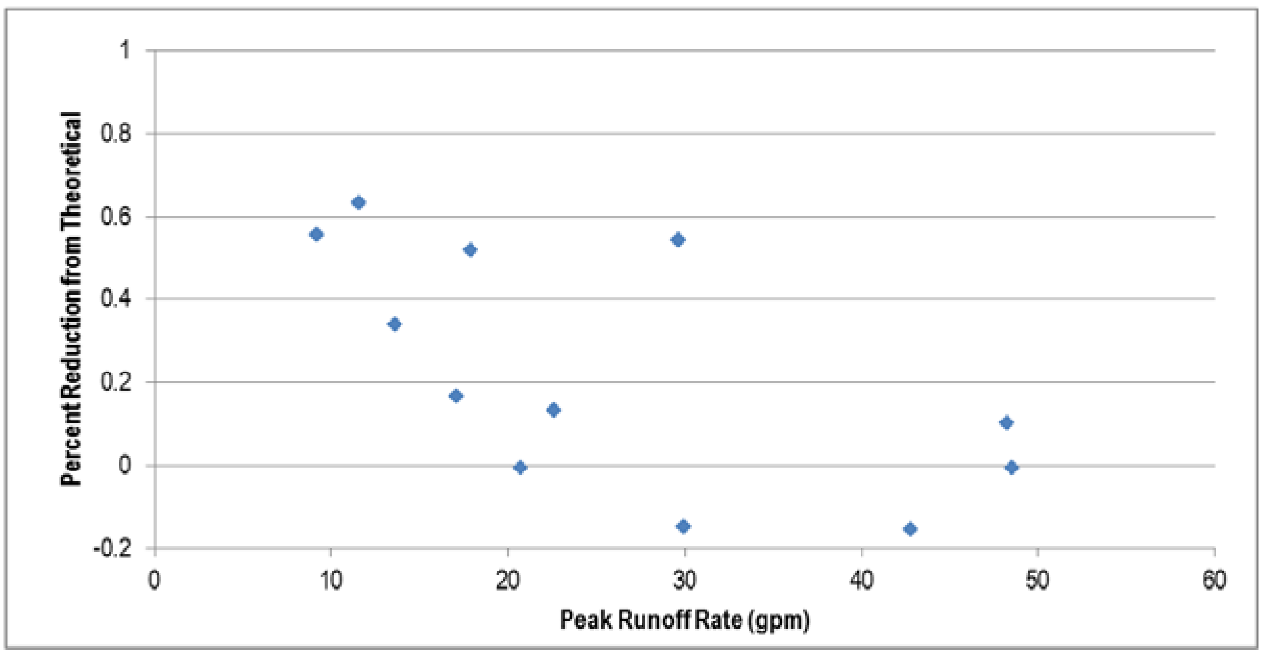


Table 5-3 Peak Runoff Reduction Percentages for Selected Events on the Zoomazium Green Roof

Event Date	Peak Rainfall Intensity[1]	Peak Runoff Rate (gpm)	Percent Reduction in Peak Runoff Rate
3/19/2007	0.11	30	54%
10/19/2007	0.06	18	52%
12/18/2007	0.03	9	56%
6/3/2008	0.04	23	13%
11/4/2008	0.09	48	10%
1/7/2009	0.03	21	-1%
4/2/2009	0.08	49	-1%
5/19/2009	0.05	12	63%
10/16/2009	0.06	43	-15%
10/26/2009	0.03	14	34%
11/22/2009	0.03	17	17%
11/26/2009	0.04	30	-15%

Notes:
[1] Peak rainfall intensity units are total per 5-minute time step.

Table 5-4 Zoomazium Green Roof Peak Runoff Reduction Summary

		Zoomazium
% Peak Flow Reduction	Range	-15% - 63%
	Median	15.0%
	StDev	28.4%

5.3 RUNOFF VOLUME REDUCTION ANALYSIS

The capacity of a green roof system to reduce long term runoff volume is a function of the storage capacity of the green roof soil. Unlike a natural system in which a portion of the moisture is passed through the soil column and continues to percolate vertically to groundwater, water that passes through the soil column on the green roofs is intercepted by an underlying impermeable layer and routed to the building roof drains. Therefore, the only mechanism for volume reduction is evapotranspiration. Evapotranspiration rates particularly during the wet season are low and the residence time of water in the thin soil column is brief diminishing the volume reduction benefit of the green roofs.

The reduction in runoff volume varies throughout the year. During the rainy season (November through March), the runoff volume reduction is much lower than it is during the drier months.

Irrigation events produce a direct, measurable runoff response on each of the green roofs. Significant percentages of irrigation water applied to each of the green roofs are present in the runoff hydrographs even during the driest portions of the monitoring period.

Irrigation on the EOC and FS10 green roof was applied through a porous, pressurized system installed at the base of the soil layer. A significant percentage of the irrigation water applied to these roofs is present in the runoff hydrographs. Irrigation on the Zoomazium roof is applied to the green roof surface with a sprinkler system. The percentage of irrigation water present in the Zoomazium green roof runoff hydrograph is lower than for the EOC and FS10 green roofs. The percentage of runoff directly attributable to dry weather irrigation events varies from one irrigation season to the next and ranges from approximately 44-66% for the EOC green roof, 70-89% for the FS10 green roof, and 5-21% for the Zoomazium green roof.

An attempt was made to remove the direct irrigation runoff response from the runoff totals. While there are identifiable, repeatable patterns in the irrigation input, the effect of the various storm events on the irrigation-runoff response (pattern and volume) varies depending on the size of the rainfall event and timing relative to the timing of the irrigation events. Therefore, a straight data subtraction using a representative irrigation pattern was not possible.

For this analysis, dry weather periods during which repeated runoff-producing irrigation events occurred were identified. Average runoff percentages resulting from these dry weather irrigation events were calculated and assumed to be representative of the entire irrigation season. The calculated percentage was applied to the total, quarterly irrigation input and the resulting volume was then subtracted from the total quarterly runoff volume for each of the green roofs. The irrigation water was not included in the input signal for this calculation. This approach is based on the assumption that, while the residual soil moisture resulting from irrigation may affect the green roof rainfall-runoff response, irrigation and the resulting residual soil moisture is necessary for any healthy green roof in this Pacific Northwest climate.

Calculating runoff volume percentages on the conventional roof was complicated by the presence of condensation from the HVAC system. HVAC condensation was present at varying levels throughout the year making quarterly runoff calculations infeasible. Instead, estimates of the rainfall-response runoff volume on the conventional roof were made for individual storm events. Condensation runoff volume leading up to or following the rainfall event was estimated and subtracted from the total event runoff volume. The conventional roof runoff volume percentages range from approximately 83% to approximately 100%. This range in runoff volume percentage, which is applicable during the wet season and the dry season, indicates that even for the conventional roof, some losses due to evaporation and initial wetting of the roof material and the conveyance system are occurring.

Quarterly green roof runoff volume percentage values are presented in Table 5-5. Runoff volume percentage values were also calculated for selected storm events and the results are presented in Table 5-6. The events for this analysis were selected from the listed CSO events at NPDES 150 and NPDES 152 in Ballard provided by SPU. Summary green roof runoff volume data are presented in Table 5-7.

Table 5-5 Quarterly Runoff Volume as a Percentage of Rainfall

Event Date	EOC GR [1]	FS10 GR [1]	Zoomazium GR
2007 Q1 (Jan-March)	N/A	N/A	71%
2007 Q2 (April-June)	N/A	N/A	7%
2007 Q3 (July-Sept)	N/A	N/A	45%
2007 Q4 (Oct-Dec)	N/A	N/A	87%
2008 Q1 (Jan-March)	N/A	N/A	72%
2008 Q2 (April-June) [2]	62%	58%	24%
2008 Q3 (July-Sept) [2]	38%	61%	46%
2008 Q4 (Oct-Dec)	73%	81%	85%
2009 Q1 (Jan-March)	78%	86%	84%
2009 Q2 (April-June)	52%	62%	45%
2009 Q3 (July-Sept) [2]	27%	100% [3]	49%
2009 Q4 (Oct-Dec)	83%	97%	83%
2010 Q1 (Jan-March)	80%	90%	N/A
2010 Q2 (April-June)	44%	52%	N/A
2010 Q3 (July-Sept)	31%	48%	N/A
2010 Q4 (Oct-Dec)	76%	94%	N/A
2011 Q1 (Jan-March)	72%	87%	N/A
2011 Q2 (April-June)	28%	32%	N/A

Notes:
[1] EOC and FS10 data culled to time steps with flow data for both green roofs
[2] Irrigation input and output approximated and subtracted out before percentages calculated
[3] Excessive daily irrigation applied throughout quarter

Table 5-6 Runoff Volume as a Percentage of Rainfall for Selected Events [1]

Event Date	EOC GR	FS10 GR	Zoomazium GR
11/6-8/2008	89%	100%	100%
1/7/2009	87%	100%	100%
5/19/2009	45%	55%	47%
10/16-18/2009	80%	99%	95%
10/25-27/2009	72%	89%	92%
11/5/2009	86%	97%	86%
11/16/2009	94%	100%	78%
11/22/2009	84%	100%	88%
11/26/2009	84%	100%	95%

Note:
[1] Selected events produce CSO events at NPDES 150 and/or NPDES 152 in Ballard

Table 5-7 Summary of Runoff Volume as a Percentage of Rainfall

		EOC GR	FS10 GR	Zoomazium GR
Runoff as % of Rainfall	Range	27% - 83%	32% - 100%	7% - 87%
	Median	57.2%	71.7%	58.2%
	StDev	62.0%	71.5%	60.0%

5.4 RESULTS DISCUSSION

Section 5.3 presented the methodology and results of the runoff volume and peak flow quantitative analyses. The following is a qualitative discussion supporting the analyses.

5.4.1 Runoff Travel Path and Lag Time

The data analyses performed as part of this study provide a general evaluation of green roof runoff control performance on the FS10, EOC, and Zoomazium green roofs. The three green roofs included in these analyses all performed differently from one another in terms of both runoff peak and runoff volume reduction. There are likely several reasons for these differences in performance including differences in roof slope, size, and shape. As is the case within natural watersheds, the shape and magnitude of the runoff hydrographs on the green roofs is affected by runoff travel path and runoff travel time. All other factors being the same, peak flow attenuation generally increases with travel time.

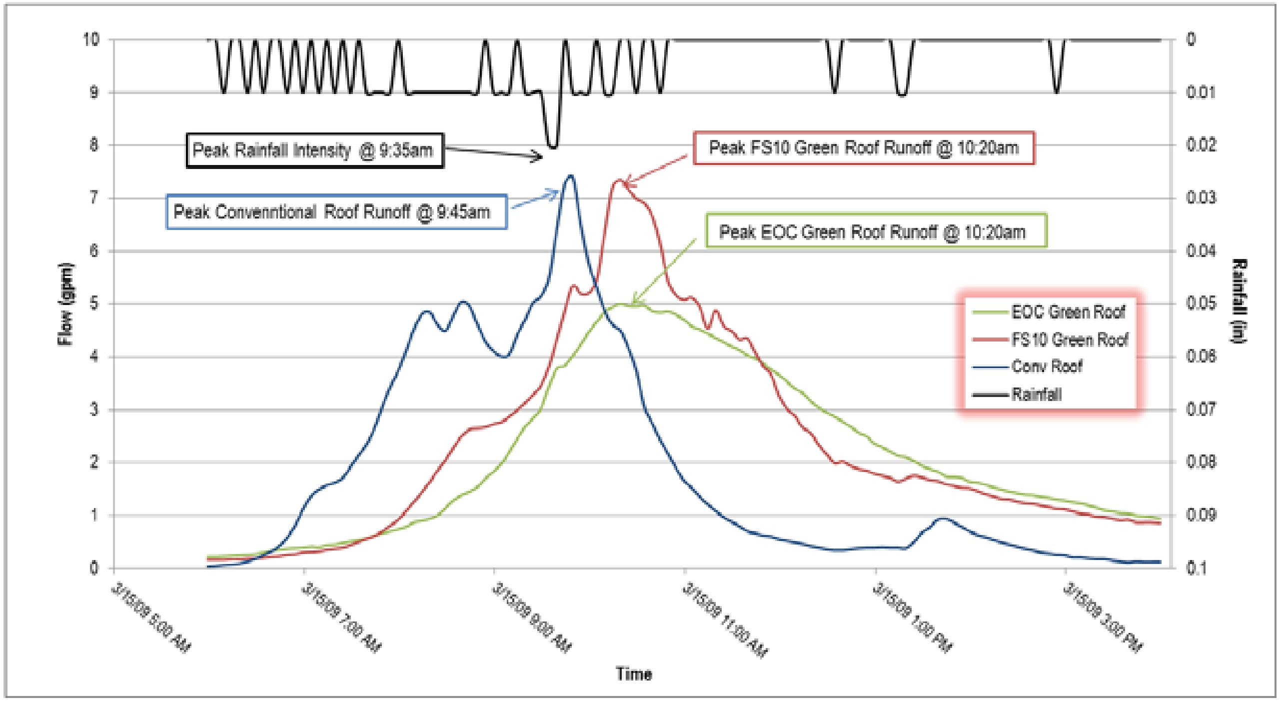
On each of the green roofs, water moves through the soil layer to the drainage layer and then moves laterally to the perimeter drains. The lateral movement through the drainage layer to the perimeter drains may vary significantly for the three green roofs due to size shape and location of drains and the medium through which flow travels. Once flows enter the roof drains, additional differences in travel time are attributable to the routing of flows through the pipe system to the sensor locations.

The differences in travel time account at least in part for the differences in rainfall-runoff response for the three green roofs. The often shorter lag time for the FS10 green roof reflects the shorter runoff travel path and travel time. In addition, the FS10 green roof has impervious areas conveying runoff to and from the green roof. There is a strip of impervious pavers along the north side of the green roof, a one-foot strip of gravel lines the remaining three sides, and a gravel area with vent fans is located in the center of the green roof. Combined, these three features represent a total impervious area of 1,280 feet. Runoff from these three impervious areas is combined with FS10 green roof runoff and routed to the flow meter. The rapid runoff response from this impervious portion of the FS10 green roof, combined with the relatively shorter travel distance, results in a larger and flashier runoff response when compared to the EOC green roof. This difference in runoff response between the FS10 and EOC green roofs occurred throughout the monitoring period.

Travel path data for each of the green roofs was estimated. It was not possible to precisely calculate lateral travel time of unsaturated, unchanneled flow through a coarse gravel medium. This calculation is not accurately represented by either the Darcy flow equation or the Manning equation. However, lag-time between the peak rainfall intensity and peak runoff rate, which is related to travel time, was calculated from the recorded data.

Lag time can be affected by residual soil moisture and was therefore variable on each of the green roofs from one rainfall event to another. Calculated lag times range from twenty to fifty minutes for both the FS10 and EOC roofs. The EOC conventional roof lag time ranges from five to ten minutes. For the Zoomazium green roof, the lag time is typically fifteen to twenty-five minutes. Figure 5-4 shows a comparison of EOC conventional roof, EOC green roof, and FS10 green roof lag times for a selected rainfall event.

Figure 5-4 Runoff Lag Time Comparison



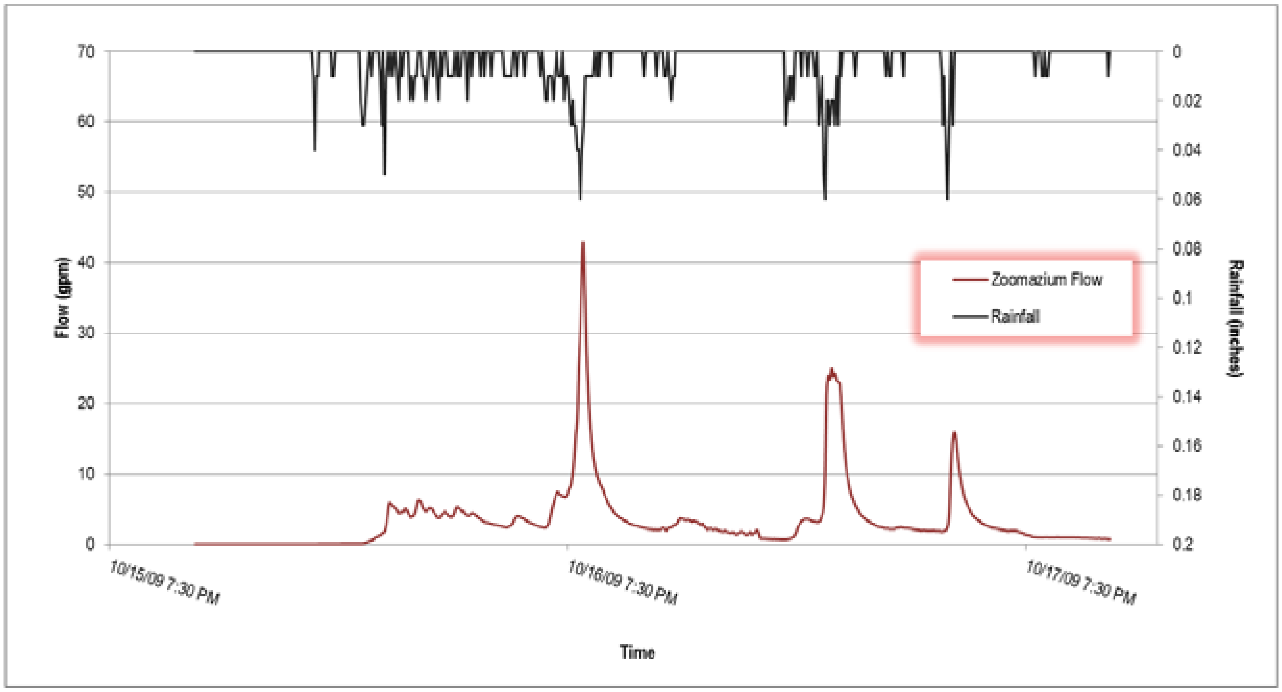
5.4.2 Antecedent Moisture, Event Rainfall Pattern, and Variability in Green Roof Runoff Control

The capacity of the green roofs to reduce runoff volume and peak flow rates is significantly affected by the amount of moisture present in the soil when a rainfall event occurs. Because of the shallow soil depth on the green roofs, there is limited soil moisture storage capacity. Even during the wet season, dry periods of only a few hours preceding a storm event can result in drying of the soil and significantly affect the rainfall-runoff response of these green roofs.

Brief dry periods of a few days or hours can result in recharge or recovery of the soil's capacity to reduce the percent of runoff resulting from a rainfall event. During the rainy season that recovery is likely slowed by a reduction in evapotranspiration. In addition to the effects of residual soil moisture, the volume and distribution of rainfall during storm events is highly variable. This random variability in rainfall distribution combined with continuous storage and release of residual green roof soil moisture results in increased variability in green roof rainfall-runoff response.

As Figure 5-5 illustrates, brief drying periods of a few days or hours can allow the soil to recover (dry-out) and provide runoff control during subsequent events. In this example, the recovery period between events and the reduced soil moisture as this sequence of rainfall events progresses results in an increased effectiveness in peak flow attenuation.

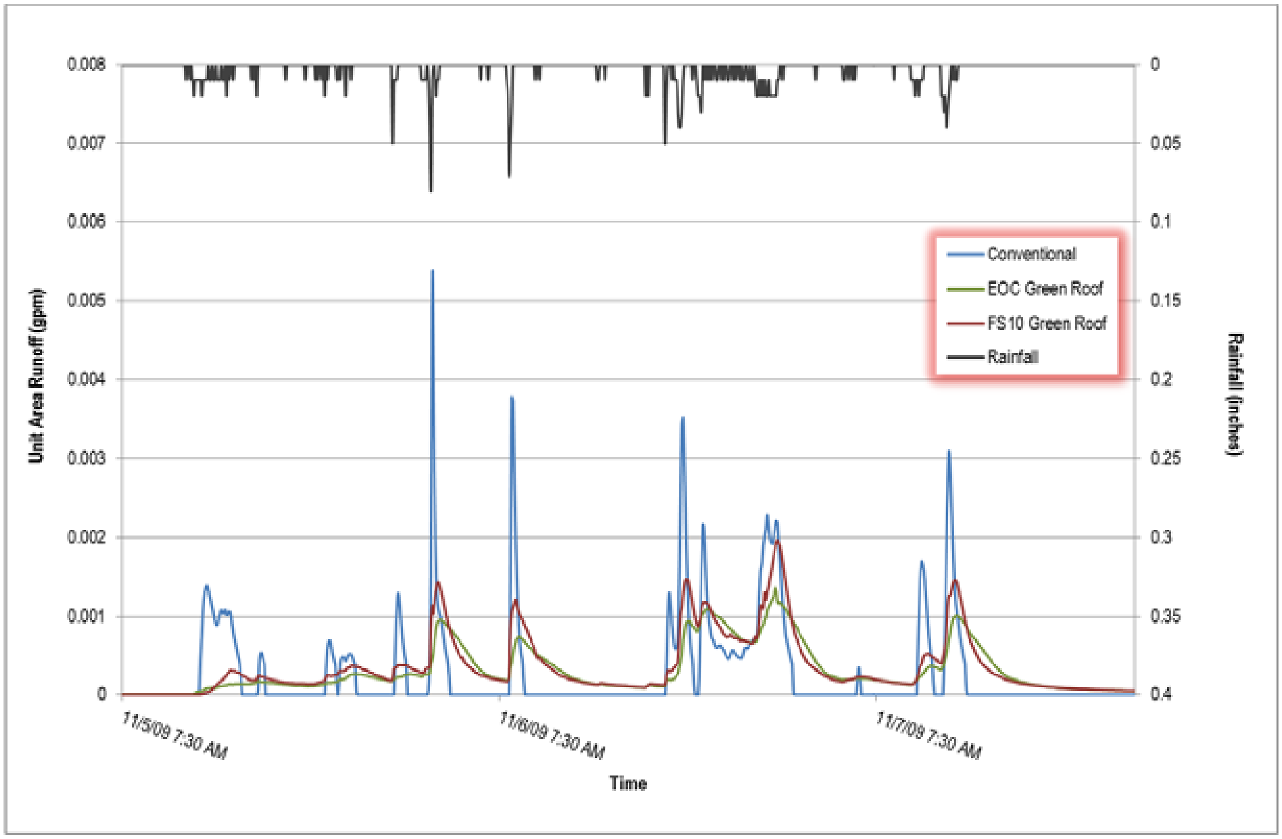
Figure 5-5 Zoomazium Rainfall-Runoff Response in Successive Events



While the shape of a runoff hydrograph from a conventional roof or other effective impervious surface closely mimics the distribution of rainfall during the storm event, the runoff hydrograph from the green roofs varies depending on the residual soil moisture. On the green roofs, the peak runoff rate is typically reduced and the recessional limb of the hydrograph is extended by several hours due to the storage and slower release of soil moisture. In fact, the moisture stored in the soil can actually result in higher runoff rates when runoff from residual soil moisture is combined with runoff from subsequent peak events.

As shown in Figure 5-6, runoff from the EOC conventional roof mimics the rainfall pattern with reduced peak rates as the storm sequence progresses. However, due to the cumulative effects of both the residual soil moisture and total volume of rainfall during the later storm event, the green roof unit area runoff is higher for the lower intensity rainfall event (occurring late on November 6) than it is for the higher intensity rainfall events earlier in the storm sequence. In fact, the peak unit area runoff rate for the FS10 green roof is almost as high as for the conventional roof for this portion of the hydrograph.

Figure 5-6 Unit Area Runoff Comparison for November 5-7, 2009



5.4.3 Comparison of Green Roof Performance

The capacity of the Zoomazium green roof to provide runoff peak flow attenuation appears more dynamic than that of both the EOC and FS10 green roofs especially in terms of peak flow reduction. The methodology used for the Zoomazium peak flow reduction calculations is less precise than that used for the EOC and FS10 green roofs. The negative peak flow reduction values calculated for some of the events on the Zoomazium green roof (included in the analysis and presented in Figure 5-3 and Table 5-3) are likely due, in part, to less precise methodology used to derive those values. More important in comparing the peak flow reduction performance of the three green roofs is the relatively wide range in percent peak flow reduction calculated for the Zoomazium green roof.

The Zoomazium green roof supports much denser vegetative growth and deeper soil layer compared to the EOC and FS10 green roofs. This means more hydrologic processes are at work both above the soil and within the soil. Above the soil a denser vegetative canopy provides for more interception and temporary storage of precipitation. The dense vegetation on the surface is supported by a well-developed root zone within the soil profile, which facilitates plant uptake and evapotranspiration. These properties and processes on the Zoomazium green roof provide for significant runoff control for the low to moderate intensity events.

For high intensity events, there may be a decreased effectiveness in peak runoff rate reduction. It is possible that during high intensity rainfall events, the volume of the rainfall exceeds the capacity for lateral movement through the green roof soil layer on the upper, flatter portion of the roof and the soil becomes saturated to the surface. At that point, the flat portion of the roof responds like an impervious surface directly connected to the downslope portions of the roof. There is no visual evidence of overland flow or associated erosion of the green roof soil surface. However, overland flow over a short segment of soil surface and at low velocity may occur. Velocities of this overland flow would be low due to the flatter slope, but very high relative to velocities of interflow movement through the soil on the flatter roof section. The process of direct response from the flat portion of the roof and potential increase in interflow flux through the soil on the steeper, lower roof section may combine to reduce overall travel time and produce higher unit area peak runoff rates.

In contrast, both the EOC and FS10 green roofs have a constant slope and a higher conductivity drainage layer beneath the soil. This allows for higher velocity lateral movement of runoff, thereby reducing the potential for soil saturating to the surface.

5.5 SUMMARY CONCLUSIONS

The effectiveness of using green roofs for stormwater runoff control in the Seattle climate is mixed. The capacity of these systems to provide long term (seasonal) runoff volume control varies significantly depending on the season. During extended rainy periods, runoff volume control provided by extensive (6 inches or shallower) green roofs (as monitored through this study) is very limited due to the relatively thin soil profile, reduced evapotranspiration and the direct connection of the underlying drainage layer to the roof drain system. Effectiveness in peak flow reduction can be significant, even during extended rainy periods, due to the increased runoff travel time compared to that of a conventional roof. Substantial recovery (drying out) of the soil profile even during the wet season can occur over a dry period of only a few hours. Therefore, peak runoff reduction for intermittent rainfall events is typically very high year round.

Maintaining healthy green roof vegetation in the Seattle climate requires irrigation during pronounced dry seasons. The contrast between the health of the vegetation on the Zoomazium compared to that on the EOC and FS10 green roofs is notable. The method of irrigation and the quantity applied on the Zoomazium green roof has resulted in healthy vegetation with relatively low volumes of wasted water. In contrast, the vegetation on the EOC and FS10 green roofs is poorly established and the percent of irrigation water applied that shows up as runoff is very high. The irrigation volume required and the associated costs should be evaluated where broad scale application of green roofs is being considered.

As previously discussed, there are differences in the stormwater runoff control performance of the three green roofs evaluated in these analyses. The differences in performance are likely attributable to differences in size, shape and slope on the roofs. On each of the green roofs, the rainfall-runoff response is affected by antecedent soil moisture conditions as well as the magnitude and distribution of rainfall events. All of these attributes affect runoff travel time, which, in turn, affect the shape and magnitude of the runoff hydrograph.

Each of the roofs produces a rainfall-runoff response reflective of their unique physical, hydrologic, and hydraulic characteristics and processes. As such, calibrating hydrologic model algorithms would likely result in some differences in runoff parameter values for models calibrated to the individual data sets. All three data sets are suitable for this purpose. Because of the more dense vegetation, deeper soil profile and varied slope, there are more complicated hydrologic processes that need to be represented in a model calibrated using the Zoomazium data. However, this more complex calibration may have applicability for simulating flows on a broader range of green roof designs compared to the calibrations developed for the FS10 and EOC green roofs.

5.6 FUTURE TASKS

The study findings presented herein reflect the stated purpose as set forth in project scope of work. Additional future work that could be performed using and building on these findings include:

- Producing hydrologic model calibrations for each of the green roof data sets.
- Applying calibrated green roof hydrologic models in evaluating the usefulness of green roof systems in reducing basin specific CSO occurrences.
- Using data and models to optimize green roof design parameters including size, shape, slope, soil depth, and drainage layer medium.
- Investigating the use of automated irrigation triggered by real time soil moisture monitoring.
- Comparing findings of this study with those of other similar studies performed in similar or different climates.
- Integrating the findings of this study with those of other studies focusing on other green roof benefits such as reducing urban heat sources or the effects of green roofs on energy efficiency related to operation of HVAC systems. This could provide for a holistic evaluation of green roof benefits to the Seattle region.

[This page intentionally left blank.]

6.0 REFERENCES

Analytical Resources, Incorporated. 2012. Method Detection Limit (MDL) and Reporting Limit (RL) Summaries. Online Source: arilabs.com/portal/downloads/ARI-MDLs.zip

Connelly, Maureen. 2011. BCIT Green Roof Research Program, Phase 1 Summary of Data Analysis. British Columbia Institute of Technology Centre for the Advancement of Green Roof Technology. Online Source: commons.bcit.ca/greenroof

Dunnett, N. and N. Kingsbury. 2004. Planting Green Roofs and Living Walls. Portland, Oregon. Timber Press.

Earth Pledge Foundation. 2005. Green Roofs: Ecological Design and Construction. Atglen, PA. Schiffer Publishing, Ltd.

Herman, R. 2003. Green roofs in Germany: yesterday, today, and tomorrow. Greening Rooftops for Sustainable Communities. Chicago, Illinois. Cardinal Group, Inc.

Hutchinson, D., Abrams, P., Retzlaff, and R., Lipton, T. 2003. Stormwater Monitoring Two Ecoroofs in Portland, OR. Greening Rooftops for Sustainable Communities, First North American Green Roof Infrastructure Conference Awards and Trade Show, Cardinal Group, Inc., Chicago, IL.

Johnston, C., K. McCreary, et al. 2004. Vancouver Public Library green roof monitoring project. Greening Rooftops for Sustainable Communities. Second North American Green Roof Infrastructure Conference Awards and Trade Show. Portland, Oregon. Cardinal Group, Inc.

Mentens, J., D. Raes, et al. 2003. Effect of orientation on the water balance of green roofs. Greening Rooftops for Sustainable Communities. The First North American Green Roof Infrastructure Conference Awards and Trade Show. Chicago, Illinois. Cardinal Group, Inc.

Mentens, J., D. Raes, and M. Hermy. 2005. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? Landscape and Urban Planning. Volume 77 (217-226). Online Source: http://www.biw.kuleuven.be/lbh/lbnl/ecology/pdf-files/pdf-art/jeroen/LUP-77_2006.pdf

Moran, A., Hunt, B., and Jennings, Greg. 2004. A North Carolina field study to evaluate green roof runoff quantity, runoff quality, and plant growth Greening Rooftops for Sustainable Communities. Portland, Oregon. Cardinal Group, Inc. Online Source: www.bae.ncsu.edu/greenroofs/GRHC2004paper.pdf

National Research Council Canada (NRCC). 2002. Research quantifies benefits of rooftop gardens. Construction Innovation, Volume 7, Number 1. Online Source: http://www.nrc-cnrc.gc.ca/eng/ibp/irc/ci/volume-7-n1-11.html

Peck, S. W. and C. Callaghan. 1999. Greenbacks from Green Roofs: Forging a New Industry in Canada. Toronto, Ontario. Peck and Associates.

Peck, S. W. and D. Goucher. 2005. Overview of North American policy development and the policy development process. Greening Rooftops for Sustainable Communities. The Third

North American Green Roof Infrastructure Conference Awards and Trade Show. Washington, D.C. Cardinal Group, Inc.

Pollution Control Hearings Board (PCHB). 2008. Proceedings from the Pollution Control Hearings Board. Washington state lawsuit over National Pollutant Discharge Elimination System (NPDES) permit language. Ruling issued in August 2008

Seattle Department of Planning and Development (DPD). 2011. Directors Rule 10-2011, Clarifying Landscape Standards, including Seattle Green Factor. Seattle, Washington Available at: web1.seattle.gov/dpd/dirrulesviewer/rule.aspx?id=10-2011

Seattle Public Utilities (SPU). 2007. Prepared by Taylor Associates, Inc. for Seattle Public Utilities. Data Quality Objectives. Water Quality Sampling Plan: Woodland Park Zoo Zoomazium Green Roof. Seattle, Washington

Seattle Public Utilities (SPU). 2009. Directors Rule 17-2009, Vol. III Stormwater Flow Control and Water Quality Treatment Technical Requirements Manual. Seattle, Washington Available at: www.seattle.gov/util/About_SPU/Drainage_&_Sewer_System/GreenStormwaterInfrastructure/StormwaterCodeCompliance/GSIResources/index.htm

Seattle Public Utilities (SPU). 2012. Seattle Green Roof Modeling Results for Emergency Operation Center. Seattle Public Utilities' Memorandum.

She, N. and Pang, J. Physically Based Green Roof Model. Journal of Hydrologic Engineering Vol. 15, No. 6, June 2010. Online Source: ascelibrary.org/heo/resource/1/jhyeff/v15/i6

Spolek, G. 2005. Multnomah County building ecoroof performance. City of Portland, Office of Sustainable Development. Portland, Oregon.

Taylor Associates, Inc. (Taylor Assoc). 2006. Guidelines for Monitoring the Hydrologic and Water Quality Performance of Green Roofs in the Greater Seattle, Washington Region. Prepared for Seattle Office of Sustainability and the Environment and Seattle Public Utilities. Seattle, Washington

Taylor, B.L. and D.A. Gangnes 2004. Method for quantifying runoff reduction of green roofs. Greening Rooftops for Sustainable Communities. Portland, Oregon. Cardinal Group, Inc.

Taylor, B.L., D.A. Gangnes and M. Ellison. 2005. Seattle green roof evaluation project: an introduction. Greening Rooftops for Sustainable Communities. The Third North American Green Roof Infrastructure Conference Awards and Trade Show. Washington, D.C. Cardinal Group, Inc.

United States Environmental Protection Agency (EPA), 2000. Meteorological Monitoring Guidance for Regulatory Modeling Applications. Office of Air Quality Planning and Standards. EPA-454/R-99-005.

Wachter, H.M., Lilly, D., Berkompas, B., Taylor, W., and Marx, K.W. 2007. City of Seattle Green Roof Policy Development Through Extended Performance Monitoring as a Basis for Hydrologic Modeling. Greening Rooftops for Sustainable Communities, Second North

American Green Roof Infrastructure Conference Awards and Trade Show, Cardinal Group, Inc., Portland OR.

Washington Department of Ecology (Ecology). 2004. Guidelines for Preparing Quality Assurance Project Plans for Environmental Studies. Publication No. 04-03-030. Environmental Assessment Program, Washington State Department of Ecology. Manchester, Washington.

[This page intentionally left blank.]