DONALD BREN SCHOOL OF
ENVIRONMENTAL SCIENCE AND MANAGEMENT
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Vegetated Roofs in the Los Angeles River Watershed:
The Environmental and Economic Impacts of Stormwater Runoff and Management

A Group Project submitted in partial satisfaction of the requirements
for the degree of Master's of Environmental Science and Management

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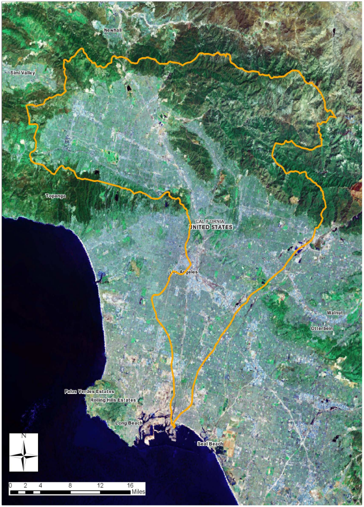

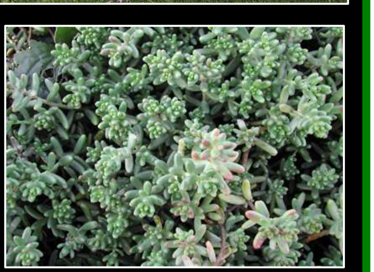

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As authors of the Group Project report, we are proud to archive it on the Bren School's website such that the results of our research are available for all to read. Our signatures on the document signify our joint responsibility to fulfill the archiving standards set by the Donald Bren School of Environmental Science and Management.

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The mission of the Donald Bren School of Environmental Science and Management is to produce professionals with unrivaled skills in the diagnosis, assessment, mitigation, prevention, and remedy of the environmental problems of today and the future. A guiding principal of the School is that the analysis of environmental problems requires quantitative training in more than one discipline and an awareness of the physical, biological, social, political, and economic consequences that arise from scientific or technical decisions.

The Group Project is required of all students in the Master's of Environmental Science and Management (MESM) Program. It is a three-quarter activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Final Group Project Report is authored by MESM students and has been reviewed and approved by:

Christina Tague, Advisor

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Abstract

Los Angeles is a highly populated and intensely urbanized landscape. Large storm events in impervious urban areas such as Los Angeles can result in stormwater runoff problems including water pollution and beach closures. Green roofs can alleviate some of these problems by intercepting precipitation and thus reducing the volume of runoff. This study addresses the environmental and economic value of green roofs as a stormwater solution in Los Angeles. Drawing on prior literature and expert opinions, the effect of green roof vegetation types, roof depth, and growing substrate on stormwater runoff from an individual roof was modeled using actual Los Angeles climate data. The model outputs reveal that green roofs could remove between 21 and 64 percent of stormwater runoff, and that they perform best in intermediate size storms. Sensitivity analysis indicates that each individual roof parameter value is highly significant ($p \leq 0.001$ or $p < 0.01$) in stormwater attenuation and roof performance. Results were extrapolated to the Los Angeles River watershed using GIS and aerial imagery to determine potential area for green roof application. A cost-benefit analysis determined that costs currently significantly exceed benefits from stormwater reduction, although recent policy advancements could improve the cost-benefit ratio. Our analysis indicates green roofs provide measurable environmental benefits.

Executive Summary

I. Introduction

Urban stormwater runoff is a major conveyance of pollution in the water bodies of the Los Angeles metropolitan area. Rain that falls on the streets and parking lots in Los Angeles drains into the Los Angeles River, picking up pollutants such as oil, heavy metals, and street trash. Urbanization in Los Angeles has replaced natural surfaces with impervious surfaces that funnel stormwater directly down the channel while restricting groundwater recharge, further increasing the river's flow and leading to high runoff rates. The water flows untreated through the series of pipes and channels that constitute the city's stormwater system.

Polluted stormwater forces beach closures and presents public health risks. Water quality along southern California beaches regularly exceeds daily and monthly thresholds for pollutants during heavy storm months. People who recreate near stormwater outflows are far more likely to contract ear, nose, and intestinal infections. To deal with these problems, some communities in southern California have implemented restrictions on runoff. The few stormwater management options that have been employed in the Los Angeles River watershed include infiltration basins, vegetated strips, and channelization.

Green roofs are an attractive option for stormwater management. In addition to runoff mitigation, green roofs provide a diversity of additional benefits, including reductions in energy usage, reduction of the urban heat island effect, improved aesthetics, and improved air and water quality.

Green roofs consist of four main layers, each of which plays a critical role in managing stormwater after it falls on the roof: vegetation, growing media, filtering and drainage, and waterproof protection. They have been utilized in several cities in the United States and Europe as an approach for the management of stormwater. Most green roof applications have been in locations with humid climates, such as Chicago, Portland, and New York, where green roofs can thrive in the regular cycles of precipitation. Given its semi-arid climate, Los Angeles presents many challenges for green roofs as a stormwater management approach. Green roofs, however, may help alleviate some stormwater management issues in the intensely urbanized parts of Los Angeles. In this project, we explore the possibilities for stormwater reduction with green roof applications in the most urbanized areas in the Los Angeles River watershed.

II. The Challenge of Los Angeles

A green roof's capacity to mitigate stormwater runoff lies in its ability to hold water in substrate during rainfall events and to remove water through plant evapotranspiration in the hours and days following rainfall events. Both the intensity of rainfall and the frequency of storm events influence this capacity.

The Los Angeles River watershed is characterized by relatively low amounts of seasonal precipitation, and is considered semi-arid. Located in a Mediterranean climate region, Los Angeles summers are characterized by hot, dry conditions while winters are wet and mild. Unlike New York or Chicago, Los Angeles receives 80 percent of its 381 mm annual precipitation during the winter months (December, January and February). The intensity of rainfall in Los Angeles is high during winter and negligible for the rest of the year. Due to Los Angeles' dry climate, a green roof may require irrigation in the summer months to keep plants alive and to maintain the roof's structure in the absence of rain. Plants native to the Los Angeles area are well adapted to semi-arid conditions, yet even their survival over a green roof's lifetime would require a minimal amount of drip irrigation.

III. Estimating Stormwater Runoff Reduction for a Green Roof in Los Angeles

To determine the impact of green roofs on stormwater runoff in Los Angeles, we reviewed literature of modeled and experimental roofs, solicited expert opinion, collected Los Angeles-specific climate data, and modeled an individual roof's response to rainfall using the Smart Stormwater 2.0 Model. Key parameters used in the model reflect the role of vegetation type, growing media type, and media depth in determining stormwater reduction. We identified vegetation types and growing media that would be both successful in the Los Angeles climate and available within the Los Angeles area and used these in the model parameterization.

Requirements of the vegetation selected for the Los Angeles roof included the plant's ability to survive long periods of intense sunshine and drought and shorter periods of intense rainfall and flooding. Additionally, plants with minimal root depth and height were selected for better performance in shallow roof beds with high winds. We selected a mix of native shrubs and grasses, such as sagebrush and Hall's bent grass, and succulents, such as *Sedum alba* and *Sedum acre*. Plant selection contributes to the potential for roofs to remove stormwater through evapotranspiration. The "crop factor" parameter in the model is equivalent to the evapotranspiration coefficient specific to individual plant species used in hydrological models. Our crop factor range, 0.20 to 1.20, was selected based on tests of economically relevant crops performed by the Food and Agriculture Organization and experiments with green roof plants by research institutions in the Midwestern and Eastern United States. The selected range is truncated from experimental ranges discovered in more humid regions to reflect the climatic differences in Los Angeles.

While roof vegetation is an essential element in trapping stormwater on roofs, porous and absorbent growing media provide a base for plants and an additional storage area for excess stormwater. Green roof substrates are typically a mix of organic and mineral components, including silt, clay, sand, perlite, and shaved limestone. Field capacity, a critical consideration of any growing medium, is the volume of water, expressed as a percentage, which is retained by the growing medium against the forces of gravity. For our model parameters, we selected field capacity values of 30, 35 and 40 percent and depth variables of 2, 4, and 6 inches (51, 102, and 152 mm).

IV. Model and Results

Field capacity and depth determine the water storage capacity of an individual roof, while the crop factor scales the potential evapotranspiration of the roof. The climate inputs used in the model include daily precipitation and potential evapotranspiration. We ran the model separately for five meteorological stations located within the watershed to account for spatial variation in precipitation. Data from the stations are daily precipitation and pan evapotranspiration records from September 1949 to May 2002.

We ran the model with inputs and parameters as described above. The model output is daily discharge for all 53 years of data analysis for all storms recorded at each of the five stations. For all storm events at all stations within the watershed from 1949 to 2002, the modeled roof reduced stormwater runoff by 21 and 64 percent. The modeled individual roof performed best during minimal and intermediate storm events. With intense storm events or following multiple storms, the roof failed to retain additional stormwater, in either vegetation or substrate, and most precipitation became stormwater runoff.

To determine the effects of roof composition on stormwater reduction, we analyzed the sensitivity of runoff to the range of parameter values. Holding each parameter value constant and globally rotating all other parameter values, we determined the significance of each parameter value. These findings indicate that a roof with the highest parameter values (deep depth, greater field capacity, more plants) of each parameter will lead to significantly greater stormwater runoff reduction over the 53 years of climate data used. The higher parameter variables, however, will result in heavier and more costly roofs.

Our model runs and analysis show us that green roofs can be as effective in the Los Angeles climate as they are in more humid climates. The average of 21 to 64 percent reduction in stormwater runoff is similar to reductions reported for green roofs in other American and European cities. Reductions occurred primarily during and after minimal and intermediate rain events. Analysis of the rain events of the study period indicated that minimal and intermediate rain events represented 65-75 percent of all rain events, while intense rain events represented 25-35 percent of all rain events. Roofs with higher parameter values provide greater stormwater attenuation benefits to Los Angeles.

V. Los Angeles River Watershed Extrapolation

The 51-mile-long Los Angeles River drains an intensely urbanized watershed basin of 834 square miles. Of that area, 462 square miles are urbanized. We estimated potential area for green roof application in order to extrapolate runoff mitigation from the single-roof model to the larger Los Angeles River watershed. We first used a data layer of impervious surfaces from the United States Geological Survey to define three classes of imperviousness: 20-49 percent (low imperviousness), 50-79 percent (medium imperviousness), and 80-100 percent (high imperviousness).

We calculated the average roof cover for each intensity class throughout the watershed to determine the area in which green roofs could be applied. We used Google Earth satellite imagery to isolate several one square mile samples representative of impervious areas of each class. We then visually estimated the amount of large, flat roof in each sample. Multiplying the estimated average roof cover for each intensity gradation by its corresponding area within the watershed, we found the total amount of building roof area that could hold a green roof to be 234 million square feet in low-imperviousness areas, 1,229 million square feet in medium-imperviousness areas and 811 million square feet in highly impervious regions for a total of 2,274 million square feet of potential green roof space in the watershed.

VI. Costs, Benefits, and Policies

The final component of our project investigated the potential costs and benefits associated with a widespread green roof program in the Los Angeles River watershed. We first calculated a cost per-square foot metric for an average roof, focusing on local sources and prices whenever possible. Based on the estimates of potential green roof area we determined through our extrapolation methods, we then calculated potential benefits resulting from stormwater reduction on 2.5 million square feet of green roof in the Los Angeles River. Benefits of stormwater reduction are difficult to calculate directly; we thus focused our research on the avoided health costs and use benefits of beaches with higher water quality near the mouth of the Los Angeles River. Our analysis assumed that a reduction in stormwater from 2.5 million square feet of green roofs would result in a proportional increase in water quality in the Los Angeles River and at the beach near the River's mouth. When only stormwater benefits are considered, the costs of a widespread green roof program in Los Angeles far exceed the potential benefits. Widespread green roof implementation would cost between $83 million and $235 million, whereas the benefits range between $23,000 and $71,000. If solely considering the economics of stormwater reduction, a green roof program would be a difficult sell.

While the economics of stormwater are negligible, stormwater is only one category of potential benefits provided by green roofs. Green roofs are appealing in urban settings because they provide multiple benefits, such as stormwater reduction, individual building energy savings, urban heat island reduction, and a host of non-quantifiable benefits, including improved aesthetics. There may be potential for green roofs to play an intriguing role in Los Angeles' environmental future. Strong political leadership, important policy tools, and local programs, including incentives toward LEED certification, Proposition O, which focuses on water quality and human health, and the Los Angeles River Revitalization Master Plan, may help establish green roofs throughout Los Angeles.

Green roofs will not crop up throughout Los Angeles overnight. Any major green roof implementation program will require long-term strategies for taking advantage of unique opportunities and synergistic projects. The combination of stormwater benefits and policy-driven economic incentives may make green roofs a powerful tool in reducing urban stormwater runoff in Los Angeles.

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Introduction and Project Objectives

Green roofs have become a popular option for generating green space and aesthetic value in cities such as New York, Portland, and Chicago, where humid climates allow green roofs to thrive. They have not yet been established in cities like Los Angeles, where dry conditions and urban layout present unique challenges to green roofs. No quantitative studies have yet investigated the potential for green roofs to take root in Los Angeles.

Our project serves as a foundation for future studies to determine some of the advantages and challenges of applying vegetated roofs throughout the Los Angeles metropolitan area. The objective of this project was to estimate the stormwater reduction and associated economic costs and benefits possible through vegetating roof surfaces in the Los Angeles River watershed. This objective was investigated at both the single-roof and basin scale under a range of green roof designs and climate scenarios.

This project:

- investigated current impacts of stormwater related to non-point source pollution and related public health issues in coastal waters, and
- determined effective vegetation types and growing media for use on Los Angeles area green roofs, concentrating on local sources and suppliers.

The team used a two-pronged approach to address stormwater attenuation:

1. We applied the existing Earth Pledge Smart Stormwater 2.0 Model, a green roof model, at a single-roof scale for use in the semi-arid Los Angeles River watershed.
    - Incorporated multiple vegetation, growing substrate, and precipitation regimes into sensitivity analysis to generate range of model outcomes with the goal of maximizing stormwater runoff attenuation.
    - Contrasted our results with results from green roof applications in other urbanized settings.
2. We extrapolated the single-roof model results to the entire Los Angeles River watershed.
    - Used a multiplicative approach to expand from a single roof to green roof application on the flat roofs of commercial and industrial buildings.

We utilized cost-benefit analysis to assess the economic impacts of green roofs and recommend appropriate policies for green roof use in the Los Angeles River basin.

- Established baseline cost per square foot metric for extensive green roofs incorporating pertinent construction, installation, infrastructure, and maintenance costs.
- Calculated benefits resulting from green roofs on two scales.
    - Determined public benefits resulting directly from stormwater attenuation by evaluating reductions in costs associated with illnesses and loss of beach use due to coastal water pollution.
- Based on economic analysis, recommended policy directions for individuals, organizations, and city officials interested in expanding green roof coverage in Los Angeles.

Through the above analysis, we produced an array of green roof composition options that identified strong attenuation combinations.

1 Stormwater

1.1 Overview of Urban Stormwater Issues

Urban stormwater runoff contains many pollutants, including heavy metals, microbes (such as fecal coliform), oils, fertilizers, pesticides, and other compounds, that can cause environmental and human health problems (Engstrom, 2004). When rain falls, the resulting runoff picks up pollutants as it flows over impervious surfaces where the pollutants rest, such as rooftops, roads, parking lots, and sidewalks. The pollutants are transported in the stormwater runoff through and out of the urban area to surrounding terrestrial ecosystems, freshwater systems, groundwater aquifers, and marine systems.

U.S. EPA's 1983 Nationwide Urban Runoff Program (NURP) found that heavy metals (copper, lead, zinc, and more) are the most prevalent pollutants in urban runoff. Trace metals are a dangerous pollutant because they are toxic to organisms (Engstrom, 2004). The study measured total suspended solids, biochemical oxygen demand, chemical oxygen demand, total phosphorous, soluble phosphorous, total Kjeldahl nitrogen, nitrite, nitrate, copper, lead and zinc. The program found significant amounts of all pollutants throughout residential, commercial, mixed, and open/non-urban areas, although they varied widely spatially (throughout different neighborhoods) and temporally (between seasons). Priority pollutants such as pesticides, metals, PCBs, hydrogenated aliphatics, monocyclic armomatics, phenols and cresols, phthalate esters, and polycyclic aromatic hydrocarbons were found in 28 sample cities across the country. Ethers and nitrosamines/other nitrogen-containing compounds could not be detected with certainty and standard methods in any of the stations. The NURP took two samples over the course of a year at 61 sites throughout the country to get a cursory picture of the potentially dangerous pollutants prevalent in stormwater. Lead, zinc, and copper were found in 75 percent or more of the samples. Chromium and arsenic were found in 50-74 percent of the samples. Cadmium, nickel, cyanides, Bis(2-ethylhexyl) phthalate, and alpha-Hexachlorocyclohexane were found in 20-49 percent of the samples. Antimony, Beryllium, Selenium, alpla-Endosulfan, Pentachlorophenol, Chlordane, Lindane, Pyrene, Phenol, Phenanthrene, Dichloromethane, 4-Nitrophenol, Chrysene, and Fluoranthene were found in 10-19 percent of the samples.

After entering freshwater and marine ecosystems, these pollutants contaminate the water column and sediments, sometimes becoming biologically available for absorption by organisms (Engstrom, 2004; US EPA, 1983). Once absorbed, pollutant effects range from increased mortality to reproductive effects (US EPA, 1983; Leduc, 2008; Roman et al., 2007). The impacts of stormwater pollution on humans have also been documented. Intense stormwater runoff can be very taxing on the drainage system and can result in costly overflows that lead to flooding and beach closures. Some studies show that people who recreate in close proximity to stormwater outflows are far more likely to contract ear, nose and intestinal infections (Shapiro, 2003).

1.2 General Management Solutions (BMPs)

With a high percentage of impervious surfaces, urbanized environments upset the hydrologic balance of the natural landscape, as they accumulate contaminants and convey more water as runoff than natural landscapes. As urbanization increases, impervious surfaces manifest a proportional increase in stormwater flow. Consequently, rainfall in urbanized environments results in various stormwater runoff problems. Polluted stormwater forces beach closures and presents public health risks. Stormwater runoff also increases flooding, negatively impacts wildlife, increases the incidence of human illnesses and can contaminate groundwater due to the associated poor water quality (Shapiro, 2003). In an effort to protect human and environmental health and to capture some usable water, stormwater problems are often mitigated with Best Management Practices (BMPs), which are also mechanisms for compliance with state and federal regulatory measures. A few United States cities, including a few in southern California, have implemented restrictions on runoff. Santa Monica enforces an ordinance requiring new developments to harvest and reuse stormwater runoff (Shapiro, 2003). There are two general classes of BMPs: non-structural and structural BMPs.

Non-structural BMPs are preventative measures which are relatively easy to implement and often less expensive than structural BMPs. Additionally, non-structural BMPs have been shown to be quite effective if the implementation is suitable for the specific situation. Non-structural BMPs include land-use planning, spill prevention and clean-up, street and storm drain maintenance, illegal dumping controls, and vehicle use reduction (NCDWQ, 2007).

Structural BMPs can be partitioned into two subcategories; mechanisms for pollutant removal and mechanisms to retain or attenuate stormwater. As such, structural BMPs are commonly engineered devices that physically remove contaminants from stormwater, attenuate the storm flow, or recharge groundwater basins. Structural BMPs include bio-retention ponds, constructed wetlands, vegetated strips, infiltration devices, permeable pavement systems and green roofs (NCDWQ, 2007).

Green roofs are a novel tool for the attenuation of stormwater runoff in the urban context and have been successful in many urban settings. Green roofs have been utilized in several cities in the United States and Europe as an alternative approach for the management of stormwater. They include a plant layer, a growing media layer, a drainage layer, and a waterproof protection layer. Through storage and evapotranspiration, the vegetation and growing medium mitigate rainfall and hold precipitation before it can flow off the roof to become stormwater runoff. Studies have shown that the primary advantage of green roofs is their ability to attenuate stormwater (Carter and Keeler, 2007; NCDWQ, 2007). In addition to runoff mitigation, green roofs provide a diversity of additional benefits, including reductions in energy usage, reduction of the urban heat island effect, improved aesthetics, and improved air and water quality. Our research project focuses on identifying the potential for green roofs to provide environmental and economic benefits related to stormwater runoff in Los Angeles.

2 Vegetated Rooftops

2.1 Green Roofs

A green roof replaces a traditional roof with engineered layers that replicate the functions of a typical soil profile. Figure 2.1 below delineates the layers and each subsequent written section describes each layer's function in managing stormwater from the topmost layer to the bottom layer. Each layer of a green roof performs a different and critical role in managing stormwater and delivering the numerous other benefits attributed to green roofs. For the purposes of this study, only the layer's role in managing stormwater is included.

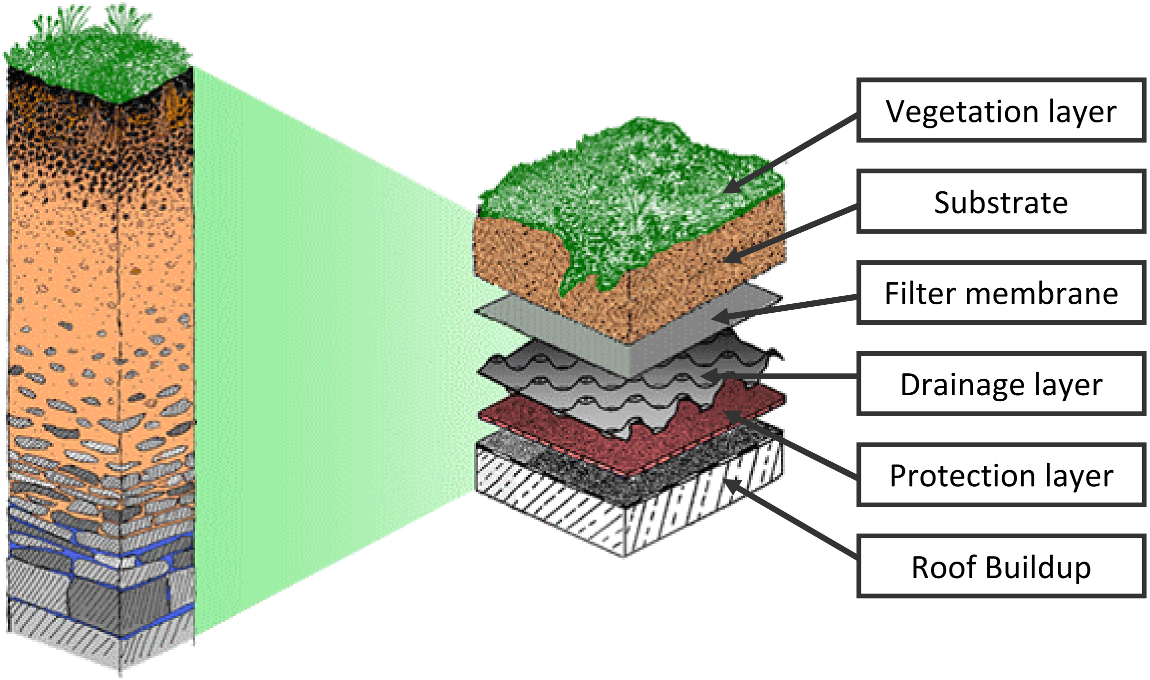

Figure 2.1 Green Roof Profile. Schematic diagram of a typical soil profile, left, compared to a green roof, right. Each layer of the green roof functions to manage stormwater and protect the building beneath the roof from intrusion of roof components (Image courtesy ZinCo-USA).

2.1.1 Extensive and Intensive Roofs

There are two major categories of green roofs: intensive and extensive. Intensive roofs are designed to be accessible to humans; thus, their design focuses primarily on aesthetics (GRHC, 2006a). Intensive roofs provide suitable habitat for a large amount of plant diversity. The growing medium depth exceeds six inches (152 mm) and sometimes extends to greater than 24 inches (610 mm). As a result, the fully saturated weight of intensive roofs ranges from 50 to 300 pounds per square foot for the entire green roof structure and requires a total system build-up height of 150-400 millimeters (GRHC, 2006b; IGRA, 2008). In addition, the cost inputs are greatest for the intensive roof. The initial installation and maintenance costs are higher than with extensive roofs. Regular irrigation is almost always required for an intensive roof to support its plant community (IGRA, 2008).

Extensive roofs are designed for practical purposes rather than aesthetic ones, such as urban heat island effect mitigation, urban stormwater attenuation, increasing roof lifespan and air quality improvements. As a result, extensive roofs have lower plant diversity, typically only containing mosses, herbs, grasses and succulents (i.e. sedums) and with growing medium depths that range from two to six inches (51 to 152 mm) for a fully saturated weight of 10-35 pounds per square foot (GRHC, 2006b; IGRA, 2008). The total build-up height for an extensive roof is approximately 60-200 millimeters (IGRA, 2008). Extensive roof systems can be designed to require no irrigation inputs. Finally, extensive roofs have the least initial and maintenance costs because of the minimal growing media and plant requirements (GRHC, 2006a; IGRA, 2008). Our study focused exclusively on extensive roofs.

2.1.2 Vegetation Layer

The vegetation layer intercepts stormwater as it falls on the roof and removes water from the roof's other layers after a storm event through evapotranspiration (ET). To be effective on a green roof, plants must first be capable of withstanding intense radiation, wind, and temperature coupled with little to no protection from rainfall on exposed roofs. They must also meet the constraints imposed by limited space resulting from green roof engineering.

Ideal green roof plants evapotranspire efficiently to maximize stormwater removal from the roof. ET rates depend on climatic factors such as wind speed, solar radiation, air temperature and humidity as well plant type, percent coverage, and vegetation management style (Allen et al., 1998). These climatic factors determine a plant's water needs and by extension, a plant's ability to evapotranspire efficiently in conditions with more or less water availability (Brouwer and Heibloem, 1986). In areas with minimal precipitation, plants have high water needs and must have high water-use efficiency to retain water during dry spells and evapotranspire slowly after precipitation. In areas with regular and frequent precipitation, plants must have a faster ET rate to quickly remove water from the substrate and deliver it to the atmosphere.

Green roof plant selection is further constrained by roof engineering. Shallow substrate depths dictate that green roof plants must have shallow roots (no more than the depth of substrate to the protection layer). However, plants with high water-use efficiency are typically drought-adapted and often employ extensive and deep root systems to tap water resources during the dry season. Finally, plants lower to the ground with a wider coverage area are also successful, as they can withstand the windier conditions found on exposed roofs.

Green roofs in the United States have included a wide range of species, but succulents, especially the *Sedum* and *Delosperma* genii, are the most common green roof species (see Appendix A for a complete list of potential green roof plants). Succulents are CAM (Crassulacean Acid Management) plants which open their stomata at night, and thus have high water-use efficiency and high survivability in water-limited conditions. Succulents take longer to establish, but *Sedum* species have been proven experimentally to survive without water for up to 89 days (Durhman and Rowe, 2006) and are thus desirable in a green roof mix.

Because succulents take longer to establish, many roofs feature grasses native to the area where the roof grows. With their fibrous root systems and fast establishment rates, grasses stabilize the soil for succulents and other hardy species. Grasses are typically C3 plants, or plants which open their stomata during the day to photosynthesize, and thus their water-use efficiency is low. To maximize the benefits of both succulents and grasses in the water-limited environment of Los Angeles, a mix of 50 percent native grasses and shrubs such as Hall's bentgrass (*Agrostis hallii*) and Sagebrush (*Artemisia californica*) and 50 percent sedums that have performed well in experimental green roofs drought conditions (*Sedum acre*, *S. alba*) were selected for a hypothetical vegetation layer in this study.

Compared to a green roof without vegetation, a green roof with vegetation can increase stormwater retention by 28-60 percent, decrease peak runoff flow and slow runoff rate (VanWoert et al., 2005b). However, green roof vegetation requires a substrate to grow in. The section below the vegetation layer is the growing media, described below.

2.1.3 Growing Media

The growing medium (or substrate) is located just above the filter and drainage layers and provides the necessary space and nutrients for the vegetation to survive. It provides another essential function for the roof: the absorption and retention of moisture (VanWoert et al., 2005a; Beattie and Berghage, 2004). As a result, the growing medium is engineered to improve field capacity; the volume of water (typically expressed as a percentage) that a medium can hold against the forces of gravity (Veihmeyer, 1931). The growing medium layer also provides thermal insulation for both the vegetation and the building, helping to temper extreme temperatures (DeNardo et al., 2003). The medium can contain many different components. D.C Greenworks (2008) used a mixture of expanded shale, mushroom compost, and mineral components. The Great Lakes Water Institute at the University of Wisconsin Milwaukee (2008) facility project used a mixture of sand, gravel, peat, organic matter, crushed brick, lightweight expanded clay aggregate, and some soil. VanWoert et al. (2005) used a mixture of 40 percent heat-expanded slate, 40 percent United States Golf Association grade sand, 10 percent Michigan peat, 5 percent dolomite, 3.33 percent compost yard waste, and 1.66 percent composted poultry litter. DeNardo et al. (2003) used a mixture of 12.5 percent sphagnum peat moss, 12.5 percent coconut fiber, 15 percent perlite, and 60 percent hydrolite. Vermiculite, a mica mineral, may also be used (Bliss, 2007). Expanded slate, dolomite, hydrolite, perlite, and vermiculite are commonly used because of their ability to retain moisture and nutrients while weighing much less than typical topsoil (DeNardo, 2003; Bliss, 2007). Many green roof builders look to use local components for growing media (Oberndorfer, 2007). Another important factor to consider is the vegetation and its moisture/nutrient demand, which will often dictate the best growing medium (Bliss, 2007).

Nutrients such as phosphorous, potassium, magnesium, nitrate and ammonium are embedded in the medium to maintain both the vegetation and the medium itself. The design of an optimal medium maximizes nutrient retention, which prevents the nutrients from exiting the roof system and entering the urban environment (Bliss, 2007; Skyland USA, 2008).

2.1.4 Filtering, Drainage and Protection Layers

Beneath the growing media lies the thin filter layer. It prevents the growing medium from seeping down into the drainage layer during precipitation events (GRHC, 2006a; Liu and Minor, 2005). Beneath the filter layer is the drainage layer, which collects a designed volume of water before allowing excess water to flow off the roof. This function prevents the over-saturation of the green roof, which can result in plant mortality, erosion, and leaching of nutrients from the growing medium (GRHC, 2006a). The drainage layer typically consists of larger granule particles (i.e. pebbles), recycled polyethylene, or caoutchouc latex (Lazzarin et al., 2005) to allow for the proper flow of water.

Preventing intrusion of vegetation into the building structure itself is essential, as root intrusion reduces building integrity and decreases the expected lifetime of the roof (GRHC, 2006b). At the bottom of the drainage layer, the root barrier prevents the vegetation roots from growing into the roof. According to Green Roofs for Healthy Cities (2006b), "thermoplastic and elastometric waterproofing membranes have root-repellent properties."

Below the root barrier, the waterproofing layer has an extremely important role – keeping moisture in the green roof and out of the building structure. Water leakage in the roof can diminish building strength (GRHC, 2006a). The waterproofing layer typically consists of a membrane. Wark and Wark (2003) found that single-ply membranes are the most cost-effective and simple. The membrane typically is made of hot applied rubberized asphalt, built-up bitumen, or modified bitumen. Thermoplastic membranes usually include polyvinyl chloride (PVC) and thermoplastic olefin membrane (TPO), whereas elastomeric membranes can include ethylene propylene diene membrane (EPDM) (GRHC, 2006b).

While all of the green roof layers from the vegetation to the waterproofing contribute to thermal insulation of the building, in some cases an additional insulation layer is required. The location (above or below the waterproof membrane) and type of roof impact the amount of insulation provided (GRHC, 2006a).

2.1.5 Roof Buildup – Structural Support

A limit to roof design is the need for structural support for the additional weight of a green roof. The roof's ability to support the entire weight of green roof components may determine growing media depth and plant composition. Fully saturated extensive green roofs (roofs that are holding their maximum possible water volume) can weigh between 10 and 50 pounds per square foot. All green roof weights are considered dead loads in that they are constant and do not change under different conditions. According to Title 24 of the California Building Standards Code, all flat roofs must support a dead load of 20 lbs/ft^2. New construction projects can be designed to handle necessary weight requirements, so any green roof design should be part of the larger building design. Retrofitting is more difficult, as loading capacity may already be determined and creative designs may be required to support the weight of the roof.

2.2 General Benefits of Green Roofs

Green roofs have grown in popularity over the past decade in part because they can alleviate multiple problems facing urban areas in one complete design. They are uniquely engineered to simultaneously offer benefits such as mitigating heat island effects, curbing stormwater problems, reducing interior noise, improving air quality and decreasing energy demand. Unlike many other stormwater BMPs, green roofs provide both public and private benefits, detailed below.

2.2.1 Public Benefits

a. Stormwater

Traditional or bitumen roofs are not designed to capture precipitation, but to funnel it to release points where it can flow off the roof, onto the ground, and eventually into a stormwater diversion system. The combination of plant life and porous growing media allows green roofs to capture a significant amount of precipitation before it leaves the roof. In particular, green roofs are adept at delaying what is known as the first flush effect, or peak runoff, which typically occurs within the first few hours of a rain event and can overwhelm combined sewer overflow systems (GRHC, 2006a).

Along with their ability to trap stormwater and prevent it from ever entering diversion systems, green roofs also can generate higher quality runoff. Rainwater can pick up metals and other pollutants resting on the surface of traditional roofs; green roofs keep these contaminants on the roof and out of the runoff. Pollutants that are already in the rainwater also get trapped on the roof through processes including soil absorption, plant uptake, and filtration in the growing media. The first flush delay from green roofs may also help improve runoff water quality. Toxicity of runoff is typically higher in the earlier stages of a storm event; in some studies, as much as 90 percent of toxic samples were collected in the first 30 percent of a storm's duration (Kayhanian et al., 2007).

A life cycle cost-benefit analysis conducted in Athens, GA, found avoided costs related to stormwater best management practices was one the most significant benefits from green roofs (Carter and Keeler, 2007). The study found some unique economic advantages in relation to stormwater attenuation. Unlike other stormwater reduction BMPs, there are few opportunity costs associated with green roofs because they are installed on surfaces that would otherwise have no economic value, as opposed to bio-retention basins, which may use extensive urban land (Carter and Keeler, 2007). Green roofs can include other features like solar panels and are especially useful in dense urban centers where other mitigation practices are not possible. Additionally, stormwater storage in green roofs is not dependent on soil profile, presenting a distinct advantage over other options like porous pavement (Carter and Keeler, 2007).

b. Urban Heat Island Effect

Energy savings can result from lower ambient air temperatures near buildings with green roofs. While these reductions are often included under the category of individual building energy savings, it is useful in this discussion to put them under the larger purview of urban heat island reduction. Due to the prevalence of dark surfaces and relative lack of vegetation, urban areas experience higher temperatures than their rural counterparts. This phenomenon is known as the urban heat island effect. Air temperature in cities can be as much as 2.5 °C higher than surrounding rural areas; urban heat island may be responsible for 5 to 10 percent of urban peak electricity demand (Akbari, Pomerantz, and Taha, 2001). Along with increased energy use, urban heat island also poses a health risk to people. Extreme heat can lead to heat exhaustion and heat stroke and can promote the formation of ground-level ozone which affects human respiratory systems (GRHC, 2006a).

Similarly, green roofs can increase individual building energy savings. Vegetative evapotranspiration naturally cools ambient air temperatures; areas with sizable evapotranspiration can be anywhere between 2 and 8 °C cooler than their surroundings (Taha, 1997). Additionally, green roofs replace black surfaces that are often the hottest in the urban setting. Traditional roof temperatures can reach as high as 70°C (GRHC, 2006a). Not only do green roofs cover these hot surfaces with cooling vegetation, but they also significantly increase the amount of solar energy reflected out of the urban area by decreasing roof albedo. Wide-scale albedo modifications can change an entire city's energy balance, leading to climate changes across the city (Akbari, Pomerantz, and Taha, 2001). A 1998 study estimated that Los Angeles could save as much as $500 million were it to implement major urban heat island reduction strategies (Rosenfeld et al., 1998).

c. Air Quality

Green roofs provide another public good through their ability to reduce and filter the poor quality air often found in urban areas. As previously mentioned, urban heat island reduction from green roofs can lead to lower levels of smog as higher temperatures catalyze the formation of ground-level ozone (GRHC, 2006a). Plants on vegetated roofs also capture airborne pollutants through respiration and atmospheric deposition on leaf surfaces, as well as filter noxious gases (GRHC, 2006a). Moreover, green roofs can address climate change concerns through reduced greenhouse gas emissions resulting from avoided energy usage of buildings with green roofs.

d. Aesthetics

Urban settings tend to be visually homogeneous; cities are dominated by gray shades of asphalt, steel, and concrete. Green roofs can provide important variety and green space by utilizing surfaces that otherwise would go unused. Green roofs are essentially small ecosystems, and all urban ecosystems have aesthetic and cultural value and contribute to a high-quality urban environment. Such an environment is a key component in attracting a highly qualified workforce (Boland and Hunhammar, 1999). Furthermore, studies have shown that natural environments can help reduce stress in individuals and help hospital patients heal faster (Ulrich, 1984; Ulrich et al., 1991).

e. Wildlife Habitat

Vegetated rooftops can introduce small, functional ecosystems back into biologically barren urban centers. As a result, they can offer refuge for birds, invertebrates, and plants that find themselves in the city center. They can also serve as resting platforms for migratory birds venturing through urban areas (GRHC, 2006a). A series of green roofs could become a functional corridor for winged animals to move throughout the city without having to risk going down to dangerous streets.

2.2.2 Private Benefits

a. Energy Savings

Decreased energy usage has been identified as one of the most significant benefits from green roofs across their entire life cycle (Carter and Keeler, 2007). Individual buildings can be energy inefficient in part due to gaps in their building envelope, which can lead to significant heat loss in the winter and cooling loss in the summer. Green roofs help reduce this loss through a number of processes. First, the growing media and plant layers provide enhanced insulation on top of the building. The plant layer also has a higher albedo than a traditional blacktop roof and can reflect much more solar radiation. The primary source of energy-saving potential for green roofs comes from the latent heat loss resulting from evapotranspiration and photosynthesis occurring in the plant layer (Gaffin et al., 2005). The vegetation on the roof captures sunlight that would have otherwise been converted into heat energy when it hit the rooftop. Studies have shown green roofs can reduce an insulated building's total energy consumption by 2 to 7 percent (Niachou et al., 2001).

b. Extended Roof Life

Constant exposure to sunlight and precipitation can take a toll on rooftop waterproofing layers. The diminishing ability of the roof over time to keep water out of the building requires traditional roofs to be replaced every 15 to 25 years (Holleran, 2007). Green roofs protect the structural parts of the roof with their vegetation and growing media layers, which can double the life of the roof to 40 years (Acks, 2006; Wong et al., 2003; Lee, 2004). Life-cycle cost-benefit studies found increased roof life is among the most significant benefits from green roofs (Carter and Keeler, 2007).

c. Noise Reduction

The excellent insulation properties of green roofs also assist in reducing the impact of outside noises. Companies in Germany have found that green roofs can provide sound insulation for roughly 3 decibels (Acks, 2006), but other studies claim extensive roofs can reduce sound by up to 40 decibels (GRHC, 2006a). The main factors in determining noise reduction are plant area cover, type of plant, and depth of growing media.

d. Food Production

While green roofs are somewhat limited in the types of plants they can support, they do have some potential to grow food crops for consumption. A hotel in Vancouver, British Columbia, has successfully grown food on its green roof (Acks, 2006). Green roofs cannot replace produce sources from rural areas, but they can supplement the food supply of tenants in single buildings.

2.3 Green Roof Programs in Other Cities

Green roofs are relatively new additions to the United States but they have been in use in Europe since the early twentieth century. Recognizing the myriad benefits of green roofs, European cities began subsidizing green roof construction in the 1980s, spurring the addition of millions of square feet of roofs throughout European countries (Handwerk, 2004). Germany is the world green roof leader with 10 to 12 percent of all flat roofs greened. In a 10-year period, German green roofs grew by 350 million square feet (Penn State GRR, 2006). Currently, over 50 square miles of roof are greened throughout the country and 5 additional square miles are added each year (AP, 2006).

Green roofs began emerging in the United States in the past 15 to 20 years. Currently, the largest roof in the country is over 10 acres and is found on Ford Motor Company's plant in Dearborn, Michigan. An entire green roof research program was founded in 2000, when Ford contacted Michigan State University's Department of Horticulture to assist in the development of the company's green roof (MSU). Green roofs have grown rapidly in popularity in the U.S.; between 2005 and 2006, total roof space grew 80 percent. The rapid adoption of green roofs is due in part to public appreciation of additional green space, in part to the positive effects green roofs have on mitigating stormwater runoff and urban heat island effects, and in part to subsidies cities are including in their general plans. Challenges with green roofs in the United States include climatic variability and city zoning laws. Green roof programs in three cities with different climatic regimes and different approaches to green roof incentives are highlighted below.

2.3.1 Portland, Oregon

Portland's climate is characterized by mild temperatures and moderate nearly year-round rainfall. Total annual rainfall is variable, but averages over 890 mm (35 inches) per year (with a range of 508 to 1270 mm (20 to 50 inches) over a five-year period). Up to 51 mm (2 inches) of precipitation occur in each of the summer months (June through September). This climate is ideal for many plants, though the dry summers and the volume of rainfall in the winter present challenges. The volume of rainfall has led to high levels of surface pollutants being delivered to the Willamette River and tributaries. As a result, the City of Portland has been under a court order to manage polluted water flow into the Willamette (Clean River Rewards, 2008).

In response to the challenge of managing stormwater runoff, Tom Liptan, the major force behind green roof development at Portland's Bureau of Environmental Services (BES) proposed offering incentives for property owners to install best practices for stormwater management on site. Green roofs, called ecoroofs by the BES, are now considered a viable best management practice as long as they meet city standards (Portland BES, 2006). Portland residents can receive up to a 100 percent discount of their stormwater charges if they manage stormwater on their property (Clean River Rewards, 2008). Further, for each foot of ecoroof on a building constructed in Central City, buildings can be developed with an additional one to three square feet of floor area ratio (Portland BES, 2006). As ecoroofs have been shown to uptake nearly 100 percent of summer rainfall and over 20 percent of winter rainfall, there is a financial incentive to include ecoroofs to reduce stormwater runoff.

In an experimental test of ecoroofs on nearly 3,000 square feet of flat roof in Portland in 1999, 80 to 100 percent of stormwater was retained from April through November, and 30 to 50 percent of stormwater was retained from December through March. On average, the roof absorbed 69 percent of total rainfall with only 72 percent vegetative cover. Further, the ecoroof mitigated the peak flow (intensity attenuation) and detained stormwater until after the main rain event, slowing the rate of runoff (Hutchinson et al., 2003). Portland's increasing population and fast pace of development is projected to result in 25 percent impervious cover of the city's 135 square mile area (Hutchinson et al., 2003). Increased impervious area will not only intensify the volume of stormwater reaching rivers but will also offer Portland's planners the opportunity to install more green roofs over time.

Based on the success of experimental tests, the incentives offered to building owners, and the Portland BES' commitment to green roof development, ecoroofs have truly grown in Portland.

2.3.2 Chicago, Illinois

Chicago was the first city to install green roofs in the United States and remains the leading city in terms of total roof coverage. Interspersed throughout the city are 2.5 million square feet of green roof, including over 20,000 square feet on City Hall. The City Hall project was initially conceived of to mitigate urban heat island effect and was paid for by a settlement with a city utility provider garnered in 1999 (Greenroofs.com, 2006). In 2006, the city began the Green Roof Grants Program, awarding $5,000 grants to small residential and business green roof projects to stimulate roof development throughout the city (Pilloton, 2006).

Chicago's climate is conducive to successful green roof application with precipitation in the form of rain or snow year-round. Precipitation ranges from 38 to 89 mm (1.5 to 3.5 inches) per month, with the heavier precipitation months occurring in the summer. For December through March, the winter months, snowfall ranges from 163 to 257 mm (6.4 to 10.1 inches). Average daily temperatures range from -9 to 4 °C in the winter months and 21 to 32 °C in the summer months (National Weather Service, 2006).

Though the name "the Windy City" sounds likes a foreboding climate for green roofs, they have performed well in Chicago due in large part to Mayor Richard Daley's influence. His administration has included policies and funding for commercial green roofs through the Green Roof Improvement Program, offering tax incentives, subsidies, and building incentives for new and existing construction projects incorporating green roofs (CityofChicago.org, 2006). From 2005 to 2006, Chicago added 300,000 square feet of green roof space. Total coverage in 2006 was 2.5 million square feet on 200 roofs (Paulson, 2006). According to Chicago's commissioner on the environment, by June 2007 Chicago's green roof total was 300 roofs totaling 3 million square feet (Taylor, 2008).

2.3.3 New York City, New York

New York City also sports a robust green roof program, focusing on bringing the benefits of green roofs to low and moderate-income residents. The program, Greening Gotham, was started by Earth Pledge in 2005 and aims to green almost 4,000 acres of roof in Manhattan. New York's climate is similar to Chicago's, with precipitation of 76 to 102 mm (3 to 4 inches) per month, distinct seasons, low temperature ranges from -4 to 4 °C and high ranges from 21 to 29 °C (CitiDex.com, 2008). However, New York's impervious area, at 64 percent, exceeds Chicago's. Due to the extent of impervious area, temperatures are up to 4 °C higher in the city than in surrounding suburban areas (Rosenzweig et al., 2007).

By 2005, approximately 50 green roofs grew in New York City, the largest being a 35,000 square foot roof atop Silvercup Studios in Long Island City. These roofs were funded by private non-profit organizations and benevolent investors. Major policy incentives have yet to gain popularity throughout the city, but green roof advocates are pushing for their adoption. In April 2007, Mayor Michael Bloomberg's office released PlaNYC, the sustainability plan for New York City. The plan includes a property tax abatement to offset 35 percent of the installation cost of a green roof project. This incentive will be reviewed in 2012 to determine its effectiveness (PlaNYC, 2007).

3 Los Angeles Overview

The geographical setting for green roofs is an important factor that affects their performance. The majority of green roofs have been applied in climatic regimes with regular precipitation and humid summers such as New York, Chicago and many German cities (NCDWQ, 2007; Carter, 2006). Similarly, much of the research on green roofs has focused on humid environments. Few, if any, research studies have investigated the feasibility of green roof application in semi-arid regions. Given its semi-arid climate, Los Angeles presents many challenges for green roofs, including highly variable annual precipitation, multi-year droughts and intense storm events. Green roofs, however, may provide opportunities to alleviate some stormwater management issues in the intensely urbanized areas of Los Angeles.

3.1 Climate and Geographical Challenges to Green Roofs

The Los Angeles River watershed is characterized by relatively low amounts of seasonal precipitation and described as semi-arid. The watershed is within a Mediterranean climate region, where the summer is characterized by hot, dry conditions and the winter is wet and mild. The region experiences average summer high temperatures around 27 °C and average winter highs near 18 °C (WRCC, 2007). The Los Angeles River watershed receives approximately 80 percent of its annual rainfall during December, January and February (Mitchel and Blair, 1997).The watershed averages 381 mm of precipitation annually, although it experiences significant annual variability. Additionally, the heterogeneous landscape and orographic features greatly influence the precipitation regime on a micro scale in the watershed, resulting in rainfall variability across the entire watershed area (Conil & Hall, 2006). Considering the climatic differences of Los Angeles and the current green roof cities, it is clear that Los Angeles presents a few challenges.

The intensity of storms in Los Angeles can reduce the efficiency of green roofs. A green roof reduces runoff by intercepting precipitation and retains the water in the substrate and releases a portion via evapotranspiration. During intense storm events, the green roof substrate quickly becomes saturated and cannot retain additional stormwater. Thus additional precipitation is conveyed over the green roof as runoff. As such, the green roof performance for intense, heavy rainfall events is low.

Moreover, the frequency of storms in Los Angeles can reduce the efficiency of the green roofs. Carter (2006) shows that during heavy storm events, or as storm events increase, the growing substrate of the green roof becomes saturated and the green roof's efficacy decreases. Therefore, any further precipitation on the roof is conveyed as runoff. Considering that 80 percent of the precipitation in the Los Angeles River watershed is received in the winter months, the antecedent moisture of the roof may be near saturation throughout the season and might thus reduce the effectiveness of the roof in attenuating stormwater. In most green roof cities, precipitation occurs throughout the year and thus the roofs attenuate stormwater during the full year. In Los Angeles, however, the green roofs may only be effective during a few months because they operate with high antecedent moisture conditions.

Because Los Angeles is relatively warm and dry for several months of the year, the already costly green roofs may require additional irrigation, which requires infrastructure and a water source. Some green roofs capture and store rainwater in cisterns that can be pumped through the irrigation system during dry periods, yet this increases costs (NCDWQ, 2007).

In addition to the warm and dry climate, temperatures atop roofs are high because the roofs are exposed to direct and consistent solar radiation throughout the day. Dark roof surfaces also significantly contribute to high rooftop temperatures. Due to prevailing climatic regime and the rooftop exposure, Los Angeles green roofs must use plants that can thrive in dry conditions and intercept and transpire precipitation effectively.

3.2 Stormwater Problems

Urban stormwater runoff is the most significant conveyance of pollution into the coastal waters near the Los Angeles metropolitan area (Dwight et al., 2002). Urbanization in the Los Angeles River watershed and the paving of the Los Angeles River bed have replaced natural surfaces with impervious surfaces that funnel stormwater directly down the river channel while restricting groundwater recharge, further increasing the river's flow and leading to high runoff rates. In a natural river channel, the porous soil of the riverbed allows water to percolate into the soil and to eventually recharge groundwater reserves. Uneven surfaces often found in riverbeds combined with debris such as rocks or downed vegetation also slow the water in the channel and can help delay major flood events. Additionally, vegetation along river banks and in other parts of the drainage basin takes up water and reduces flows down the main river channel during storm events. Because of the higher percentage of impervious surfaces in the watershed and the river channel, the Los Angeles River is prone to stormwater runoff problems during large storm events. The water flows untreated through the series of pipes and channels that constitute the city's stormwater system (LA Stormwater, 2007). Pollution in Los Angeles stormwater has increased 200 to 700 percent over the past 20 years (Shapiro, 2003).

Polluted stormwater forces beach closures and presents public health risks. Water quality along Southern California beaches regularly exceeds daily and monthly thresholds for pollutants during heavy storm months (Noble, 2000). As a result, the Los Angeles River and its terminus, San Pedro Bay, are notoriously polluted water bodies. Los Angeles is listed among the 10 most polluted U.S. cities and the Los Angeles River is a state-listed 303(d) water body, indicating that it does not meet state water quality standards (ALA, 2007; SWRCB, 2006). People who recreate near stormwater outflows are far more likely to contract ear, nose, and intestinal infections (Shapiro, 2003).

The urbanized landscape, current stormwater management system, climatic regime and population density of the Los Angeles River watershed presents managers with a unique stormwater problem. Los Angeles is home to more than 8 million people and is intensely urbanized, as such more than half of the watershed area is impervious and densely populated. Heavy metals are associated with vehicles and are a primary stormwater pollutant due to their prevalence and high toxicity. The Los Angeles River and its terminus at the Long Beach and Los Angeles Harbors are state-listed for heavy metals, diazinon, DDT, cyanide, coliform bacteria, trash, PCBs and more than 50 other pollutants (SWRCB, 2006). These metals and other toxics accumulate on the urban landscape during dry periods and are then quickly conveyed over the impervious areas during the intense rainfall events.

A handful of stormwater management options have been employed in the Los Angeles River watershed, including infiltration basins, vegetated strips, and channelization. River channelization was carried out in the 1930s in an effort to control stormwater. The river was completely channelized by 1938. The channelization of the nation's waterways is now viewed as a major mistake, as it has been shown that many deleterious environmental effects are borne through channel paving. Currently, the Los Angeles River Revitalization Master Plan is considering reconfiguring the river channel for increased ecological and human use value. As such, additional stormwater management tools will be a valuable addition to management repertoire. Infiltration devices capture stormwater and convey the water into groundwater stores. The BMP effectively reduces the volume of stormwater, reduces pollutant loading, and recharges the groundwater. Currently, the University of California is working conjunctively with the County of Los Angeles and other stakeholders to investigate the feasibility of this management solution within the Los Angeles River watershed (Dewoody et al., 2006).

4 Project Model and Methods

4.1 Green Roof Experiments in Other Climates

Though green roofs continue to crop up throughout the United States, only a handful of research institutions have modeled roof performance or tested roofs experimentally. Researchers have conducted numerous studies testing different green roof composition and its effects on runoff, a few of which are described below. Though the literature on green roof studies is growing, none of the peer-reviewed papers within our literature review described studies in climates similar to Los Angeles.

Carter and Rasmussen (2006) performed a hydrologic study of green roofs at the University of Georgia in Athens, Georgia from November 2003 to November 2004. Their analysis compared the difference in runoff quantity between a conventional gravel roof and a green roof consisting of a 7.62 cm (3 in) growing medium (containing stalite, United States Golf Association sand, and worm castings) and six drought-tolerant succulents: *Sedum album* "Murale," *Sedum album* "Jellybean," *Sedum kamtschaticum, Sedum sexangulare, Delosperma nubigenum*, and *Delosperma cooperi*. Both roofs were then connected to stainless steel weirs (for water collection) in the building basement directly below the test roof plots where the water depth was recorded with a rain gauge. Through 31 recorded precipitation events during the study period, stormwater retention in the roof ranged from 39 to 100 percent, with an average of 78 percent. The roof operated best with light precipitation events of 1.39 cm/0.6 in or less and the least retention occurred during a 5.38 cm (2.1 in) storm.

Villareal and Bengtsson (2005) performed an analysis of an extensive, sedum covered roof at the Lund University in Sweden. Their study roof (0.80 by 1.93 m, 2.6 by 6 ft) contained 4 cm (1.6 in) of substrate (composed of 5 percent crushed limestone, 43 percent crushed brick, 37 percent sand, 5 percent clay, and 10 percent organic material). They used a mathematical model to calculate runoff with respect to precipitation ($Q_j = U_1 R_j + U_2 R_{j-1} + \ldots + U_i R_{j-i+1};$ Q=direct runoff, R=effective precipitation, j=total number of intervals spaced over time, i=number of hydrograph ordinates, and U=ordinates of a unit hydrograph over a change in time, constrained to a linear function, and to be greater than zero). They found a range of retention ranging from 10 percent (1.3 mm/min at a 14 degree slope) to 62 percent (0.4 mm/min at a 2 degree slope). The most important factor in determining retention in the study was the rate of precipitation, which caused a range in retention from 21 to 62 percent given a roof with a 2 degree slope.

Similarly, VanWoert et al. (2005b) tested a green roof at Michigan State University to determine stormwater runoff and retention. For their study, they used a completely covered roof with no visible growing media, composed entirely of sedums, including "golden carpet" and "stonecrop." The growing media consisted of 40 percent heat expanded slate, 40 percent USGA sand, 10 percent Michigan peat, 5 percent dolomite, 3.33 percent composted yard waste, and 1.67 percent composted poultry litter. Rain gauges were placed on the building underneath to measure the amount of runoff. They found that in light (under 2 mm) precipitation events, a roof with only growing media (no vegetation) retained the most stormwater at 99.3 percent, with vegetation retaining slightly less (96.2 percent) and the conventional gravel roof retaining 79.9 percent of the precipitation. In medium events (2-4 mm), the vegetated and growing media roofs retained nearly equal volumes (82.9 and 82.3 percent, respectively) of stormwater while the gravel retained only 33.9 percent stormwater. Large events (over 6 mm) proved the importance of including vegetation in a green roof as the roof with vegetation retained 52.4 percent, while the growing media roof retained only 38.9 percent and the gravel roof 22.2 percent. The study also found that the rate and volume of precipitation were most significant in determining the runoff and retention. A storm event of 73 mm over three days resulted in 12 percent retention by the vegetated roof.

These studies gave us a baseline to which we could compare our modeled results, described below.

4.2 Smart Stormwater 2.0 Model

The Smart Stormwater 2.0 Model ("the model") was written by Eliza Bradley for Earth Pledge, for use in modeling green roofs in New York City. The model estimates the volume of runoff captured by a hypothetical green roof during storm events. Substrate field capacity, plant evapotranspiration coefficient, and substrate depth can be manipulated within the model to simulate different green roof compositions. Actual daily precipitation and potential evapotranspiration data from the Los Angeles River watershed were used as inputs, allowing the model to directly simulate green roof performance under Los Angeles' climatic conditions.

The model runs through each day of input data (precipitation and potential evapotranspiration), calculating the total water held by the roof, the total precipitation addition, the evapotranspiration subtraction and any discharge that may occur. The model assumes that, on days with precipitation, there will be no evapotranspiration. For each day, the model starts with the total moisture content (or "roof bucket") left over from the day before. If no precipitation occurs on the day in question, and if the amount of water left in the roof bucket is greater than the chosen wilting point value, the model subtracts the evapotranspiration amount (scaled by the crop factor) from the roof bucket, and moves on to the next day. If there is precipitation on the day in question, the model adds the precipitation to the existing roof bucket, and this roof bucket amount will be used to compute the next day's values. If the roof bucket exceeds its capacity, as determined by the specific combination of field capacity and depth, then discharge will occur and the roof bucket will enter the next day at full capacity. The model's primary output includes discharge from the roof, evapotranspiration on the roof, and the "roof bucket," which is a recording of the depth of water that the roof stores on a given day. The main features of the model are illustrated below in Figure 4.1.

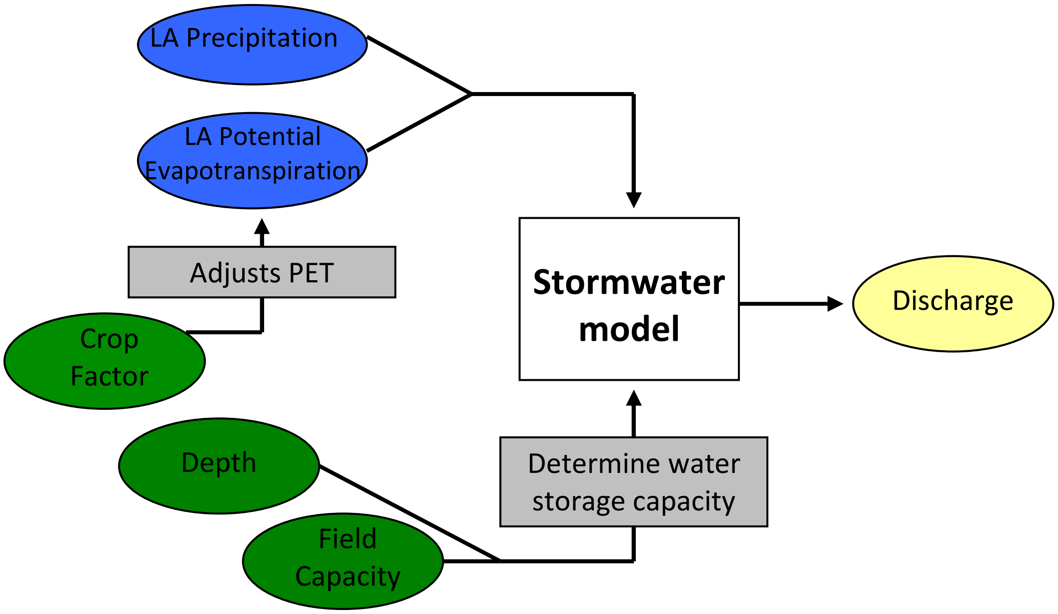

Figure 4.1 Smart Stormwater 2.0 Model Conceptual Diagram. Model parameters, determined through literature review and expert opinion, are in green. Model inputs, from actual Los Angeles data, are in blue. Model functions are in gray and the major output is in yellow.

The model also incorporates two initial values for wilting point and initial volumetric water content. Wilting point, set at 0.05 mm in the model, is the roof bucket amount below which plants cease to evapotranspire. The initial volumetric water content is the measure of moisture that is on the roof at the beginning of the simulation period.

To adapt the model for application in Los Angeles, all processes involving snowfall or snowmelt were removed, as the Los Angeles River watershed receives negligible snowfall. Additionally, climate inputs and model parameter values specific to Los Angeles were determined to most accurately simulate green roofs in a semi-arid climate. Data collected at rain gauge stations within the Los Angeles River watershed from September 1949 to May 2002 were adapted for inputs to the model (the process to select the specific stations is described in Section 4.3.1). The model's parameters, plant evapotranspiration coefficients ("crop factor"), growing media depth ("depth"), and growing media field capacity ("field capacity"), were determined from extensive literature review and expert opinion (described below in Sections 4.3.2 and 4.3.3).

4.3 Model Inputs

4.3.1 Precipitation Data

Actual precipitation (mm/day) and potential evapotranspiration (mm/day) measurements collected at rain gauge stations within the Los Angeles River watershed serve as the primary model inputs. The Water Resources Division of the County of Los Angeles Department of Public Works (LACDPW) provided daily precipitation data for 27 geographically distinct stations throughout the Los Angeles River watershed, many with continuous data for at least 50 years (Brown, 2007). Station metadata, listed in Appendix B, includes information about the station's physical location, latitudinal and longitudinal coordinates, and elevation. We conducted a diagnostic search of the data to determine the magnitude of missing data points for each station. Nearly all stations were missing precipitation data for small periods of time (typically one to three days). Because our modeling program required records for each day, we manually entered zeroes for the days without precipitation data, assuming no precipitation occurred that day. We were confident in our decision to replace blank data with zeros because the majority of the missing data points occurred in the dry season (summer months). In the event that multiple months or years were missing from the data, we did not replace missing data with zeros. Because the model runs with daily precipitation and specific rain events rather than an aggregate of precipitation over time, we aimed to select stations for which data existed for as many days as possible during the rainy season. Figure 4.2 below summarizes the average total yearly precipitation in inches for 21 stations where long-term continuous data existed.

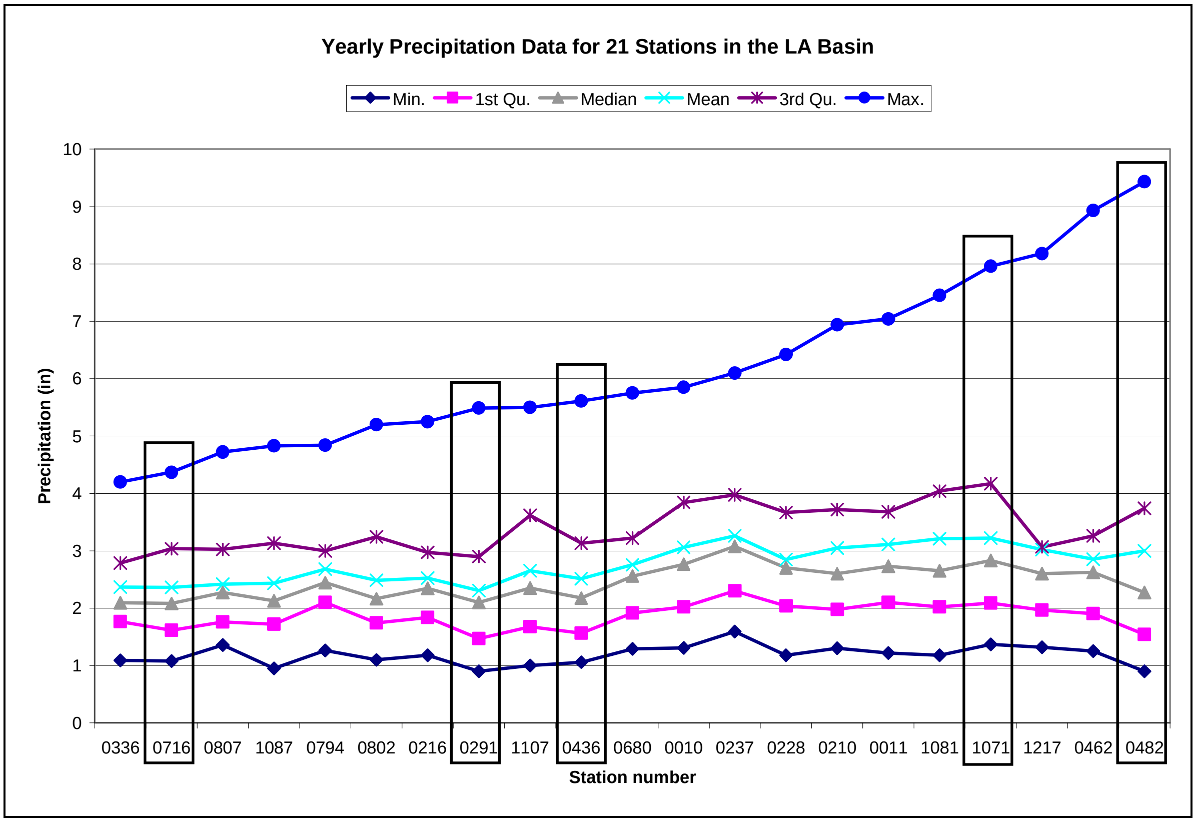

Figure 4.2 Rain Gauge Station Summary Statistics. Summary statistics of daily rainfall data for 21 rain gauge stations in Los Angeles. Stations selected for model input are highlighted in black.

After extensive analysis of the stations, their locations, and the duration of data available, we chose data from five stations to use as inputs to the model: 96th Street (291), Hansen Dam (436), USC (482), Ducommun (716), and Descanso (1071). Care was taken to include stations from both the upper and lower reaches of the watershed. The upper watershed is dominated by foothills, tends to receive slightly higher precipitation, and includes less impervious area than the lower watershed, which is at lower elevations, is relatively flat and includes the most urbanized and impervious surface areas in the watershed. Stations were also chosen to include locations with high maximum yearly rainfall and low maximum yearly rainfall. The five selected stations visible in Figure 4.3 below represent a range of geographically heterogeneous locations in the Los Angeles River watershed, as well as a range of high, low and average maximum daily precipitation values. This assortment of stations provides a reasonable representation of the different precipitation regimes in the Los Angeles River watershed. Further, the selected stations have long, continuous periods of overlapping data, which maximizes the period over which simulations can be run. The overlapping time period allowed us to run the Smart Stormwater 2.0 Model simulations for a time period of over 50 years, from September 30, 1949 to May 20, 2002.

The LACDPW also provided evapotranspiration data for the Los Angeles River watershed, which was measured and recorded at Station 1071 (Descanso). After selecting the five stations, we formatted the precipitation and potential evapotranspiration input data to be used in the model. Next, we determined a range of values for the model's parameters – growing media depth, field capacity and crop factor.

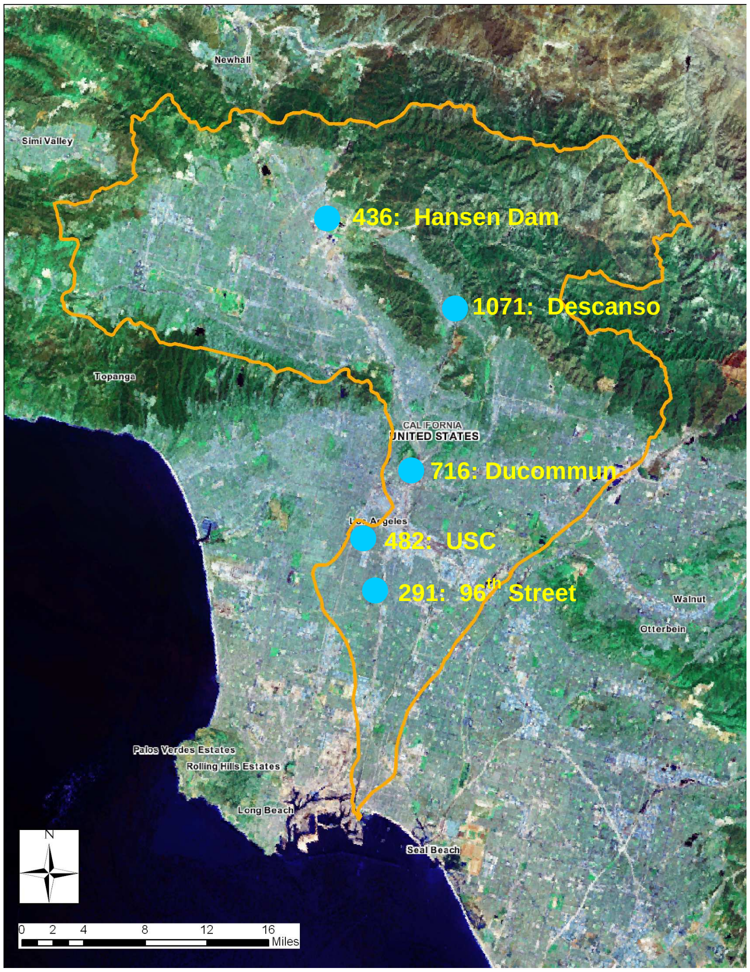

Figure 4.3 Rain Gauge Station Locations. Locations of rain gauges used for Smart Stormwater 2.0 Model inputs. The Los Angeles River watershed is outlined in electron gold.

4.3.2 Growing Media Depth and Field Capacity

Of the three parameters within the model, substrate depth is the most standard across all extensive green roofs. We chose to use a depth range from 2 to 6 inches, with the three parameter values being 2 inches, 4 inches and 6 inches. These depths cover the typical range of an extensive green roof and would support vegetation such as grasses and sedums that are used in extensive roofs (Monterusso et al., 2005; VanWoert et al., 2005a; Dunnett and Nolan, 2004).

Field capacity is the percentage of a soil's volume that can hold water (Veihmeyer, 1931). A substrate's field capacity is determined by media granule size (and thus porosity) and surface area (Veihmeyer, 1931). For green roofs, the field capacity is a design feature and depends on the substrate components used. However, climate features such as temperature and precipitation will impact the evapotranspiration of any substrate. Thus, while field capacity is not dependent on climate, these variables must be considered in the design of a green roof. In the model, the field capacity input determines how much moisture will be available for plant evapotranspiration after a precipitation event. This measure is an important component for a green roof in a semi-arid location like the Los Angeles River watershed because the survival of plants through the dry season is a concern. The model requires a selected range of values, all of which assume an extensive roof. The default range set for an extensive roof in New York City was 25, 35 and 45 percent. However, a 25 percent field capacity will not retain enough moisture to sustain plants in Los Angeles (Loosvelt, 2007). No studies that list field capacities measured on roofs in semi-arid areas currently exist. To determine an appropriate field capacity for the Los Angeles roof model, we reviewed the literature of experimental roof studies throughout the United States and Europe.

DeNardo et al. used a medium with a 33.6 percent field capacity in Pennsylvania and demonstrated an average stormwater runoff reduction of 40 percent (DeNardo, 2003). Growing media with field capacities greater than 35 percent retain moisture for longer periods between rain events (VanWoert et al., 2005b). In Los Angeles, the dry season can extend from April to October, and a growing media with a higher field capacity will retain water longer into the dry season than a lower field capacity. When VanWoert et al. used a non-organic medium-only substrate (i.e. shale, limestone, perlite), they achieved a field capacity of 50.4 percent, but the addition of organic and large granule components for roof stabilization reduced the overall field capacity to 27.2 percent. Large granule media is required on the top level to stabilize the layer and protect it from erosion by wind and excessive precipitation. While this service is necessary for the roof to function, it results in a loss of field capacity. The VanWoert et al. study occurred in Michigan, and the precipitation frequency was great enough to allow for a field capacity below 30 percent without any resulting damage to the plants. Researchers in Sweden experimented with field capacities of 30 to 40 percent on seven different roofs throughout the country, and the incorporation of a stabilizing (large granule) top-layer to prevent erosion. The roofs functioned desirably regarding stormwater attenuation, ranging from 21 percent (in a 1.3 mm/min rain event) to 64 percent (in a 0.4 mm/min rain event) retention with a two-degree slope (Bengtsson et al., 2005). Based on this literature analysis, we set the minimum field capacity value at 30 percent and the maximum value at 40 percent for our Los Angeles-based model. The middle value remained at 35 percent.

4.3.3 Evapotranspiration Coefficients - Crop Factors

Determining the evapotranspiration coefficients, or crop factors, for the plant mix selected for this study required understanding plants' water needs and evapotranspiration rates, as determined by climatic factors. Evapotranspiration rates reflect plant water needs as a measurement of the speed with which plants remove water from growing media. High crop water needs are associated with hot, windy, dry, and sunny climates, while low crop water needs are associated with cool, not-too-windy, humid, and cloudy climates. The Food and Agriculture Organization (FAO) typically publishes crop water needs for baseline crops and crops of economic importance. Final evapotranspiration rates for other plants are scaled using an evapotranspiration coefficient specific to each plant, which is called the crop factor. Crop factors are determined experimentally or through modeling. Full-grown crops have higher crop factors as they can uptake and manage more water than newly planted or early season crops (Brouwer and Heibloem, 1986). Our model incorporates crop factors for fully grown plants of mixed species (50 percent sedums and 50 percent grasses, as described in section 2.2.1). The crop factors used in our model account for the variation of weather in Los Angeles. The leaf-area index (LAI), a measure of a plant's ability to intercept water, can have an effect on overall ET rates, but was not incorporated in the model.

The crop factors originally included in the New York-scaled model were 0.8 to 1.2. This range emerged from discussions with green roof scientists and a series of three papers published by Robert Berghage and members of his group at Pennsylvania State University (PSU) using the best fit of experimental roof results with the Penman-Monteith, Blaney-Criddle, and FAO Penman equations (Berghage et al., 2007). According to green roof scientists and experts Thomas Whitlow (Cornell University), Berghage, Brad Rowe (Michigan State University), Tom Liptan (City of Portland) and an extensive literature search, a peer-reviewed study of crop factors for green roof plants in Los Angeles or any other semi-arid area has not been completed. Studies have, however, determined crop factors for many economically relevant agricultural species. Sedums and grasses, species typically used in green roofs, have only been tested in greenhouse and field conditions in Midwestern, Southern, and Northeastern environments. Because climatic conditions are considerably different in the semi-arid Los Angeles River watershed, none of the crop factor ranges discovered in an experimental setting could be transferred directly to the model.

We selected the range of crop factors based on a plant mix of 50 percent native grasses and 50 percent sedums. However, as neither this mix nor the specific Los Angeles green roof conditions had been modeled or tested experimentally, determining the crop factor required analysis of other studies. Members of the PSU group estimated a range of crop factors under experimental field conditions for sedums (*S. acre* and *Delosperma* sp.). The range determined through regression analysis of the best fit with Penman-Monteith, FAO Penman, Original Penman, and Blaney-Criddle equations, 0.24 – 3.25 (Rezaei and Jarrett, 2006; Rezaei et al., 2005), encompasses the model range. The highest value, 3.25, was recorded in late summer, a period of intense heat and humidity, in Pennsylvania. For the adaptation of the model to the Los Angeles climate, we truncated the crop factor range to 0.20 to 1.2. The lower half of that range matches crop factors of numerous grass species tested by the FAO in sub-humid climates using Penman-Monteith (FAO). We did not model the highest ranges found by other studies because the testing conditions in Pennsylvania are not replicated in the Los Angeles climate. Water is not widely available during the hottest times of year in Los Angeles, as it is in Pennsylvania, thus evapotranspiration will drop off during the summer months. We believed this range to be a good representation of the crop factors that might be determined experimentally on green roofs in Los Angeles. Focused research and green roof testing is necessary to better delineate the ideal crop factor range.

4.4 Running the Model

To simulate the stormwater retention capacity of various hypothetical roofs, the Smart Stormwater 2.0 Model was run using the following parameter value ranges: depth (inches) = [2 4 6]; field capacity = [0.3 0.35 0.4]; and crop factor = [0.2 0.56 0.88 1.2]. The field capacity and depth parameter values determine the water storage capacity of a given roof. For example, a roof with growing media of depth 4 inches and field capacity of 0.4 could retain a column of water up to (4 inches)*(0.4) = 1.6 inches, or 40.64 mm deep. The crop factor parameter values scale up or down the evapotranspiration input data, simulating greater or lesser potential evapotranspiration than was measured at the 5 rain gage stations in the watershed.

Because there are three parameters with three, three and four possible values, respectively, the model runs its simulations for 3*3*4 = 36 potential parameter value combinations for each of the five precipitation stations. Each combination of parameter values simulates a roof with a unique composition, thus the model tests the function of 36 potential green roofs. A modeled roof could have a depth of 2 inches, field capacity of 0.3, and a crop factor of 0.2, and this roof would function differently from a roof with a different parameter value combination. Modeled roofs with parameters at the lowest end of the range – 2 inches depth, 0.30 field capacity and 0.2 crop factor – have less capacity to absorb stormwater than roofs modeled with parameters at the highest end of the range – 6 inches depth, 0.4 field capacity and 1.2 crop factor. Throughout the results and analysis sections, "lowest parameter values" or "low parameters" means those values at the bottom of the parameter ranges, while "highest parameter values" or "high parameters" means those values at the top of the parameter ranges. Sections 4.5 and 4.6 further expand on the relative effects of each of the parameter values.

Using these parameter ranges and the Los Angeles daily precipitation and evapotranspiration data, we ran the model once for each of the five selected stations over the period from September 1949 to May 2002. The model calculates the water flux for each of the 36 possible green roof combinations, using the precipitation and evapotranspiration data for a given station. The model keeps track of the roof bucket and discharge for every day of the simulation, for all 36 possible green roof parameter combinations.

The model output was then analyzed to determine the degree to which different green roofs can reduce the amount of stormwater that becomes runoff. Sensitivity analysis was performed in order to determine the degree to which the different values in the range of model parameters affected roof performance. Model outputs and sensitivity analysis indicate the level of uncertainty in the modeling process. Uncertainty stems from the methods used to determine model parameter ranges and the degree to which climatic factors affect roof performance. Even if all roof parameters were selected using values derived experimentally in the specific Los Angeles microclimate in which the roof would sit, overall roof performance would vary according to precipitation frequency and intensity.

4.5 Model Results and Sensitivity Analysis

Because the goal of this project was to determine the effects of green roofs on stormwater discharge, we analyzed only discharge (runoff) outputs from the model runs. We first generated several hydrographs to visually estimate the roof's function during and after specific rain events and with a variety of parameter values. The stormwater from large storm events turned almost entirely into runoff regardless of parameter values as seen in Figure 4.4 (a and b), though runoff was minimally attenuated. Stormwater from minimal or intermediate events was retained in the modeled roof as seen in Figure 4.5 (a and b). We classified storm events as small, intermediate or large after analyzing all the days with precipitation and visually estimating the frequency of events and the extreme event outliers. For 8,000 storm events, we classified 65-75 percent of storms as minimal to intermediate, and 25-35 percent of storms as large or extreme. This classification held true through analysis of results from all five rain gauge stations.

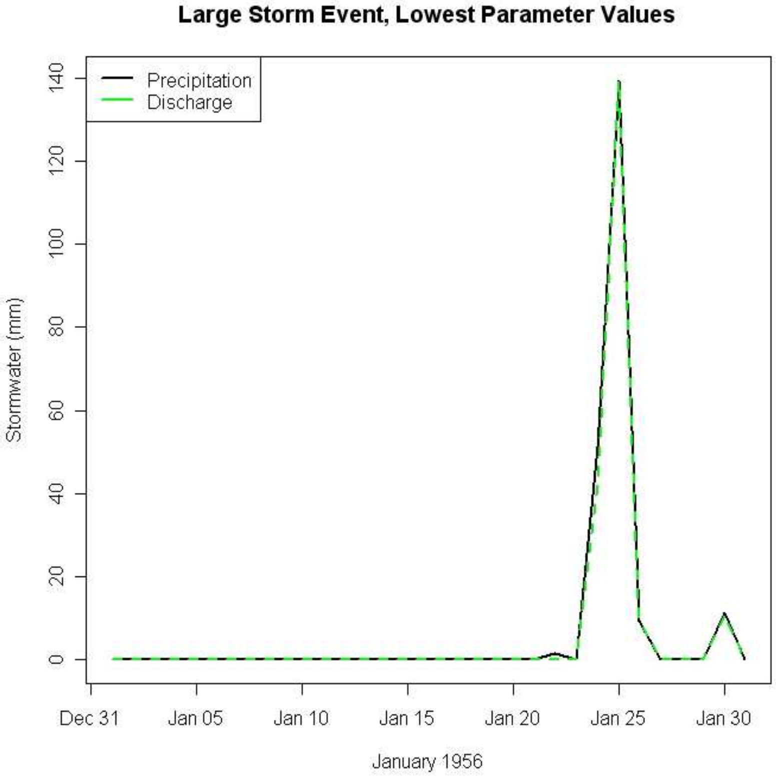

Figure 4.4a Effects of Large Storm on Discharge – Low Parameters. Representative results of model performance for a 140-mm storm event at station 291 in January 1956. The roof modeled with the lowest parameter values has no effect on attenuating runoff.

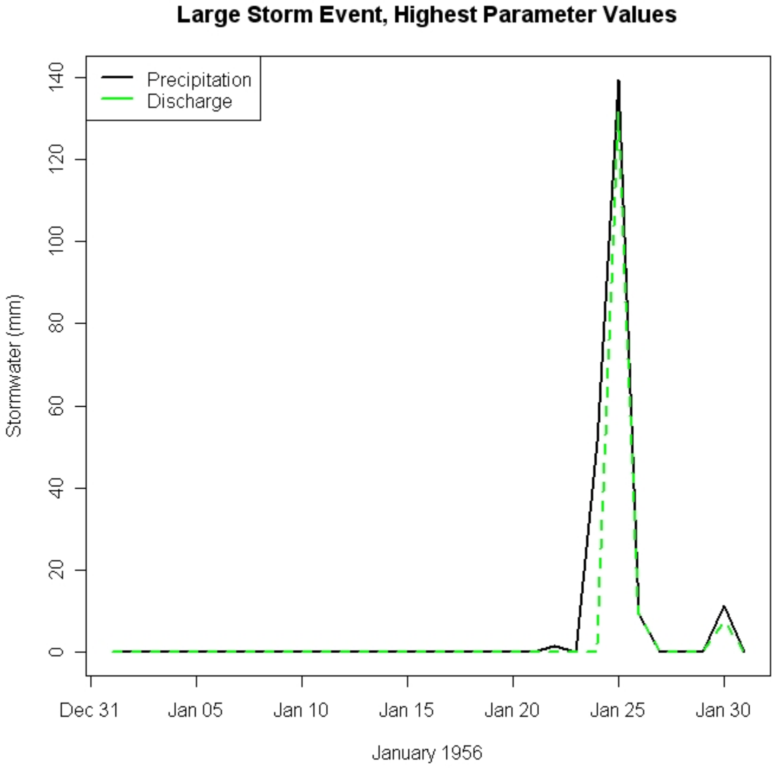

Figure 4.4b Effects of Large Storm on Discharge – High Parameters. Representative results of model performance for a 140-mm storm event at station 291 in January 1956. The roof modeled with the highest parameter values delays peak runoff by one day and absorbs a minimal amount of rainfall.

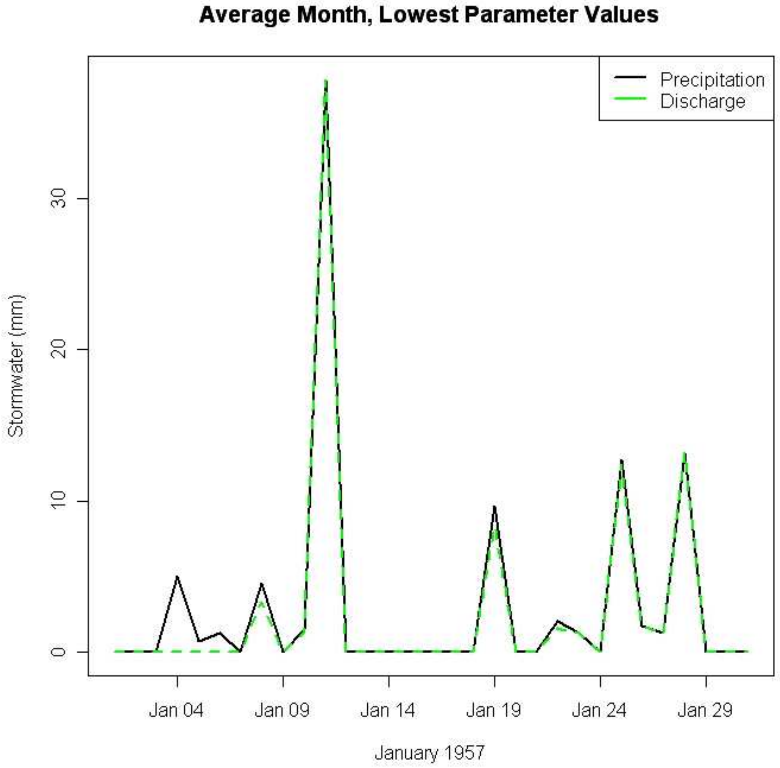

Figure 4.5a Roof Performance – Rainy Month, Low Parameters. Representative results of model performance for minimal and intermediate storm events on a roof modeled with the lowest parameter values at station 291. Runoff was only mitigated in the first small storm, while every storm thereafter turned entirely to runoff.

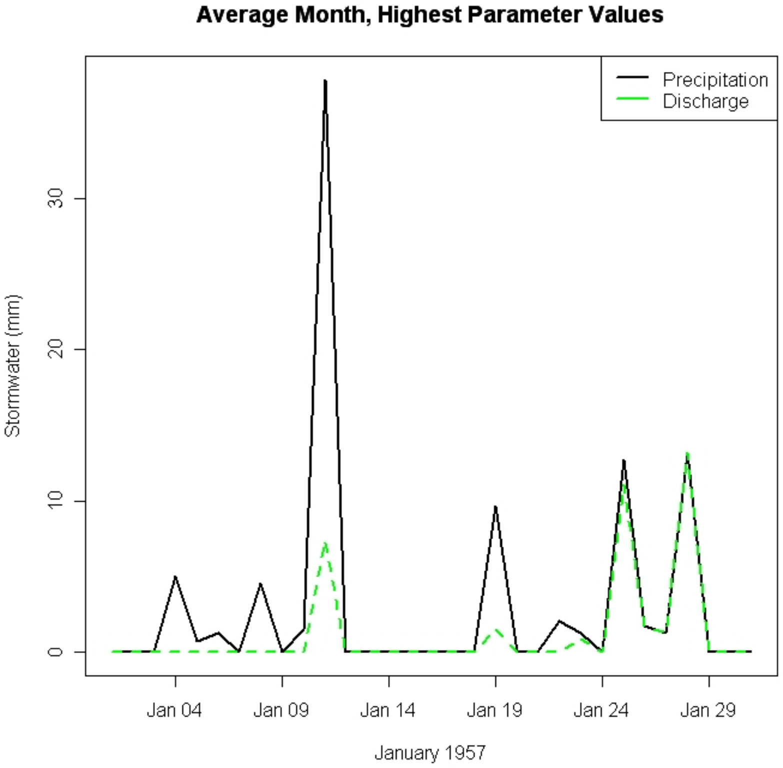

Figure 4.5b Roof Performance – Rainy Month, High Parameters. Representative results of model performance for minimal and intermediate storm events at station 291. The roof performed best when modeled with highest parameter values, retaining nearly all of the stormwater from events until the end of the month when the antecedent moisture in the roof saturated the roof and all rainwater turned to runoff.

Figure 4.6a-c shows the effect of the roof over three of the rainiest sequential months in the precipitation data set. The effect of antecedent moisture is visible in all hydrograph figures. The green roof can mitigate runoff through absorption or evapotranspiration to a saturation point (in Figure 4.5, the saturation point occurs on January 24). After the saturation point, any stormwater reaching the roof runs off immediately.

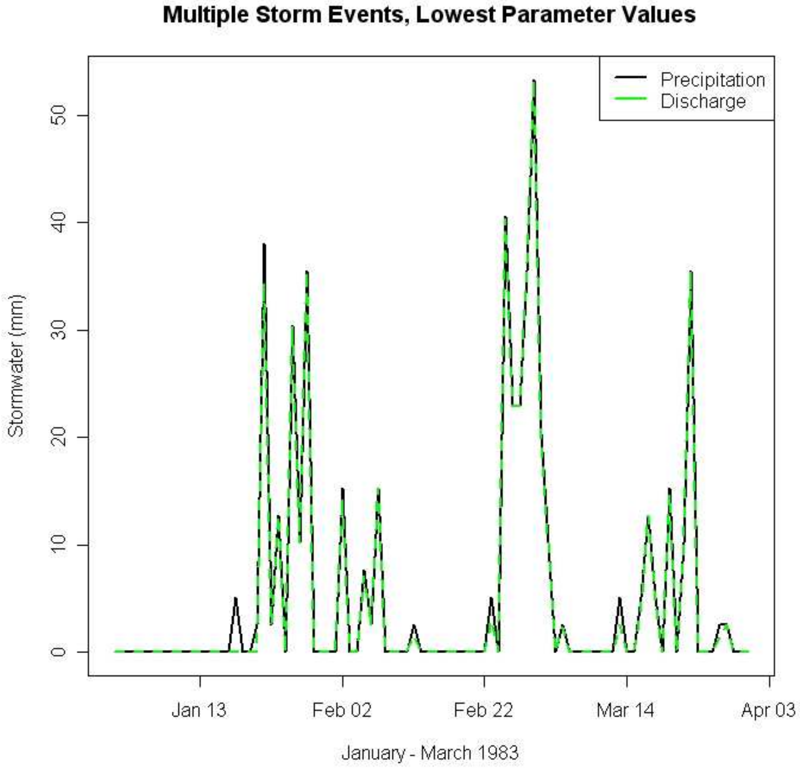

Figure 4.6a Roof Performance – Three Rainy Months, Low Parameters. Modeled results of the effects of three of the rainiest sequential months on runoff from the modeled green roof at station 291. Lowest parameter values had almost no effect on attenuating runoff, retaining stormwater in only the first event on January 13.

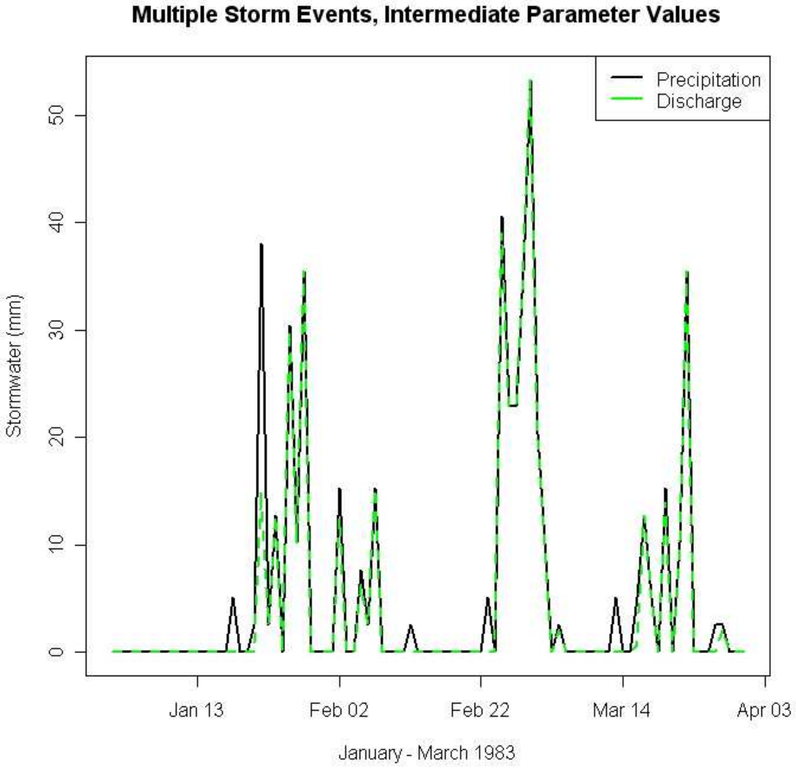

Figure 4.6b Roof Performance – Three Rainy Months, Intermediate Parameters. Modeled results of the effects of three of the rainiest sequential months on runoff from the modeled green roof at station 291. Parameter values in the middle of the range had a bigger effect on stormwater than roofs modeled with lower parameter values, managing stormwater for all small events until the end of March.

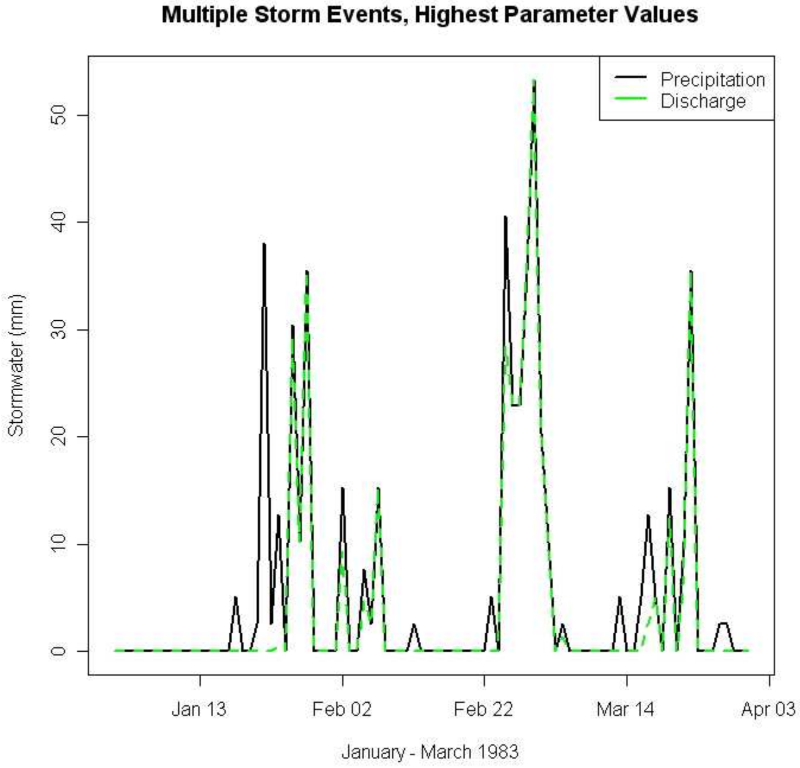

Figure 4.6c Roof Performance – Three Rainy Months, High Parameters. Modeled results of the effects of three of the rainiest sequential months on runoff from the modeled green roof at station 291. The roof modeled with the highest parameter values had the best effect of all parameter combinations, though runoff during the largest events following other storms resulted in nearly 100 percent runoff due to antecedent moisture in the roofs.

For each of the five stations for all storm events for all years, we determined the average stormwater runoff avoided by aggregating total precipitation and total discharge over all years. Avoided runoff is the difference between total precipitation from all storm events for all years and total discharge from all storm events for all years, divided by total precipitation from all storm events for all years and multiplied by 100. Average avoided runoff for all five stations for the entire modeling period ranged from 21 to 64 percent, depending on the roof composition modeled. Tables 4.1 and 4.2 below show the range of avoided runoff at each station using the lower end of the parameter range (Table 4.1) and the upper end of the parameter range (Table 4.2). Figures 4.7 and 4.8 accompany those tables and show graphically the avoided runoff and ranges for each station with the different roof compositions.

Table 4.1 Avoided Runoff – Low Parameters. Range of avoided runoff for all storm events throughout all modeled years at all five precipitation stations within the Los Angeles River watershed. Modeled roofs were those with parameter values at the bottom of the range.

Station Number	Mean Avoided Runoff (%)	Maximum Avoided Runoff (%)	Minimum Avoided Runoff (%)	Standard Deviation
436	21	56	10	10
1071	17	33	7	8
482	23	46	8	12
291	22	63	11	12
716	20	41	10	10

Table 4.2 Avoided Runoff – High Parameters. Range of avoided runoff for all storm events throughout all modeled years at all five precipitation stations within the Los Angeles River watershed. Modeled roofs were those with parameter values at the top of the range.

Station Number	Mean Avoided Runoff (%)	Maximum Avoided Runoff (%)	Minimum Avoided Runoff (%)	Standard Deviation
436	64	100	26	21
1071	54	100	18	20
482	69	100	23	23
291	68	100	26	22
716	64	100	21	22

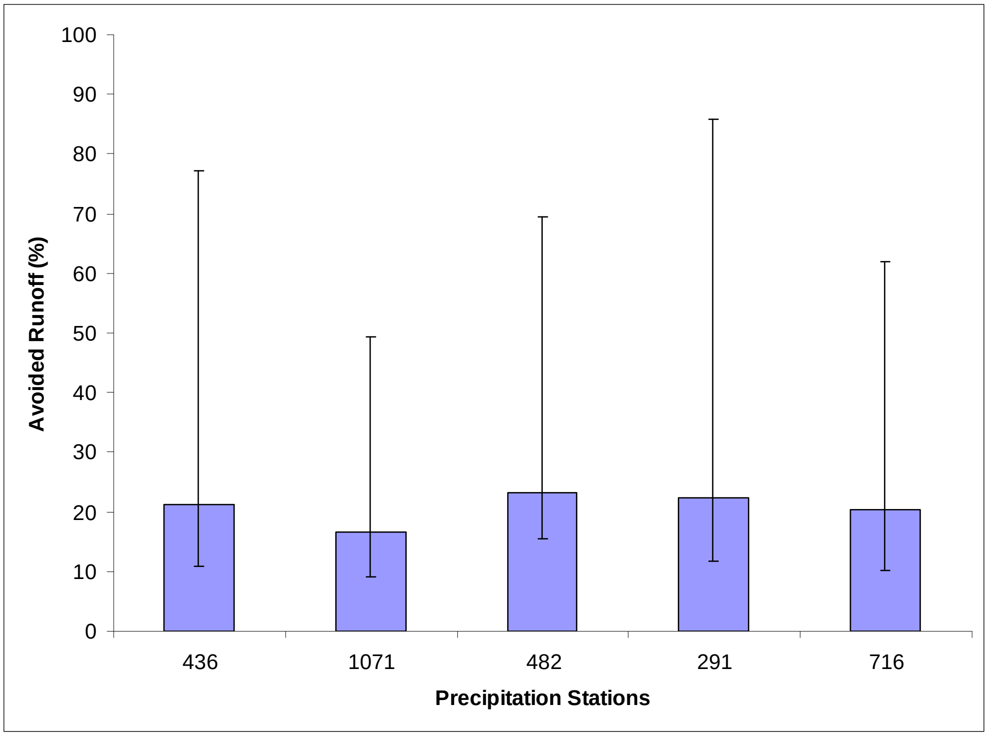

Figure 4.7 Mean Avoided Runoff – Low Parameters. Mean avoided runoff ranges of all precipitation and discharge at all five stations using the lowest parameter values.

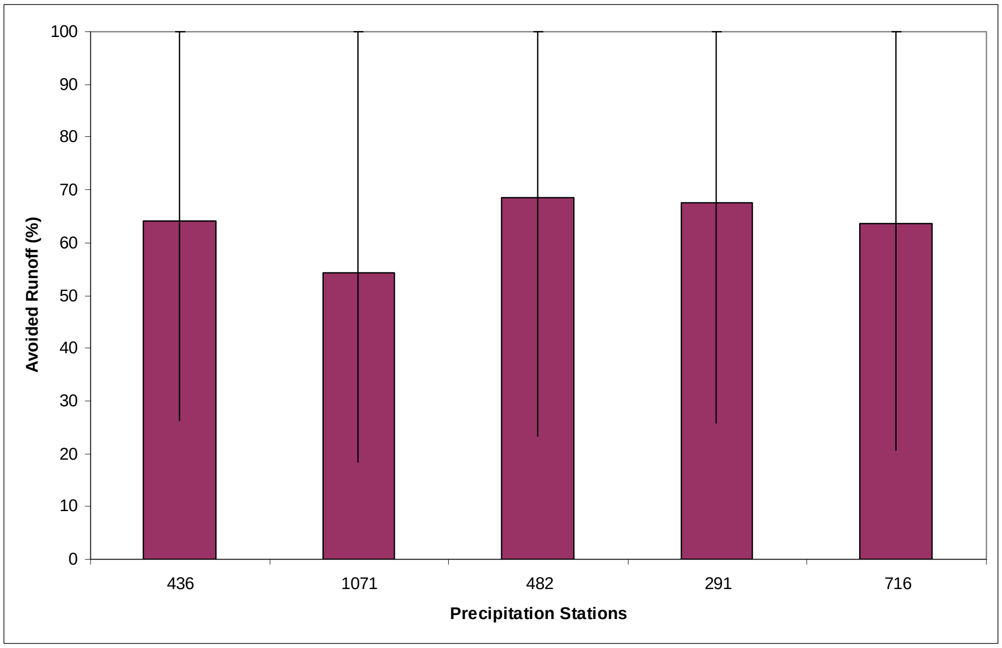

Figure 4.8 Mean Avoided Runoff – High Parameters. Mean avoided runoff ranges of all precipitation and discharge at all five stations using the highest parameter values.

The considerable range in avoided runoff stems from yearly differences in precipitation frequency and intensity, daily differences in precipitation intensity and spatial differences in rain gauge station locations. In a rainy year with several consecutive large storm events, runoff from the roof would be high, as antecedent moisture in the roof from prior events would render the model's "roof bucket" full. When the "roof bucket" is full, all storm water turns to runoff (visible above in Figures 4.5 and 4.6). In a year with only small storms or more sporadic rainfall, the roof could remove precipitation between storm events, resulting in a greater amount of avoided runoff.

Spatial differences between the rain gauge stations also have an effect on the range of avoided runoff. Stations 436 and 1071 are in the upper part of the watershed and receive more precipitation than the three stations in the lower watershed. Stations 436 and 1071 received 21,000 and 29,000 mm (825 and 1,140 in) of precipitation, respectively, over the 53-year period of study, while stations 291, 482 and 716 received 18,200, 18,500, 21,000 mm (710, 725 and 825 in) of rainfall, respectively. Because precipitation is concentrated in the rainy season (a two- to four-month period in winter), more precipitation indicates either greater frequency or greater intensity of storms. Both of these effects translate to decreased stormwater management capacity in the roofs due to increased days with antecedent moisture.

Results from the model and general intuition indicated that different roof compositions affect runoff from the roof. To determine the effect of the different roof compositions on stormwater runoff, we performed a sensitivity analysis on each of the ranges of parameter values at each rain gauge station. This process involved subsetting the data, analyzing parameter effects using statistical analysis tools, including analyses of variance and regression models, and visually estimating the changes in runoff using boxplots.

We first subset the data to remove all days where discharge was equal to zero in order to focus on the roof composition types that led to discharge. Once we subset the data without zero-discharge days, we further subset the data to avoid autocorrelation by selecting only one discharge day in a series of discharge days per storm event. The final data set size for analysis included up to approximately 8,000 points per station, pared down from 200,000 to 600,000 points.

Using the selected dataset, we tested the sensitivity of stormwater reduction to each of the parameters. First, we visually represented the effects of parameters on runoff for all storms. Figure 4.9 (a-c) shows the effects of all three ranges of parameter values on runoff (using a logarithmic scale) for station 291.

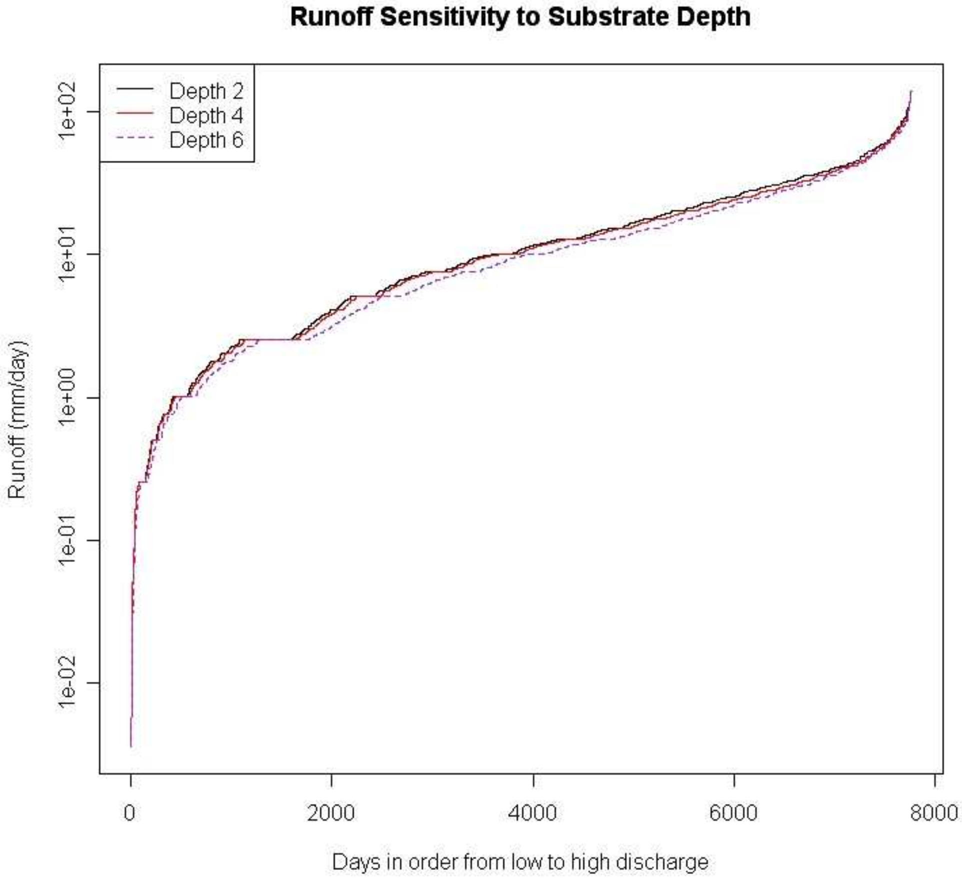

Figure 4.9a Graph – Runoff Sensitivity to Substrate Depth. Effects of changes in substrate depth on runoff (log scale). The higher the parameter value, the greater the effect on decreasing runoff.

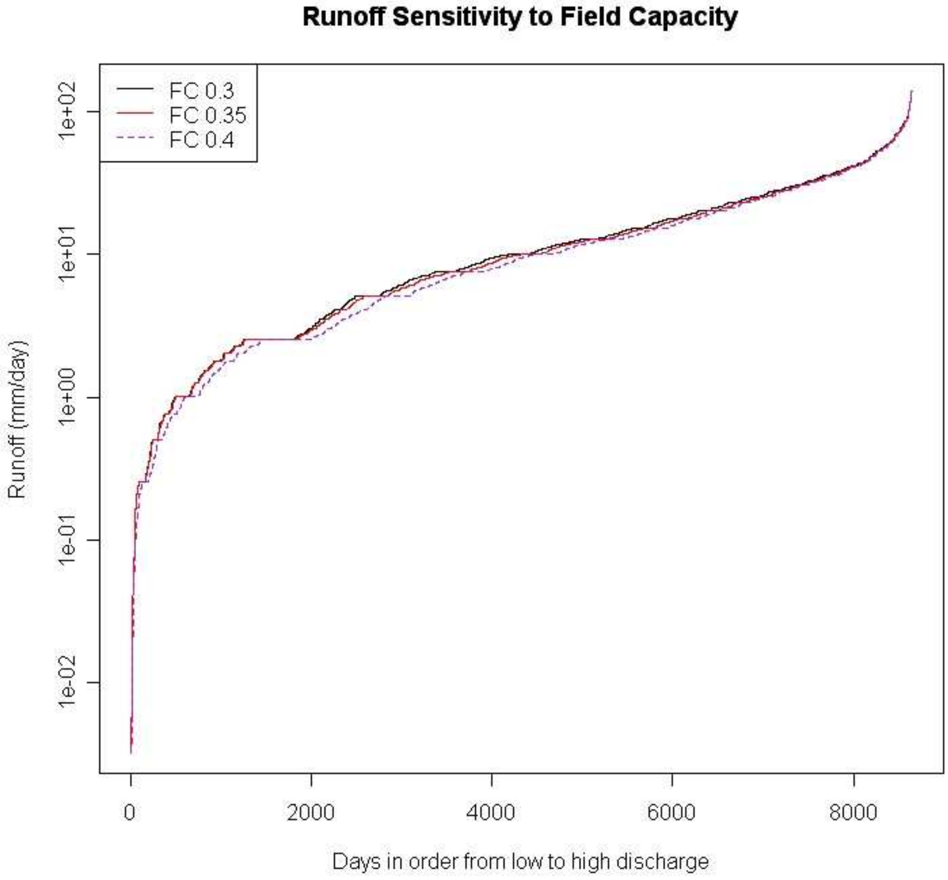

Figure 4.9b Graph – Runoff Sensitivity to Field Capacity. Effects of changes in field capacity on runoff (log scale). The higher the parameter value, the greater the effect on decreasing runoff.

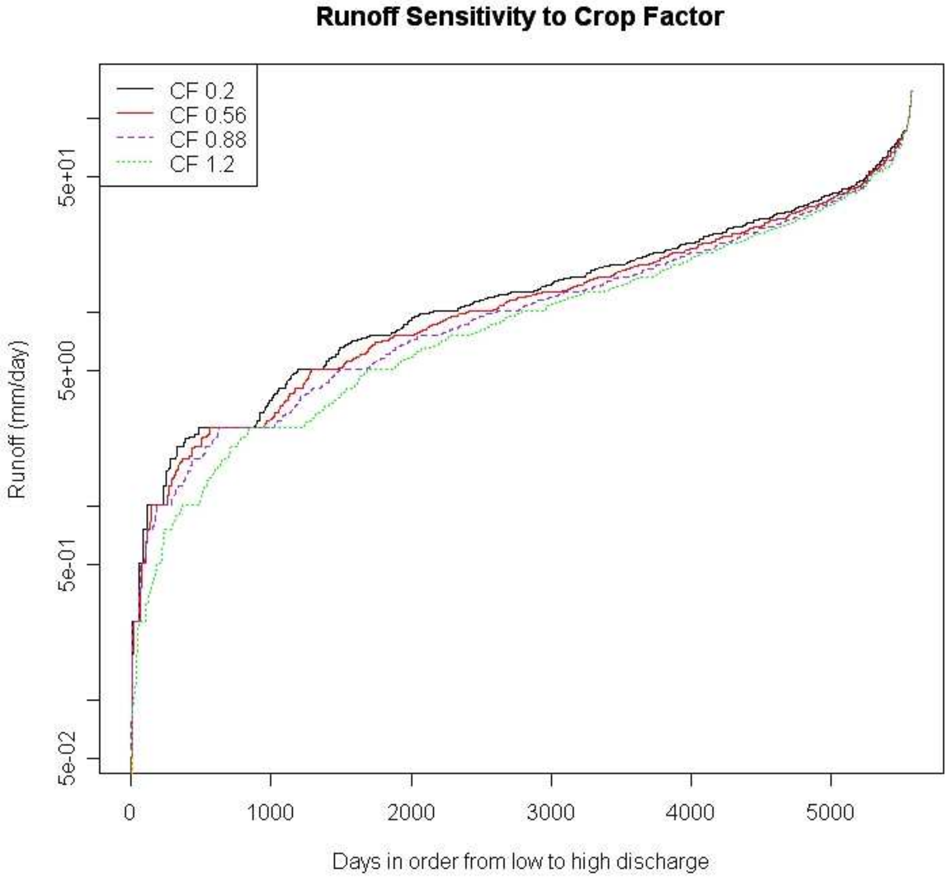

Figure 4.9c Graph – Runoff Sensitivity to Crop Factor. Effects of changes in crop factor on runoff (log scale). The higher the parameter value, the greater the effect on decreasing runoff.

Figure 4.10 (a-c) further illustrates the fine differences in the effect of the parameter values on runoff through boxplots. The horizontal black bar in each boxplot represents the median runoff amount averaging over all days with runoff. Runoff noticeably decreases as parameter value increases.

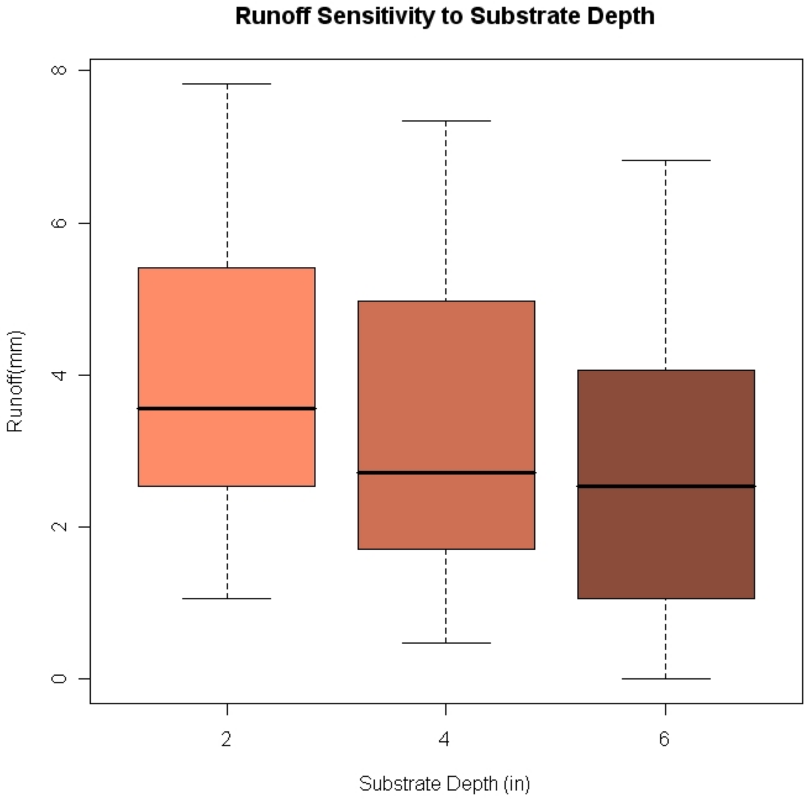

Figure 4.10a Boxplot – Runoff Sensitivity to Substrate Depth. Effects of substrate depth on runoff as shown in summary boxplots. The black bars represent the median runoff range. The boxes represent the first through third quantile (25 to 75 percent) of runoff ranges. The range bars show the full range of all runoff volume. Any outlying points would fall as dots outside of the bars.

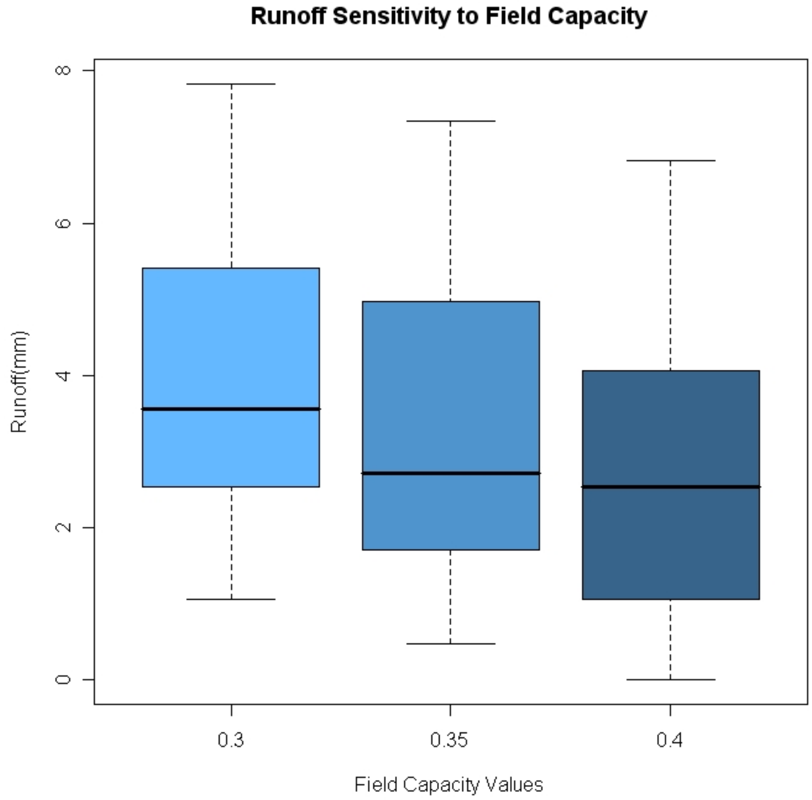

Figure 4.10b Boxplot – Runoff Sensitivity to Field Capacity. Effects of field capacity on runoff as shown in summary boxplots. The black bars represent the median runoff range. The boxes represent the first through third quantile (25 to 75 percent) of runoff ranges. The range bars show the full range of all runoff volume. Any outlying points would fall as dots outside of the bars.

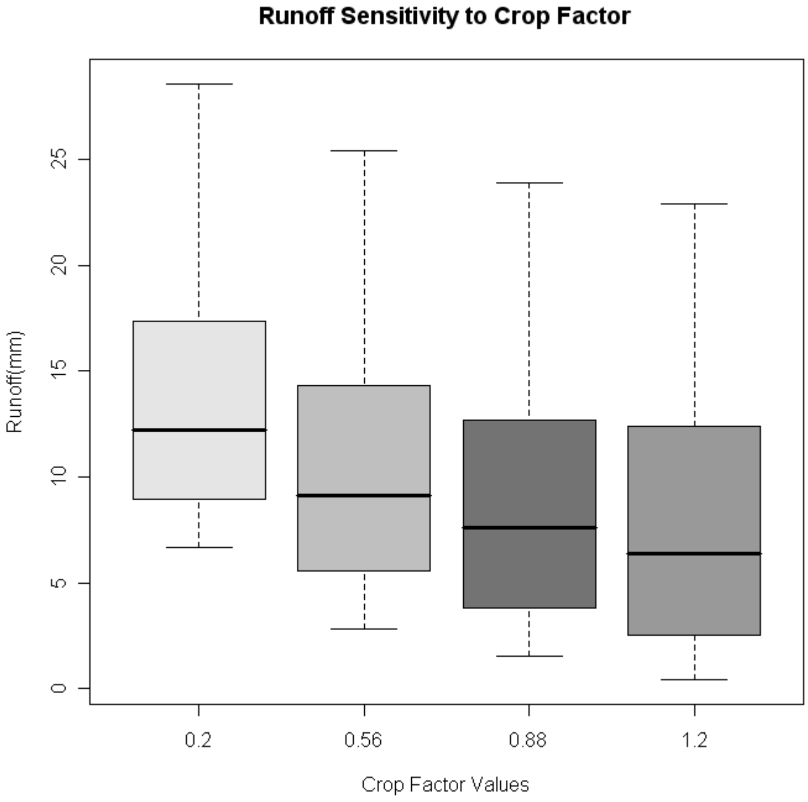

Figure 4.10c Boxplot – Runoff Sensitivity to Crop Factor. Effects of crop factor on runoff as shown in summary boxplots. The black bars represent the median runoff range. The boxes represent the first through third quantile (25 to 75 percent) of runoff ranges. The range bars show the full range of all runoff volume. Any outlying points would fall as dots outside of the bars.

We performed a three-way analysis of variance (ANOVA) to determine the significance of the effects of each parameter on discharge and the effects of parameter interactions on discharge. Results of the ANOVA are below in Table 4.3. 13 of the 15 parameter values were significant to $p \leq 0.001$ with two significant to $p < 0.01$. The former p-value means that the parameter has a measurable effect on roof discharge with a certainty of 99.9 percent. Only the interaction between crop factor and depth was substantial at one station (1071) with $p < 0.1$ and at a second station (436) with $p = 0.1$. Both of these stations are located outside of the highly urbanized impervious area of the watershed.

Table 4.3 Runoff Sensitivity to All Parameters - ANOVA. P-values for a three-way ANOVA of individual and interacting parameter values at all five stations

Station	Field Capacity (FC)	Crop Factor (CF)	Depth (D)	FC v CF	FC v D	CF v D	FC v CF v D
436	<0.001	<0.001	<0.001	0.78	0.69	0.10	0.79
1071	0.002	<0.001	<0.001	0.76	0.89	0.09	0.77
482	0.001	<0.001	<0.001	0.86	0.70	0.14	0.74
291	<0.001	<0.001	<0.001	0.92	0.73	0.32	0.65
716	<0.001	<0.001	<0.001	0.89	0.64	0.23	0.75

We also used regression analysis with individual and interacting parameters to determine the effect size of each parameter. In the first model, a simple equation with discharge equaling the sum of each individual parameter or the interacting parameters, none of the coefficients were significant, though in some cases the entire regression model was significant. However, R-squared values were 0.02 at best. In the second model, we divided discharge by precipitation to incorporate the correlation between discharge and precipitation on each day. The second model proved more informative with R-squared values of up to 0.11. None of the parameter coefficients, however, were significant. Results of both models suggest that the effects of the parameters, though significant, were not linear.

4.6 Discussion of Results

Uncertainty exists within our calculations. Sources of uncertainty include the methods to determine parameter values associated with specific roof substrate and vegetation types, the changing nature of a roof over time, and the robustness of our model. Further uncertainty arises from the model's design. The model automatically zeroes evapotranspiration for the entire 24-hour period during which any precipitation occurs, thus neutralizing the presence of plants and treating growing media as the only form of storage. This factor may underestimate the roof's storage capacity during short rain events, when the plants could still evapotranspire. The Smart Stormwater 2.0 Model was neither validated nor verified with actual roof data or data from another model. However, the modeled results we found were consistent with the experimental results described in section 4.1.

These findings indicate that a roof with the deepest substrate depth, highest field capacity and largest crop factor values will lead to significantly greater stormwater runoff reduction given the 53 years of climate data used. However, a roof consisting of the highest parameter values will be heavy and costly due to the increased depth and water holding capacity of the substrate as well as the increase in plant coverage. Increasing roof load could render a green roof project untenable without additional costly structural support.

Though the roof with the highest parameter values seems most effective, climatic variability also affects roof performance, thus in years with minimal rainfall, even the roof with the lowest parameters could retain the nearly all stormwater. The effect of Los Angeles' climate is clear in our results. Roofs can attenuate 64 percent of total stormwater one year, as was found when modeling roofs with the highest parameters, and then attenuate runoff 21 percent in the next year. Consistently high levels of attenuation are unrealistic even in roofs engineered with highest parameter values. After numerous storm events, roofs might lose growing media depth to runoff, field capacity might shift as the growing media erodes and weathers, and crop factor might change (decrease or increase) with plant die-off and growth. Our results also prove, though, that green roofs can be as effective in the Los Angeles climate as they are in more stable climates.

5 From Roof to Watershed - Extrapolation

5.1 Methods and Results

The next step in our analysis was to make a rough estimate of the potential roof area available in the Los Angeles River watershed for green roof application. Land-use data was recovered from the 2001 National Land Cover Data-set (US EPA, 2001). The data-set was compiled by consortium of federal agencies known as the Multi-Resolution Land Characteristics (MRLC) Consortium. The NLCD data contained impervious data layers for the Los Angeles River watershed. The impervious cover was defined by a classification and decision-tree method utilizing Landsat imagery and supplementary data. Utilizing Geographic Information Systems, we characterized the impervious areas within the Los Angeles River watershed and determined subsequent roof areas. With impervious land-use data, we identified three classes of imperviousness: 20-49 percent (low intensity – mostly single-family homes with some commercial development), 50-79 percent (medium intensity – some single family homes, large-scale residential developments, commercial development), and 80-100 percent (high intensity – large scale residential, commercial, industrial). We focused on large-scale residential, commercial, and industrial buildings because green roofs perform well on large, flat roofs and wide-scale green roof application may favor larger single-roof projects. Due to the significant investment required for the installation of a green roof and the typically high slopes of residential roofs, we did not include single-family homes in our analysis.

We placed the NLCD data within the boundaries of the Los Angeles River watershed to calculate the percent cover of each impervious class. The watershed consists of 12.21 percent low-intensity, 26.39 percent medium-intensity, and 9.61 percent high-intensity impervious surfaces; the remaining land area is less than 20 percent impervious surfaces. Based on the total area of 834 square miles in the watershed, we were able to find the area cover for each impervious class (101.85 square miles, 220.12 square miles, and 80.18 square miles, respectively). Downtown Los Angeles had the greatest amount of high-intensity development, along with other areas scattered throughout the rest of the watershed, such as the City of Commerce and the Vernon neighborhood. Long Beach, the San Fernando Valley, and Burbank reflected medium intensities of impervious surfaces.

To determine an average proportional coverage of rooftop in each impervious category, we used Google Earth satellite imagery to isolate several representative one-square-mile samples (See Figure 5.2). The images offered clear aerial representations of roof areas in the watershed. We collected three one square mile images for each impervious class. We then visually estimated the area covered by large, flat roofs for each of the three images for each class. The averages of these calculations were then used to characterize the roof area in the three impervious classes.

Multiplying the estimated average roof cover for each impervious class by its corresponding area within the watershed, we found the total building roof area that could hold a green roof to be 234 million square feet for low-intensity imperviousness, 1,229 million square feet for medium-intensity imperviousness, and 811 million square feet for high-intensity imperviousness. Cumulatively, we found a total of 2,274 million square feet of potential green roof area in the watershed. This calculation does not account for individual building integrity. For many of the roofs sampled in the visual estimation, such as warehouses, the cost of retrofitting the roof to hold the additional weight of a green roof may be prohibitive. As highlighted earlier, Chicago leads all U.S. cities with 2.5 million square feet of green roofs, which we believe is a desirable and achievable goal for Los Angeles. This area represents 0.11 percent of the total potential roof area in the Los Angeles River watershed.

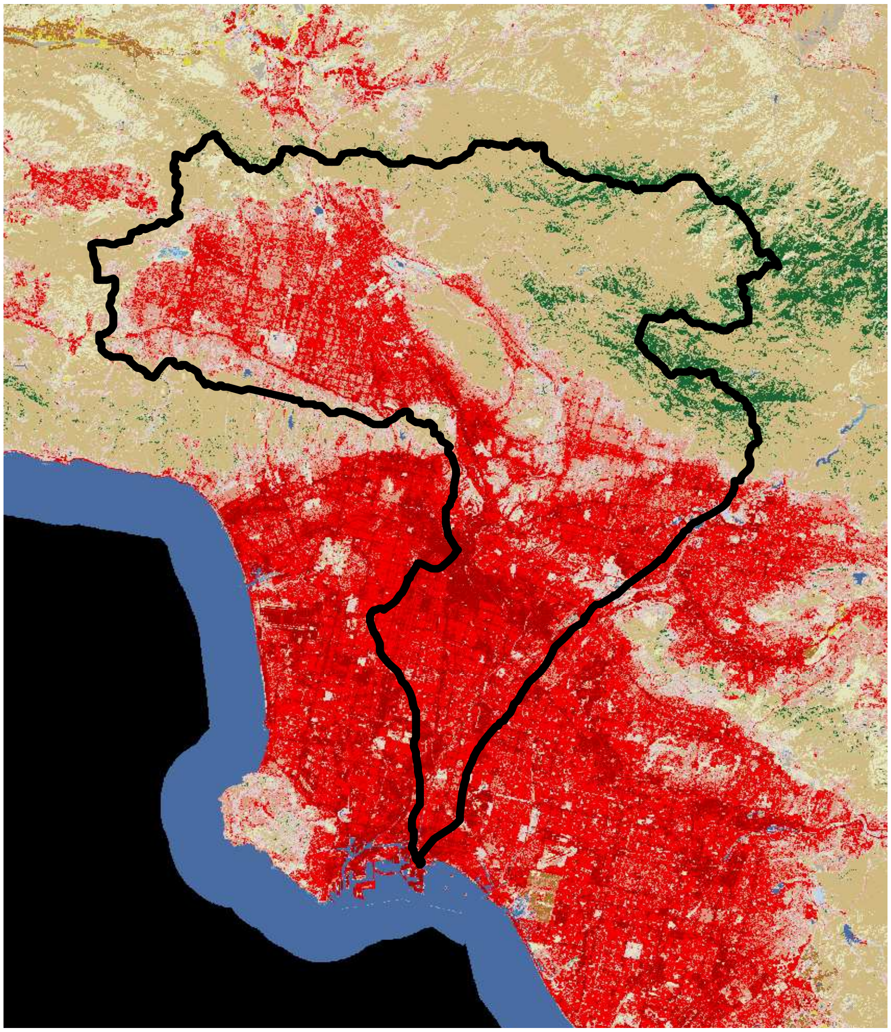

Figure 5.1 Impervious Surface Area Map. Los Angeles River watershed impervious surface image. The watershed is outlined in black. The lightest red represents 20-49%, medium red 50-79%, and darkest red 80-100% impervious surface.

5.2 Discussion

Uncertainty arises from two steps in our analysis. First, the impervious surface data layer from the NLCD uses a one-acre scale. While this is a relatively fine scale for a watershed, the nature of urban development in the Los Angeles River watershed (with drastic and abrupt changes from residential, commercial, and urban zoning areas) introduces uncertainty in the accuracy of each pixel that is labeled as “low,” “medium,” or “high” intensity development. Second, a large amount of uncertainty comes from the visual estimation of satellite imagery of selected one square mile sections of the watershed. The group reviewed one square mile images to estimate the amount of potential green roof area in the watershed. Each image was examined to dissociate the flat roof from urban features that are not considered by the study, such as single-family houses, roads, sidewalks, parking lots, and open space. This visual assessment also does not take into account the structural integrity of the building, since it will need to bear an additional weight load if a green roof is installed. Since our extrapolation is for theoretical work, we believe it is more important for Los Angeles to have a general idea of how much rooftop area has the potential to be greened. It will then be the responsibility of planners, architects, and building owners to determine the weight-bearing capacity of their roofs and if any retrofitting will be necessary.

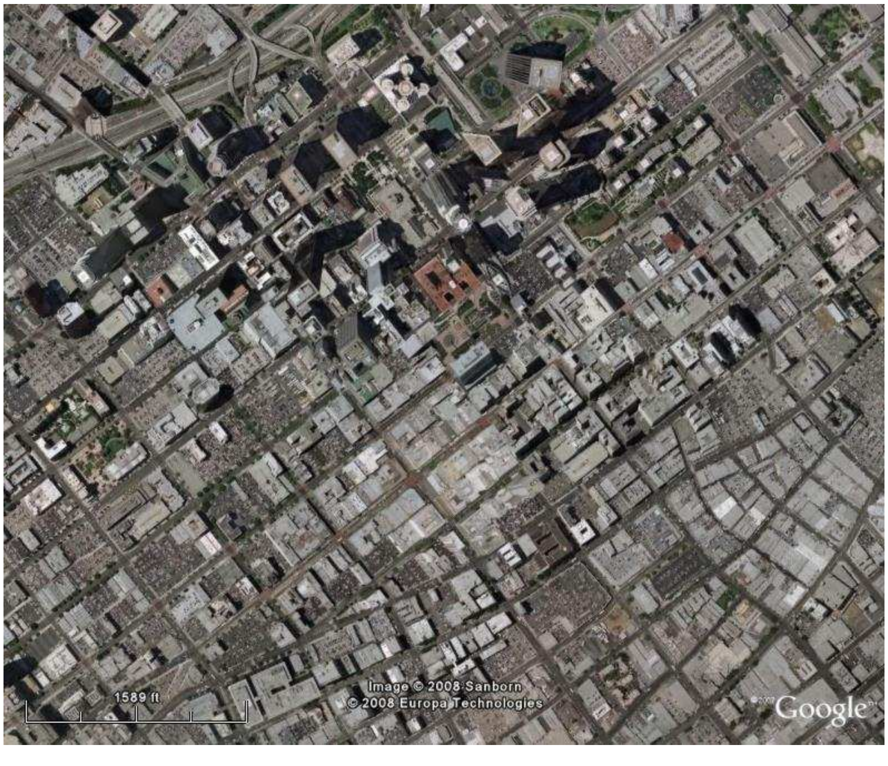

Figure 5.2 Rooftops in Downtown Los Angeles. The aerial image of downtown Los Angeles utilized to determine the proportional roof-top area for the high intensity impervious class (80-100%). The roof area is approximately 34%.

6 Cost-Benefit Analysis

Green roofs provide a range of direct and indirect economic benefits to both the private owners of the buildings on which the roofs are constructed and to the public. Determining the total economic value of green roofs is challenging, however, because the costs of construction and maintenance fall on the private owners of the building, whereas many of the benefits are primarily experienced by the public. These wide-ranging benefits can help make green roof implementation attractive on a social level, but some benefits only manifest when quantified across a large-scale green roof installation program.

Both public and private benefits count toward the overall value of the green roof, yet researchers must be careful that they do not count benefits more than once. Moreover, some green roof benefits, such as improved aesthetics, are not always easily translated into a dollar value. Green roofs are also not homogeneous in their application, the costs they incur or in the benefits they provide. Intensive roofs designed for aesthetic purposes will have a much different cost profile than an extensive roof designed for more functional purposes, such as reducing stormwater or urban heat island. Moreover, green roof systems in New York City will function differently from those in Los Angeles, simply based on the difference in precipitation patterns and climate between the two cities. In fact, stormwater mitigation and other benefits can be heterogeneous in various areas of the same city (Acks, 2006).

Cost-benefit analysis is a useful tool for analyzing the economic effects of a green roof implementation program in Los Angeles. This analytical approach is beneficial because it highlights some of the most desirable and undesirable economic outcomes of a project (Arrow et al., 1996). Cost-benefit analysis will also allow decision-makers to better comprehend the effects of green roof installation on both micro and macro scales.

Considering the multiple benefits provided by vegetated roofs, incorporating them into Los Angeles urban infrastructure could be economically advantageous. There is, however, little to no research quantifying the benefits of green roofs in Los Angeles or other semi-arid urban areas. Other prominent green roof cities, such as Chicago and New York City, are located in more humid climates with more regular precipitation intervals and may more easily support green roofs. Few studies have analyzed the cost and benefits associated with widespread implementation, though research shows green roofs are cost-effective only when all measurable benefits are incorporated (Acks, 2006). Without tangible measurements of benefits, policymakers are ill-equipped to make informed decisions about green roofs. Thus, we attempted to estimate potential costs and benefits to help policymakers understand the gains and risks associated with wide-scale green roof implementation throughout Los Angeles.

To conduct our analysis, we first made a number of assumptions. The costs and benefits have been calculated over a 40-year timeframe, which represents the average expected life of a green roof, according to literature and green roof professionals (Acks, 2006; Holleran, 2007). All values were multiplied across 2.5 million square feet of green roof application. We selected this area size because it is equal to the current area of green roof in Chicago, the nation's current leader in vegetated roofs. This is a desirable goal because it is realistic for Los Angeles and would place the city on the leading edge of green roof infrastructure. We originally intended to estimate costs based on some proportion of the total available green roof area in the watershed based on our spatial analysis, but we later determined even extremely small proportions were prohibitively large in terms of costs. Future values were calculated with a discount rate of 3 percent, based on current market rates. All values are in 2006 dollars.

6.1 Costs

6.1.1 Cost Per Square Foot Metric

The first step in the cost analysis was to determine a Los Angeles-specific cost per square foot metric. The goal was to establish reliable average cost estimates which we could extrapolate over a substantial area of green roof coverage. Los Angeles-specific values were used whenever possible and came from a number of sources, including Henry Co., a roof coating manufacturer based in southern California (Holleran, 2007). When specific costs were not available for Los Angeles, we used values from the green roof literature. Costs were separated into two categories: initial costs and cumulative costs, which were estimated over 40 years. Table 6.1 below shows a range of the average initial costs per square foot of green roof.

Table 6.1 Green Roof Component Costs.
Initial costs of components for green roofs in Los Angeles per square foot.

Green Roof Component	Low ($)	Med ($)	High ($)	Source
Design	3.00	3.50	4.00	Moore, 2007
Insulation and Deck Protection	6.00	8.00	10.00	Holleran, 2007
Drainage and Filter	3.00	3.50	4.00	Holleran, 2007
Growing Media	3.00	5.50	8.00	Appel, 2006; LBC, 2007
Sedums (2 per sq. ft)	1.60	1.60	1.60	Hayden, 2008
Grasses (2 per sq. ft)	1.60	2.02	2.80	Hayden, 2008
Drip Irrigation System	2.00	3.00	4.00	Peck and Kuhn, 2001
Architecture and Engineering	1.01	1.36	1.72	Peck and Kuhn, 2001
Total Initial Costs	**21**	**28**	**36**	

Embedded in this table are a number of assumptions. First, we assume that roofs in Los Angeles will use a mix of 50 percent sedum species and 50 percent grass species. One square foot can support up to two grasses and two sedums (Hayden, 2008). Second, we assume that green roofs in Los Angeles will need some kind of irrigation system. The original intent of our analysis was to determine a composition of plants and growing media that would not need irrigation in Los Angeles. After significant review and discussion, we determined irrigation is necessary because the plants need regular water inputs to firmly establish themselves on the roof (Hayden, 2008) and Los Angeles is too dry to not have some kind of support for plant life. The need for irrigation is partially why Los Angeles does not have more green roofs (Holleran, 2007). Third, we assume that architecture and engineering costs are 5 percent of the project installation costs (Peck and Kuhn, 2001), but this value may not entirely incorporate the additional costs associated with retrofitting an existing building to hold a green roof. The cost per square foot of green roofs in Los Angeles ranges from a low of $21 to a high of $36. This falls within cost ranges for other cities and is actually less than ranges estimated by a green roof report for the Los Angeles City Council, which predicted $30 to $40 per square foot for a new building and $35 to $45 per square foot to install a green roof on an existing building (Moore, 2007).

With these estimates for initial costs of installation, we were then able to estimate the costs over the entire life of a green roof. The two major cost categories are irrigation costs and maintenance costs. We estimated costs over 40 years, the expected life of a green roof. Table 6.2 below shows the results.

Table 6.2 Annual and total costs for green roofs in Los Angeles per square foot.
Cost information from Holleran, 2007; Peck and Kuhn, 2001; Moore, 2007; LA EAD, 2006.

Annual Costs	Low ($)	Med ($)	High ($)
Irrigation (per yr)	0.50	1.00	2.00
Maintenance (per yr)	0.02	0.25	0.50
Cost (per yr)	0.52	1.25	2.50
40 Year Irrigation Total	11.56	23.11	46.23
40 Year Maintenance Total	0.46	5.78	11.56
Total Costs	**$33**	**$57**	**$94**

Irrigation and maintenance costs are assumed to be constant over the 40-year timeframe, though actual irrigation costs are likely to fluctuate based on yearly changes in precipitation and temperature. Additionally, we were only able to locate a single estimate of $1 in yearly irrigation costs (Moore, 2007). To capture more of the variability in the cost range, we varied this figure from $0.50 to $2.00. Maintenance costs were also difficult to identify; some groups argue that maintenance is unnecessary after the first two years (Peck and Kuhn, 2001). With the irrigation systems, we assumed yearly maintenance would be needed to preserve the maximum functionality of the roof. Overall, the total 40-year cost of a green roof ranges from $33 to $94 per square foot.

Green roofs are significantly more expensive per square foot than traditional roofs, as expected. Table 6.3 highlights some of the costs for a typical bitumen or other type of roof. Some of the assumptions implicit in our previous analyses carried over here.

Architecture and engineering are assumed to be 5 percent of installation costs. Maintenance costs are assumed to be the same as a green roof because while a traditional roof is not as complex as a green roof, the infrastructure receives more exposure to elements than the green roof.

Table 6.3 Initial, annual, and total costs for traditional roofs in Los Angeles per square foot.
Cost information from Holleran, 2007; Peck and Kuhn, 2001

Traditional Roof Costs	Low ($)	Med ($)	High ($)
Installation	6.00	9.00	12.00
Architecture and Engineering	0.30	0.45	0.60
Initial Costs	6.30	9.45	12.60
Maintenance (per yr)	0.02	0.25	0.50
Total Costs (20 yrs)	$7	$13	$20
Total Costs (40 yrs)	$14	$26	$40

Cost estimates were made for a 20-year timeframe, which is the average life of a traditional roof. Those results were doubled to be comparable with the lifespan of a green roof. The increase in costs from traditional roofs to green roofs ranges from a low of $19 to a high of $54.

6.1.2 Wide-scale Application Costs

After establishing the total cost per square foot of an average green roof, we were then able to extrapolate those values across 2.5 million square feet. As previously stated, Chicago is the current green roof leader in the U.S. with a total area of 2.5 million square feet. Our analysis assumed if Los Angeles implemented a green roof program, the city would want to supplant Chicago as the country's leader. We believe 2.5 million square feet is a reasonable and achievable goal. Table 6.4 below shows the initial and total 40-year costs associated with our hypothetical scenario. The total price tag ranges from $83 million to $235 million. These significant price figures suggest that some kind of public support will be necessary to establish this scenario, regardless of calculable benefits.

Table 6.4 Total costs for 2.5 million square foot application of green roofs in Los Angeles.

2.5 Million Sq. ft Application	Low (Millions)	Med (Millions)	High (Millions)
Initial Costs	$53	$71	$90
Total Costs (40 yrs)	$83	$143	$235

6.2 Benefits

6.2.1 Approach to Benefit Calculation

As this report has highlighted, there are multiple benefits associated with vegetated rooftops. We initially hoped to analyze the benefits gained by stormwater reduction, individual building energy savings, and urban heat island reduction in our cost-benefit analysis. After thorough literature review, however, we determined that energy savings and urban heat island reductions fall outside the scope of our project. Moreover, without an energy model, reasonable and robust calculations would be extremely difficult to obtain. As such, we focused our cost-benefit analysis solely on the benefits of green roofs from stormwater runoff reduction. Our decision was not arrived at lightly, and we knew that by not considering other benefit categories, it would be nearly impossible to generate positive cost-benefits ratios. Regardless, we determined there would be value in comparing the proportional benefits of stormwater reduction to help identify the most economically beneficial aspects of green roofs.

Our initial approach was to emulate the stormwater reduction cost-benefit analysis performed in New York City (Acks, 2006). The study assumed that capturing rainfall on green roofs would reduce the volume of stormwater entering New York City's combined sewer overflow system. The benefits would be calculated as the avoided capital expenditure and operating costs of treating those avoided stormwater volumes. While this is a sound approach, it is not feasible in Los Angeles because stormwater does not receive any treatment in the stormwater system. Precipitation that lands on a traditional roof will runoff, drop to and flow across the city's streets, accumulating pollutants, until it reaches a diversion. Stormwater in the city flushes directly into channelized rivers and streams like the Los Angeles River, where it will flow through the impervious channel to the river's outlet, eventually streaming into the ocean or washing up on nearby beaches. With no treatment in the system, our analysis instead focused on the costs of untreated stormwater flowing directly into the San Pedro Bay.

The beaches of southern California are famous across the world and are responsible for significant economic inputs to the larger economy of the state. Studies estimate that 79 percent of ocean-based jobs are directly related to tourism (Dwight et al., 2007). Pollution from urban runoff has deleterious effects of the beaches of southern California and can result in major economic losses. The health effects of urban runoff on beach users are not especially well researched, but untreated urban runoff has been identified as the most significant source of water pollution in coastal waters of Los Angeles (Dwight et al., 2002; Dwight et al., 2005) For the benefit analysis, we assumed that a reduction in stormwater runoff volume would result in an increase in beach water quality. We then calculated the volume of stormwater reduction from 2.5 million square feet of green roof in the watershed. To do this, we calculated the proportion of total potential green roof area that our hypothetical program would cover, which is roughly 0.11 percent of available roof coverage area in Los Angeles. We combined that information with our predicted stormwater reduction range of 21 to 64 percent to determine that a green roof program could affect between 0.02 and 0.07 percent of water quality in the Los Angeles River and at Long Beach. Our research focused specifically on Long Beach, the closest beach to the mouth of the Los Angeles River, because it would be the most negatively affected from water pollution coming from the river. Establishing water quality effects on beaches farther away from the river's outlet would be tenuous at best, so they were not included in our calculations.

Our project employed two beach-related values to determine what benefits can be gained from stormwater reduction. The first value addressed health benefits of avoided runoff and the second dealt with the economic use value of beaches. Each method is described in detail below.

6.2.2 Health Value

To determine the economic value associated with the reduction of stormwater in the Los Angeles River, we used a cost-of-illness calculation to determine the value lost from illnesses caused by urban stormwater pollution on Long Beach. Our analysis assumes the benefit of green roofs is equal to the proportional avoided cost-of-illness from stormwater reduction achieved by 2.5 million square feet of green roof in the watershed. This analysis also assumes there is a linear relationship between stormwater flow reduction and water quality and illness infection rates (i.e. a one percent reduction in stormwater results in a one percent increase in water quality and one percent reduction in cost-of-illness).

We calculated negative health effects using a cost-of-illness study conducted on Huntington Beach in Orange County, CA, which was based on an epidemiology study of recreational coastal water users (Dwight et al., 2005; Fleisher et al., 1998) and a model that estimated the number of water-related illnesses for Huntington and Newport Beaches (Turbow et al., 2003). Fleisher et al. (1998) measured the proportion of total beach visitors infected with a gastrointestinal (GI), respiratory, eye or ear infection and the number of days [1 2 3] of lost normal economic activity resulting from the infection. Due to the relatively close proximity of Huntington Beach to Long Beach, we assumed illness infection rates would remain essentially the same.

For our study, one day of normal economic activity is equal to one day's worth of earned wages based on an average annual wage of $48,524 in Los Angeles County (U.S. Department of Commerce, 2006) and 250 annual workdays. Average daily wages for Los Angeles County are $132.94. The studies also estimated the proportion of infections that required professional medical attention. Nichol (2001) estimated the average value of a medical visit at $102.00 in 1998; our study adjusted this value, based on inflation, to $124.62. All values are in 2006 dollars. While our study maintained the illness rates from the other studies, we had to adjust for differences in visitation between Huntington and Long Beach. According to Turbow et al. (2003), 36,778 GI infections occur at Huntington Beach annually. Long Beach receives roughly 800,000 less visits per year (Dwight et al., 2007), which means its GI case total would be 31,568 cases every year.

The total cost-per-illness value incorporated lost income per illness event and medical costs. For Long Beach, the total health costs associated with water pollution from urban runoff is approximately $3.43 million. Additionally, we multiplied this value over the 40-year life expectancy of a green roof for a total health cost at Long Beach of $79.41 million. Assuming there is a linear relationship between stormwater reduction from green roofs and water quality and, by proxy, health costs, we predict a range from $18,000 to $56,000 in avoided health costs will result from our hypothetical green roof program.

6.2.3 Use Value

The second metric we used to identify the benefits of reduced stormwater from green roofs was an economic use value derived from day visits to Long Beach. Our analysis assumed beach day-use value would increase with higher coastal water quality. To determine this use value, we utilized values from an economic study conducted for the National Oceanic and Atmospheric Administration (NOAA) with the Southern California Beach Valuation Model (Leeworthy and Wiley, 2007). The study investigated the potential change in economic use in a scenario where the water quality of Long Beach improved to levels measured at Huntington City Beach, according to the water-quality standards developed by the non-profit organization Heal the Bay (HTB). These water-quality metrics are used to assign grades to California's beaches for Heal the Bay's beach report card; grades are assigned by measuring total and fecal coliform indicator bacteria present in coastal waters and translating their findings into a number on a traditional 4.0 grading system (Leeworthy and Wiley, 2007). The NOAA study compared Long Beach's 2000 baseline score of 2.8545 to Huntington City Beach's baseline score of 3.915, a score change that is analogous to an annual average grade change from a C to B on the HTB beach report card. The model runs show that water quality changes could result in a total yearly economic use value increase of $928,000 due to increases in day visits and the spending and job growth associated with those increased visits. Over 40 years, the increased beach value is worth $21.36 million.

Much like with the health value, we argue that green roof implementation would not be responsible for the entire increase in water quality at Long Beach, but could provide a proportional increase in water quality based on the volume of stormwater trapped on green roofs. Assuming a linear relationship between stormwater volume reductions and improvements in water quality, green roofs could provide approximately $5,000 and $15,000 worth of increased beach use value at Long Beach.

The differences between the costs of green roof implementation and the benefits related to stormwater reduction are so significant that it was not useful for our analysis to include a traditional cost-benefit ratio. The total potential benefits based on our calculations ranges from $23,000 to $71,000. Even though we knew that green roofs typically yield positive cost-benefit ratios only when the full portfolio of benefits is considered, we chose to focus solely on stormwater benefits because they are one of the most significant benefits of green roofs (Carter and Keeler, 2007). A cost-benefit analysis performed in New York City showed the stormwater benefits were responsible for between 11 and 50 percent of the total direct public benefits from green roofs (Acks, 2006). Similar results did not manifest in Los Angeles. Our analysis shows that the calculable benefits of green roofs related to stormwater would offset less than one percent of the costs of installation and maintenance.

Infrastructure is the major reason why stormwater in Los Angeles has such a low associated economic value. New York City and other cities like Portland employ combined sewer overflow systems where all water from storm drains and the sewer must be treated before it is released into the environment. Thus, stormwater benefits in these cities are the avoided costs of water treatment. Los Angeles' lack of stormwater treatment deprives the city of a reliable metric to measure potential stormwater benefits and partially explains the huge discrepancy between stormwater costs in Los Angeles and in other major green roof cities. Furthermore, green roof applications in other cities did not only consider stormwater reduction potential, but also recognized the entire portfolio of benefits presented by green roofs.

6.2.4 Additional Benefits – Future Research

When only stormwater benefits are considered, the costs of a widespread green roof program in Los Angeles far exceed the potential benefits (less than one percent of costs) and a green roof program would be a difficult sell based solely on the economics of stormwater reduction. Were green roofs capable of only reducing stormwater runoff, the associated economics would prevent most projects from moving forward. As this report has previously highlighted, though, green roofs provide a number of benefits that might increase cost-benefit ratios. Professionals and policymakers interested in further investigating green roof benefits should focus on private energy savings, urban heat island reduction, air quality improvements, enhanced aesthetics, and additional wildlife habitat. Studies show major savings can result from reducing the urban heat island of Los Angeles, including a 12 percent reduction in ozone exceedance, which is larger than estimated reductions from increasing the number of hybrid automobiles (Rosenfeld et al., 1998). Green roofs are also excellent insulators that can reduce the inside temperature of a building on hot summer days. Additionally, the reflectivity and latent heat exchange provided by the vegetation can help reduce the urban heat island surrounding the roof, which can help reduce energy costs in other buildings.

Energy-related savings show the most potential for green roof benefits, but other green roof functions may yield significant benefits. Future studies should focus on these additional benefits in order to truly showcase the entirety of the economics of green roofs. Economic analysis may not be the best tool to achieve a realistic overall picture of green roofs. Things like aesthetics, new wildlife habitat, and improved well-being of people in a building with a green roof can be extremely difficult to capture with a simple dollar value. Social implications of wide-spread green roof installation should also be considered in future research efforts.

7 Policy

There are still many questions regarding the economics of green roofs in Los Angeles. The potential stormwater benefits are tiny in comparison to the costs of a major green roof initiative, but there are many other reasons why green roofs would be desirable in Los Angeles. Since taking office, Mayor Antonio Villaraigosa has advanced the idea that Los Angeles can become the cleanest and greenest big city in the country. Green roofs can play a significant role in achieving the mayor's goals, and can generate green open space without having to take up valuable land area throughout the city. For green roofs to flourish, public funds are a necessary component, as few private building owners are willing to bear the cost burden of installation without some kind of governmental support. Our project thus identifies below some important policy tools and programs that may be useful for individuals or organizations interested in seeing green roofs sprout up through Los Angeles.

7.1 LEED Standards

In 2002, the City of Los Angeles required that all new city building projects constructed by the Department of Public Works larger than 7,500 square feet achieve "Leadership in Environmental and Energy Design" (LEED) certification and allocated $10 million annually to help offset the cost of some of the more stringent energy requirements. These requirements continue to be bolstered by the council. On February 15, 2008, two City Council committees voted to require all private developments over 50,000 square feet to meet LEED standards; the full council could adopt the standards before the end of March 2008.

Green roofs can help buildings meet a number of specific LEED standards. First, they address a number of stormwater credits in the LEED rating system. Sustainable Sites Credit 6.1 addresses quantity of runoff; stormwater runoff from the building site must be reduced by 25 percent. Sustainable Site Credit 6.2 addresses runoff quality; a project must develop a stormwater management plan that captures and filters 90 percent of all stormwater. Green roofs increase the area of pervious surfaces on-site and are specifically mentioned as an effective way to meet these two requirements.

Green roofs are identified as a solution to the urban heat island standard as well. Sustainable Sites Credit 7.2 specifically requires buildings to reduce the urban heat island generated by their roofs. This credit can be achieved by installing green roofs on 50 percent of the entire roof area. Green roofs can also help attain Sustainable Site Credit 7.1, which requires urban heat island reduction from non-roof surfaces. While these strategies also indirectly address energy usage, green roofs can help achieve points toward Energy and Atmosphere Credit 1, which focuses on optimizing energy performance.

Additionally, LEED standards consider the aesthetic and natural concerns related to buildings. As such, they have Sustainable Site Credits 5.1 and 5.2, which address wildlife habitat and open space. Green roofs can help a project achieve both of these credits by emphasizing native plants on the roof and can provide open space in highly developed areas where no other options are available. Overall, depending on how green roofs are integrated with other building systems and their design, green roofs can help a building meet up to fifteen LEED certification credits (GRHC, 2006; USGBC, 2005).

7.2 Proposition O

The city of Los Angeles has struggled for years to handle stormwater properly. In 2004, the citizens of Los Angeles took action to try and protect coastal waters and beaches from stormwater runoff by voting to approve Proposition O. The measure, passed in the November 2004 election, authorized the city of Los Angeles to issue a number of general obligation bonds to meet regulations laid out in the Federal Clean Water Act through cleaning up waters affected by polluted stormwater runoff throughout the city. The bonds will be paid for through increased property taxes (LA Stormwater, 2008; Woolson, 2005).

According to Proposition O, up to $500 million may be spent on four funding categories: to protect rivers, bays, lakes, and beaches; improve open space and flood protection; capture, clean, and reuse stormwater; and conserve water and provide drinking water source protection. Each category receives different funding levels, but $75 million has been set aside to capture, clean, and reuse stormwater (LA Stormwater, 2008). Green roofs are designed to directly address many of these concerns and are perfectly suited to receive support from Proposition O, yet no green roof projects have applied for funding. Proposition O is a powerful and useful tool for any potential green roof program in Los Angeles.

7.3 Los Angeles River Revitalization Master Plan

Any successful major green roof implementation program will require long-term visioning and should work in concert with other efforts to solve Los Angeles' stormwater runoff problems. Green roof infrastructure combined with other management efforts could have a significant positive impact on the water quality of the Los Angeles River. One unique project that takes a holistic approach to cleaning up and restoring parts of the watershed and the river itself is the Los Angeles River Revitalization Master Plan. Approved by the city council in April 2007, the plan aims to reclaim major parts of the Los Angeles River from its origin in Canoga Park to directly south of downtown Los Angeles.

The plan consists of four major organization principles: revitalize the river, green the neighborhoods, capture community opportunities, and create value. Green roofs can play major roles in both revitalizing the river and greening the surrounding neighborhoods. Specific recommendations in the plan present some excellent opportunities for green roof implementation. Recommendation #4.3 emphasizes the importance of landscape-based treatment strategies that can provide aesthetic value and potential habitat along with stormwater treatment and 'green infrastructure' improvements. Similarly, Recommendation #4.4 stresses the need for treating stormwater on multiple scales, including on-site drainage treatment, which green roofs could provide (LA DPW, 2007).

Greening the neighborhoods surrounding the river is a necessary aspect of the Revitalization Master Plan, but it could prove challenging, as many neighborhoods are almost completely built out to capacity. Green roofs may provide alternative opportunities to achieve the plan's goals. For instance, Recommendation #5.9 asks that BMPs be incorporated in streetscapes and public landscapes to increase pervious surfaces and reduce pollutant loading. A widespread green roof project could be a major component of neighborhood greening efforts related to the Revitalization Master Plan to vastly improve the environmental condition of the Los Angeles River watershed.

7.4 Additional Considerations

Currently, Los Angeles does not address green roofs directly in any of its zoning laws and ordinances. If city officials are interested in encouraging green roof proliferation, they should consider establishing specific zoning laws for green roofs, so potential projects have official guidance and support when they are designed. Additionally, zoning laws can provide bonuses for green roof projects. The city of Portland has a green roof zoning bonus that allows buildings to expand the overall size of the building without penalty based on the proportion of roof covered with vegetation (Liptan, 2003). A similar code in Los Angeles could be the catalyst need to see green roofs grow throughout the city.

The structure of future green roof policies will be a critical component of spurred their wide-spread implementation, but strong policies cannot do the job alone. With its diverse urban landscapes and massive scale, Los Angeles may struggle to increase its coverage of green roofs if it relies solely on useful policy tools. The city will likely need a green roof champion who can advocate the use of green roofs to a wide audience and nurture their growth. This champion can either be an elected politician or a committed public employee. Chicago and Portland once again provide useful examples for Los Angeles. In Chicago, green roofs first took off because Mayor Richard Daley demanded a green roof be installed on City Hall after seeing their effectiveness firsthand on a trip to Germany. His leadership continues to stimulate green roof growth throughout the city. Portland found its own champion in Tom Liptan, who works for the city's Bureau of Environmental Services. His work spreading the gospel of "ecoroofs" has helped them flourish throughout Portland and made significant contributions to increasing understanding of how green roofs operate in urban settings. Such an individual could fertilize the seed of a successful green roof program in Los Angeles.

8 Conclusion

As government efforts to "green" cities within the United States increase, green roofs will receive more attention from policy-makers, politicians, and private citizens. Los Angeles, situated in the country's leading state for green initiatives such as AB 32 (The California Global Warming Solutions Act of 2006), the Hydrogen Highway, and Zero Universal Waste, is politically ripe for green roof growth. Our environmental analysis defined the potential for the positive effects of green roofs on stormwater reduction in Los Angeles. Our economic analysis proved that policy initiatives are a tool to make green roofs more financially feasible in semi-arid environments. Although savings from stormwater alone do not translate to a compelling economic argument for green roofs, political leaders can add to the equation by bringing attention to the numerous other benefits green roofs offer overpopulated, overheating cities. Below is a list of the major conclusions we reached and some of their implications:

- <u>Green roofs can grow and function in Los Angeles</u>
    - **Environmental benefits**: Green roofs reduce, on average, 21 to 64 percent of stormwater runoff. Green roofs decrease and delay peak runoff, reducing the amount of precipitation reaching storm drains and washing away surface pollutants for delivery to adjacent public waterways.
    - **Roof composition matters**: Each iterative change in increased substrate depth, field capacity and vegetation coverage affects roof performance. By enhancing the components of roof composition, more stormwater can be retained. However, this additional retention is accompanied by increased costs and roof loads.
    - **Location, location, location**: Frequency and intensity of precipitation varies spatially. Maximum precipitation at one rain gauge station we modeled was over 9 inches, whereas at a different modeled station, maximum precipitation was over 4 inches. Intense and frequent precipitation can render a green roof ineffective in mitigating stormwater, as all precipitation turns to runoff. However, green roof application in areas with less frequent, but intense precipitation can be highly effective.
- <u>Costs of green roof application exceed benefits of stormwater runoff attenuation</u>
    - **Costs of green roofs**: Installation costs of green roofs range from $21 to $36 per square foot, which are close to other estimates for Los Angeles. Over the lifetime of the roof, totals range from $33 to $94 per square foot, dependent on irrigation and maintenance costs. The total costs of 2.5 million square feet of new green roof over 40 years ranges from $83 million to $235 million.

- **Economic benefits**: In the Los Angeles River watershed, economic benefits related to stormwater reduction manifest as higher water quality on the beaches near the river's outlet. These benefits include avoided health costs from decreased waterborne infections and increased day usage of a cleaner beach. Total benefits range from $23,000 to $71,000.

- **Consider the full portfolio of benefits**: Stormwater reduction alone will not make green roofs economically feasible. There are a number of quantifiable and non-quantifiable values, like energy savings and improved aesthetics, that make green roofs attractive and they all must be considered to generate a realistic picture of the overall benefits of green roofs.

- **Policy is the key**: Green roofs deliver many benefits to the public, but private owners must exclusively absorb the costs. Governmental support in the form of public funding and advantageous policies will give building owners the incentives they need to green their rooftops. Los Angeles has current and future policy tools that can give green roofs the boost they need to sprout up throughout the watershed.

Additional research is necessary before widespread application of green roofs occurs in semi-arid or arid areas. Experimental studies of different roof compositions and their functions in the entire Southern California region are needed. Though our findings are consistent with experimental roof results in other areas, validation and verification of the Smart Stormwater 2.0 Model would lend greater credibility to our findings. More peer-reviewed publications about green roofs and their effects will lead to a richer array of information on which to base conclusions. Due to the dearth of peer-reviewed articles about green roofs generally and their effects in different climates, background information and data for portions of our analysis was scarce or available only through green roof suppliers. As green roofs grow in popularity, research will necessarily increase. The emphasis on rigorous science to determine green roof effects will benefit the industry and the areas where green roofs are applied. This work serves as a strong baseline for future studies.

9 References

Acks, K.A., 2006. Framework for Cost-Benefit Analysis of Green Roofs: Initial Estimates IN *Green Roofs in the New York Metropolitan Region: Research Report*. Rosenzweig, C et al. (Eds.). New York: Columbia University Center for Climate Systems Research and NASA Goddard Institute for Space Studies.

Akbari, H., Pomerantz, M., and Taha, H., 2001. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy* **70**(3): 295-310.

Allen, R.G. et al., 1998. Crop Evapotranspiration – Guidelines for computing crop water requirements. Food and Agricultural Organization of the United Nations. Irrigation and Drainage Paper, 56. Chapter 1.

American Lung Association (ALA), 2007. The State of the Air. Retrieved from: http://lungaction.org/reports/stateoftheair2007.html.

Appel, J., 2006. Perlite on Green Roofs. Retrieved from: http://www.greenroofs.com/archives/gf_may06.htm.

Arrow, K.J. et al., 1996. Is there a role for benefit-cost analysis in environmental, health, and safety regulation? *Science* **272**: 221-222.

Associated Press (AP), 2006. Landscape Architects Tend to a Green Roof. Retrieved from: http://www.msnbc.msn.com/id/12512892/.

Beattie, D. and Berghage, R., 2004. Green Roof Media Characteristics: The Basics. In *Proc. Greening Rooftops for Sustainable Communities: Portland 2004*: June 2-4, 2004; Portland, Oregon.

Bengtsson et al., 2005. Hydrological function of a thin extensive green roof in southern Sweden. *Nord. Hydrol.* **36**: 259–268.

Berghage, R. et al., 2007. Quantifying Evaporation and Transpirational Water Losses from Green Roofs and Green Roof Media Capacity for Neutralizing Acid Rain. National Decentralized Water Resources Capacity Development Project. From personal communication.

Berghage, Robert. Personal communication, October – November, 2007.

Bliss, J. D., 2007.Stormwater runoff mitigation and water quality improvements through the use of a green roof in Pittsburgh, PA. University of Pittsburgh.

Boland, P., and Hunhammar, S., 1999. Ecosystem services in urban areas. Ecological Economics **29**(2): 293-301.

Brown, Rodney. Water Resources Division, County of Los Angeles Department of Public Works (LACDPW). Personal communication. October-December, 2007.

Brouwer, C. and Heibloem M., 1986. Irrigation Water Management Training manual no. 3. Part I, Ch. 3: "Crop Water Needs." Food and Agricultural Organization. Retrieved from: http://www.fao.org/docrep/S2022E/s2022e00.HTM.

California Building Standards Commission, 2001. California Code of Regulations, Title 24 (California Building Standards Code). Retrieved from: http://www.bsc.ca.gov/title_24/t24_2001tried.htm#part2.

Carter, T.L., 2006. Vegetated roofs for urban ecosystems remediation: performance and policy in the Tanyard Branch Watershed. PhD Dissertation, The University of Georgia.

Carter, T.L. and Keeler, A., 2007. Life-cycle cost-benefit analysis of extensive vegetated roof systems. Journal of Environmental Management. *In press.*

Carter, T. L. and Rasmussen, T. C., 2006. Hydrologic behavior of vegetated roofs. *Journal of the American Water Resources Association* **42**(5): 1261-1274.

Center for the Advancement of Green Roof Technology, 2006. Case studies of green roof regulations in North America. Retrieved from: http://commons.bcit.ca/greenroof/publications/2006_regulations.pdf.

CitiDex.com, 2008. New York City Climate. http://www.citidex.com/213.htm.

City of Los Angeles, Department of Public Works (LA DPW), 2007. Los Angeles Revitalization Master Plan. Retrieved from: http://www.lariverrmp.org/CommunityOutreach/masterplan_download.htm.

City of Los Angeles, Environmental Affairs Department (LA EAD), 2006. Green Roofs – Greening Los Angeles: A Resource Guide. Los Angeles, CA. Retrieved from: http://www.fypower.org/pdf/LA_GreenRoofsResourceGuide.pdf.

City of Los Angeles Stormwater Program (LA Stormwater), 2007. About the Los Angeles Storm Drain System. Retrieved from: http://www.lastormwater.org/Siteorg/general/lastrmdrn.htm.

City of Los Angeles Stormwater Program (LA Stormwater), 2008. Proposition O Background. Retrieved from: http://www.lapropo.org/index.htm.

CityofChicago.org, 2006. Green Roof Improvement Program Overview. Retrieved from: http://www.cityofchicago.org/webportal/COCWebPortal/COC_ATTACH/GRIF_Overview_and_Application.pdf.

Clean River Rewards, 2008. Portland Bureau of Environmental Services. Retrieved from: http://www.portlandonline.com/bes/index.cfm?c=41976.

D.C. Greenworks, 2008. Greenroof Components: An Amazing Feat of Engineering!. Retrieved from: http://www.dcgreenworks.org/LID/grcomponents.html.

DeNardo, J.C. 2003. Green roof mitigation of stormwater and energy usage. MS thesis. University Park, Pa.: The Pennsylvania State University, Department of Agricultural and Biological Engineering.

DeNardo, J. C., Jarrett, A.R., Manbeck, H.B., Beattie, D.J., and Berghage R.D., 2003. Green Roof Mitigation of Stormwater and Energy Usage. ASAE Meeting Paper No. 032305. Retrieved from: http://asae.frymulti.com/request.asp?JID=5&AID=14027&CID=lnv2003&T=2.

Dewoody, A., Cutter, W., and Crohn, D., 2006. Costs and Infiltration Benefits of the Watershed Augmentation Study Sites. Department of Environmental Sciences, University of California, Riverside, Study. Retrieved from: http://www.lasgrwc.org/WAS/Documents/UCR_LASGRWC_041806.pdf.

Dunnett, N. and Nolan, A., 2004. The effect of substrate depth and supplementary watering on the growth of nine herbaceous perennials in a semi-extensive green roof. *Acta Hort.* 643: 305-309.

Durhman, A and Rowe, D., 2006. Effect of Watering Regimen on Chlorophyll Fluorescence and Growth of Selected Green Roof Plant Taxa. *HortScience* Vol. **41**(7).

Dwight, R.H., Fernandez, L.M., Baker, D.B., Semenza, J.C., and Olson, B.H., 2005. Estimating the economic burden from illnesses associated with recreational coastal water pollution - a case study in Orange County, California. *Journal of Environmental Management* **76**: 95-103.

Dwight, R.H., Baker, D.B., Semenza, J.C., and Olson, B.H., 2004. Health Effects Associated With Recreational Coastal Water Use: Urban Versus Rural California. *American Journal of Public Health* **94**(4): 565-567.

Dwight, R.H., Semenza, J.C., Baker, D.B., and Olson, B.H., 2002. Association of Urban Runoff with Coastal Water Quality in Orange County, California. *Water Environment Research* **74**(1): 82-90.

Dwight, R.H., Brinks, M.V., SharavanaKumar, G., and Semenza, J.C., 2007. Beach attendance and bathing rates for Southern California beaches. *Ocean and Coastal Management* **50**: 847-858.

Engstrom, A.M., 2004. Characterizing Water Quality of Urban Stormwater Runoff: Interactions of Heavy Metals and Solids in Seattle Residential Catchments. Master's Thesis, The University of Washington.

Fleisher, J.M., Kay, D., Wyer, M.D., Godfree, A.F., 1998. Estimates of the severity of illnesses associated with bathing in marine recreational waters contaminated with domestic sewage. *International Journal of Epidemiology* **27**: 722-726.

Food and Agricultural Organization (FAO). Mean Crop Coefficients for Subhumid Climates. Retrieved from: http://texaset.tamu.edu/cropcoe.php#Wetlands.

Gaffin, S., Rosenzweig, C., Parshall, L., Beattie, D., Berghage, R., O'Keeffe, G., and Braman, D., 2005. Energy balance modeling applied to a comparison of white and green roof cooling efficiency. Greening Rooftops for Sustainable Communities Conference submission. Retrieved from: http://www.roofmeadow.com/technical/publications/GaffinetalPaperDC-0009.pdf.

Great Lakes Water Institute. Retrieved from: http://www.glwi.uwm.edu/research/genomics/ecoli/greenroof/rooftech.php.

Green Roofs for Healthy Cities (GRHC), 2006a. Green Roof Design 101: Introductory Course, Second Edition - Participant's Manual. Green Roofs for Healthy Cities. Toronto, Canada.

Green Roofs for Healthy Cities (GRHC), 2006b. Green Roof Infrastructure: Design and Installation. p. 201.

Greenroofs.com, 2006. Chicago City Hall. Retrieved from: http://www.greenroofs.com/projects/pview.php?id=21.

Handwerk, B., 2004. Landscaped Roofs Have Chicago Mayor Seeing Green. *National Geographic News*. Retrieved from: http://news.nationalgeographic.com/news/2004/11/1115_041115_green_roofs.html.

Hayden, Martha. Mountain Crest Gardens. Personal Communication. January, 2008.

Holleran, Judy. Building Science Specialist. Henry Co. Personal Communication. October, 2007.

Hutchinson, D. et al., 2003. Stormwater Monitoring Two Ecoroofs in Portland, Oregon, USA. Presented at Greening Rooftops for Sustainable Communities: Chicago, 2003. Retrieved from: http://www.seattle.gov/dpd/stellent/groups/pan/@pan/@sustainableblding/documents/web_informational/dpds_009575.pdf.

International Green Roof Association (IGRA), 2008. Types of Green Roofs. Retrieved from: http://www.igra-world.com/green-roof-types/index.html.

Kayhanian, M., Stransky, C., Bay, S.M., Lau, S., and Stenstrom, M.K., 2008. Toxicity of urban highway runoff with respect for storm duration. The Science of the Total Environment **389** (2-3): 386-406.

Lazzarin, R.M., Castellotti, F., and Busato, F., 2005. Experimental measurements and numerical modeling of a green roof. *Energy and Buildings*. **37**(12): 1260-1267.

Leduc, F., Whalen, J.K., and Sunahara, G.I., 2008. Growth and reproduction of the earthworm *Eisenia fetida* after exposure to leachate from wood preservatives. *Ecotoxicology and Environmental Safety*. **69**(2): 219-226.

Lee, A., 2004. Life cycle cost analysis – green roofs from an investment perspective. Presentation at Greening Rooftops for Sustainable Communities, Portland, 2004.

Leeworthy, V.R., and Wiley, P.C., 2007. Economic Value and Impact of Water Quality Change for Long Beach in Southern California. National Oceanic and Atmospheric Administration, National Ocean Service, Special Project.

Lifecycle Building Challenge, 2007. Affordable green roofs for existing buildings. Retrieved from: http://www.lifecyclebuilding.org/entries/106259text.htm.

Liptan, Tom. Personal communication. May – November, 2007.

Liptan, T., 2003. Planning, Zoning and Financial Incentives for Ecoroofs in Portland, Oregon. Presentation at Greening Rooftops for Sustainable Communities, Chicago, 2003.

Liu, K. and Minor, J., 2005. Performance evaluation of an extensive green roof. National Research Council of Canada/City of Toronto.

Loosvelt, Greg. Earth Pledge Chief Operating Officer. Personal communication. October, 2007.

Los Angeles City Council, Office of the City Clerk, 2004. Council File 02-0182. Leadership in Energy and Environmental Design. Los Angeles, CA. Retrieved from: http://www.sustainla.org/020182.pdf.

Michigan State University, Department of Horticulture, Green Roof Research Program. http://www.hrt.msu.edu/greenroof/.

Mitchel, T. and Blier, W., 1997. The Variability of Wintertime Precipitation in the Region of California. *Journal of Climate* **10:** 2261-2276.

Monterusso, M.A., Rowe, D.B. & Rugh, C.L., 2005. Establishment and persistence of *Sedum spp.* and native taxa for green roof applications. *HortScience* **40**: 391–396.

Moore, G.L., 2007. Incorporate rooftop green spaces as an energy efficient mechanism – Council File 04-0074. Los Angeles, CA. February 8, 2007.

National Weather Service Forecast Office, 2006. Chicago, IL. Retrieved from: http://www.weather.gov/climate/index.php?wfo=lot.

New York City Mayor's Office, 2007. PlaNYC 2030. Retrieved from: http://www.nyc.gov/html/planyc2030/html/home/home.shtml.

Niachou, A., Papakonstantinou, K., Santamouris, M., Tsangrassoulis, A., and Mihalakakou, G., 2001. Analysis of the green roof thermal properties and investigation of its energy performance. *Energy and Buildings* **33**: 719-729.

Nichol, K., 2001. Cost benefit analysis of a strategy to vaccinate healthy working adults against influenza. *Archives of Internal Medicine* **161**(5): 749-759.

Noble, R., et al., 2000. A Regional Survey of the Microbiological Water Quality along the Shoreline of the Southern California Bight. *Environmental Monitoring and Assessment* **64** (1).

North Carolina Division of Water Quality (NCDWQ), 2007. Stormwater Best Management Practices Manual. Staff Report.

Oberndorfer, Erica, et al. 2007. Green roofs as urban ecosystems: ecological structures, functions, and services. *Bioscience* **57**:10.

Paulson, A., 2006. Plants, Grass on the Rooftop? No Longer an Oddity. *Christian Science Monitor*, July 10, 2006. Retrieved from: http://www.csmonitor.com/2006/0710/p02s02-ussc.html.

Peck, S., and Kuhn, M, 2001. Design Guidelines for Green Roofs. CMHC-SCHL/OAA. Retrieved from: http://egov.cityofchicago.org/webportal/COCWebPortal/COC_ATTACH/design_guidelines_for_green_roofs.pdf.

Peck, Steven, 2004. The greening of North America. *Professional Roofing*. Retrieved from: http://www.professionalroofing.net/article.aspx?A_ID=421.

Penn State Green Roof Research (GRR), 2006. About Green Roofs. Retrieved from: http://hortweb.cas.psu.edu/research/greenroofcenter/history.html.

Pilloton, E., 2006. Chicago Green Roof Program. Inhabitat.com. Retrieved from: http://www.inhabitat.com/2006/08/01/chicago-green-roof-program/.

PlaNYC 2030, 2007. Status Report. Retrieved from: http://home2.nyc.gov/html/planyc2030/downloads/pdf/oct_22nd_status_report.pdf.

Portland Bureau of Environmental Services (BES), 2006. Ecoroofs. Environmental Services Fact Sheet. Retrieved from: http://www.portlandonline.com/shared/cfm/image.cfm?id=127469.

Rezaei, F and A. Jarrett, 2006. Measure and Predict Evapotranspiration Rate from Green Roof. Pennsylvania State University Research Symposium, 2006.

Rezaei, F, A. Jarrett, R. Berghage and D. Beattie, 2005. Evapotranspiration Rates from Extensive Green Roof Plant Species. Presentation at the 2005 ASAE Annual International Meeting.

Roman Y.E., De Schamphelaere, K.A.C., Nguyen, L.T.H., and Janssen, C.R., 2007. Chronic toxicity of copper to five benthic invertebrates in laboratory-formulated sediment: Sensitivity comparison and preliminary risk assessment. *Science of the Total Environment.* **387**(1-3): 128-140.

Rosenfeld, A.H., Akbari, H., Romm, J.J., and Pomerantz, M., 1998. Cool communities: strategies for heat island mitigation and smog reduction. *Energy and Buildings* **28**: 51-62.

Rosenzweig, C. et al., 2007. Mitigating New York City's heat island with urban forestry, living roofs, and light surfaces. American Meteorological Society conference submission. Retrieved from: http://ams.confex.com/ams/pdfpapers/103341.pdf.

Rowe, Bradley. Personal communication. October – November, 2007.

Shapiro, N, 2003. The Stranger Amongst Us: Urban Runoff, the Forgotten Water Resource. Proceedings of the National Conference on Urban Storm Water: Enhancing Programs at the Local Level. Chicago, IL February 17-20, 2003.

Skyland USA, 2008. Rooflite extensive mc Analysis. Retrieved from: http://www.skylandusa.us/prodimg/extimg/analysis_rooflite_ext_mc.pdf.

State Water Resources Control Board (SWRCB), 2006. Clean Water Act Section 303(d) list of water quality limited segments requiring TMDLs. *Staff report.*

Taha, H., 1997. Urban climates and heat islands: albedo, evapotranspirtation, and anthropogenic heat. *Energy and Buildings* **25**: 99-103.

Taylor, David, 2008. Growing green roofs city by city. *Environmental Health Perspectives.* **6**(115): A306-311.

Turbow, D., Osgood, N., and Jiang, S., 2003. Evaluation of recreational health risk in coastal waters based on Enterococcus densities and bathing patterns. *Environmental Health Perspectives* **111**(4): 598-603.

Ulrich, R., 1984. View through a window may influence recovery from surgery. *Science* **224**: 420–421.

Ulrich, R.S., Simons, R.F., Losito, B.D., Fiorito, E., Miles, M.A. and Zelson, M., 1991. Stress recovery during exposure to natural and urban environments. *Journal of Environmental Psychology* **11:** 201–230.

United States Department of Commerce, 2006. Bureau of Economic Analysis, Regional Economic Accounts, Local Area Personal Income, Average wage per job in 2006, California, Los Angeles County. Retrieved from: http://www.bea.gov/regional/reis/default.cfm?catable=CA34&section=2.

U.S. Environmental Protection Agency, 2001. Multi-Resolution Land Characteristics Consortium (MRLC): 2001 National Land Cover Data (NLCD 2001). Retrieved from: http://www.epa.gov/mrlc/nlcd-2001.html.

United States Environmental Protection Agency, Water Planning Division, 1983. Results of the National Urban Runoff Program: Volume I – Final Report. Washington, D.C.: WH-554.

United States Green Building Council, 2005. LEED for New Construction and Major Renovations: Version 2.2. Retrieved from: http://www.usgbc.org/ShowFile.aspx?DocumentID=1095.

VanWoert, N.D. et al., 2005a. Watering regime and green roof substrate design affect *Sedum* plant growth. *HortScience* **40**(3): 659-664.

VanWoert, N. D. et al., 2005b. Green Roof Storm water Retention: Effects of Roof Surface, Slope, and Media Depth. *J.Environ. Qual.* 34: 1036-1044.

Veihmeyer, F.J. and Hendrickson, A.H., 1931. The moisture equivalent as a measure of the field capacity of soils. *Soil Science* **32**: 181–193.

Villareal, E. L. and Bengtsson, L., 2005. Response of a *Sedum* green-roof to individual rain events. *Ecological Engineering.* **25**(1): 1-7.

Wark, C.G. and Wark, W., 2003. Green roof specifications and standards: Establishing an emerging technology. *The Construction Specifier* **56**(8).

Western Regional Climate Center, 2007. Historical Climate Information. Retrieved from: http://www.wrcc.dri.edu/CLIMATEDATA.html.

Woolson, E., 2005. Passing Proposition O. *Stormwater: The Journal for Surface Water Quality Professionals* **6**(2).

Whitlow, Thomas. Personal communication. November, 2007.

Wong, N.H., Tay, S.F., Wong, R., Ong, C.L., and Sia, A., 2003. Life cycle cost analysis of rooftop gardens in Singapore. *Building and Environment* **38**: 499-509.

ZinCo-USA Green Roof Systems, 2008. Green roof schematic model. Retrieved from: http://www.zinco-usa.com/.

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Appendix A: Los Angeles-Specific Green Roof Plants

The following plants are suitable for inclusion in green roofs in Los Angeles. Not only do they function in the Los Angeles climate because many of them are native or endemic to Los Angeles, but they also fit within the substrate depth constraints imposed by roof engineering because they have shallow root systems. Botanists, gardeners, green roof specialists and the California Native Plant Society website were consulted for the compilation of this list. Nearly all the recommendations were for succulents, short grasses, perennials and annuals. Thus, the list below is by no means complete, as the list of plants in those groups is extensive, but the selection represents a starting point for southern Californians considering creating a green roof. In selecting plants, species with minimal water needs were preferred. Of note is the dearth of academically reviewed sources for successful green roof species and the plethora of for-profit companies promoting their green roof products. As this analysis is the first of its kind, the listed species have not been tested for persistence on roofs in semi-arid climates.

Rock plants and wildflowers (determined through a search for plants native to Southern CA with adaptation to full sun and drought and shallow root depth)
Achillea millefolium
Allium bivalve
Cosmos bipinnatus, sulphureus – self-seeding annual that requires less maintenance
Opuntia drummondii – prickly pear
Hieracium venosum – grows in granite
Liatris microcephala – grows in granite
Potentilla Canadensis – grows in granite
Sedum pusillum, smallii – grows in granite
Yucca filamentosa – grows in granite
Tradescantia hirsutocaulis – grows in granite
Mimulus
Penstemon
Nassella

Arid climate plants (take 6 months lead-time to fully develop)
Sedum dasyphyllum – lilac mound
Sedum dasyphyllum suendermannii
Sedum kimnachii
Sedum confusum
Sedum mexicanum
Sedum sediforme
Sedum acre
Sedum album
Sedum spurium
Sedum sexangulare
Sedum spathulifolium – in place in numerous green roof acres in the San Francisco area

Sedum reflexum
Dudleya sp.

Grasses (establish quickly)
Encelia sp. – sage grass
Clarkia sp. – sage grass
Artemisia californica – sage brush – likes full sun, prefers no water in summer months, grows wide in diameter, not deep in root
Agrostis hallii – Hall's bentgrass
Bouteloua gracilis – Blue grama grass – needs watering only 1x/month, slower to establish, but durable
Clematis ligusticifolia – white clematis, prefers full sun
Eschscholzia californica – California poppy

The preferred plant list from Emory Knoll Farms, a major green roof supplier in the east and Midwest is below:
Allium schoenoprasum
Delosperma nubigenum – non-native to CA
Sedum acre
Sedum album
Sedum album
Sedum floriferum
Sedum kamtschaticum
Sedum reflexum
Sedum sexangulare
Sedum spurium
Talinum calycinum

Resources:

Almeda, Frank. Curator of Botany, California Academy of Sciences, San Francisco, CA.

Brosius, Joe. Magic Growers.

California Native Plant Society Los Angeles/Santa Monica Chapter

Rana Creek Nursery (Brent Bucknum and Cooper Scollan)

Green Roof Plants: A Resource and Planting Guide: http://www.greenroofplants.com/

GSky Green Roofs and Walls: http://www.greenrooftops.com/

Appendix B: Rain Gauge Station Metadata

Metadata for each rain gauge station from which we drew precipitation data for model is in the table below. After analyzing stations for continuity in data and amount of missing data, we selected five stations for use in modeling. The stations we used are shown in bold (stations 291, 436C, 482, 716 and 1071).

Station Number	Station Name	North Latitude	West Longitude	Gauge Elevation (Feet)	Season Total (in)
10A	Bel Air Hotel	34-05-11	118-26-45	540	18.92
11D	Upper Franklin Canyon Reservoir	34-07-10	118-24-35	867	20.92
13C	North Hollywood-Lakeside	34-08-46	118-21-13	550	18.38
210C	Brand Park	34-11-18	118-16-20	1250	16.28
216D	Glendale - Jackson	34-09-54	118-15-01	615	18.72
228C	Beverly Hills City Hall	34-06-00	118-23-40	245	5.34
237C	Stone Canyon Reservoir	34-06-21	118-27-13	865	22.05
280C	Flintridge-Sacred Heart	34-10-54	118-11-08	1600	21.84
291	**Los Angeles-96th and Central**	**33-56-56**	**118-15-17**	**121**	**13.96**
336	Silver Lake Reservoir	34-06-08	118-15-54	445	17.87
355	Los Angeles Junior College	34-05-14	118-17-28	310	
436C	**Hansen Dam**	**34-16-08**	**118-23-59**	**1110**	**14.67**
453D	Devil's Gate Dam	34-10-53	118-10-27	980	14.68
482	**Los Angeles-U.S.C.**	**34-01-14**	**118-17-15**	**208**	**14.22**
680	Westwood - UCLA	34-04-10	118-26-30	430	
716	**Los Angeles-Ducommun St.**	**34-03-09**	**118-14-13**	**306**	**18.31**
749	Burbank	34-11-11	118-20-54	655	
794	Lower Franklin Reservoir	34-05-43	118-24-40	585	17.28
802C	Eagle Rock Reservoir	34-08-47	118-11-20	970	18.25

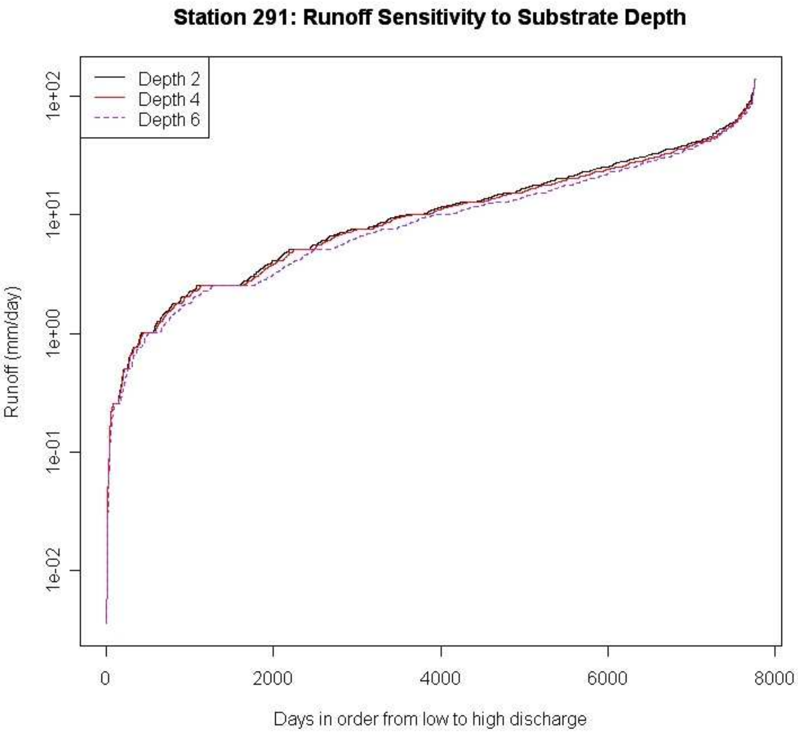
Station Number	**Station Name**	**North Latitude**	**West Longitude**	**Gauge Elevation (Feet)**	**Season Total (in)**
807	Ascot Reservoir	34-04-46	118-11-14	620	16.04
1071B	**Descanso Gardens**	**34-12-07**	**118-12-46**	**1325**	**22.58**
1081B	Glendale-Gregg	34-11-45	118-14-30	1350	21.08
1087	Green-Verdugo Pumping Plant	34-15-25	118-20-11	1340	18.59
1107D	La Tuna Debris Basin	34-14-13	118-19-37	1160	14.12
1217	Los Angeles Country Club	34-04-10	118-25-17	380	20.56
1265	Scholl Canyon Landfill	34-08-38	118-11-07	1000	10.87

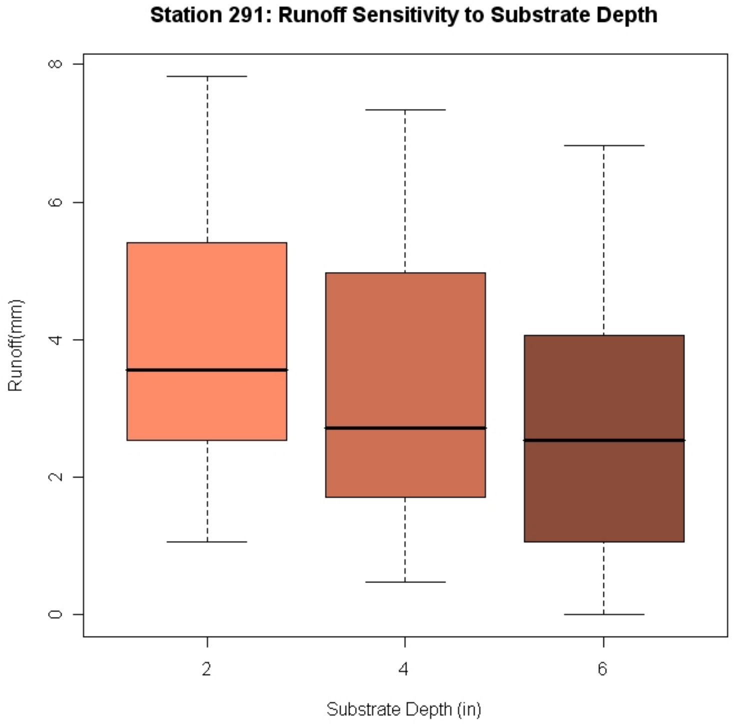
Appendix C: Sensitivity Analysis Figures for Each Station

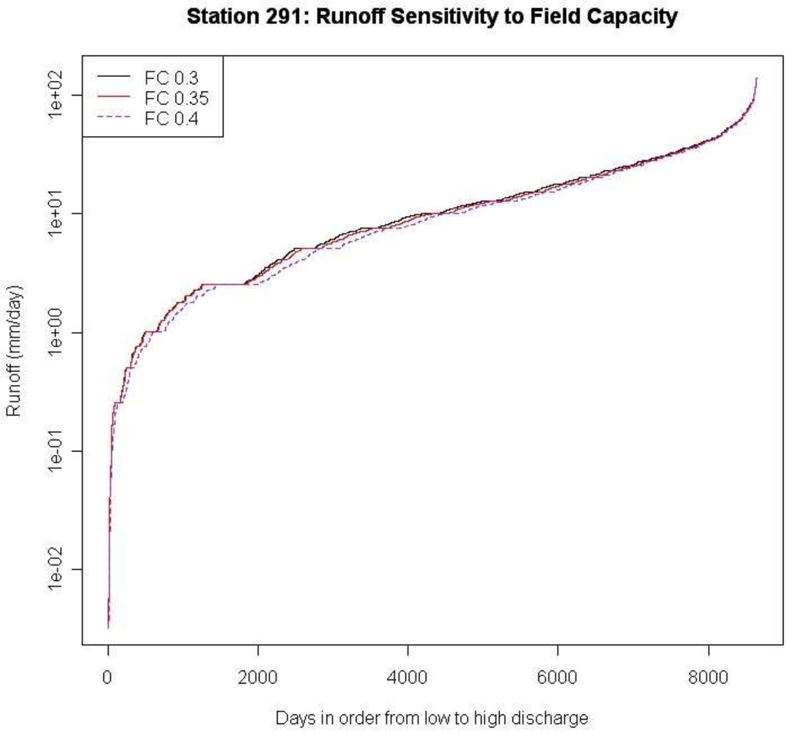
Each page of this appendix contains two figures correlating to the sensitivity analysis described in Section 4 of the final report and Table 4.3, Runoff Sensitivity to All Parameters, within Section 4. On the left side of the page is a line graph showing the effects of parameter values on runoff for all days with runoff. The y-axis of the line graph is runoff on a logarithmic scale. The x-axis represents all of the days in the entire modeling period when runoff existed at that particular station. Days with no runoff were not included. The line graphs were created by varying all parameter ranges simultaneously across specified ranges, and selecting results for each parameter. For each line, the number of days with runoff varies slightly since parameter values impact the number of days where runoff occurs. The number of days with runoff also differs for different stations since precipitation varies across stations.

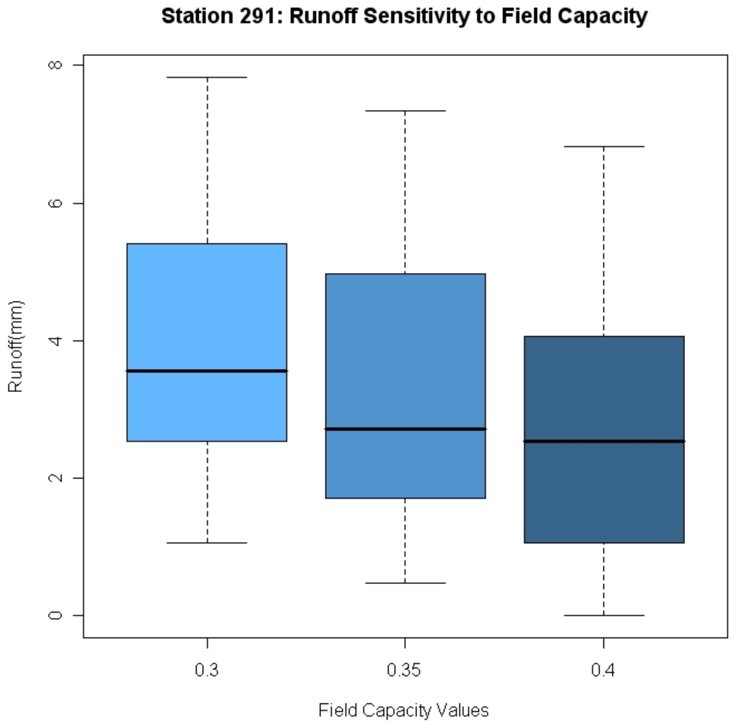
On the right side of each page, the effect of parameter values on runoff is explored further through the use of a boxplot. The spaces between lines visible in the line graphs on the left correlate to the vertical (y-axis) differences in the dark black bars in the boxplot on the right. The y-axis represents runoff in mm while the x-axis represents the values for each parameter range. The data used to create the boxplot is subset to include only days with runoff. In addition, we further subset to also include only one day per series of runoff days to avoid autocorrelation (i.e. if precipitation occurred five days in a row, only one day was included in the boxplot analysis). We subset the data further by looking at only the middle of the range of the days with runoff (days 3,000 to 5,000). This range allows us to remove days with minimal precipitation when all stormwater would be retained by roofs of any composition and days with maximum precipitation where no stormwater would be retained by roofs of any composition.

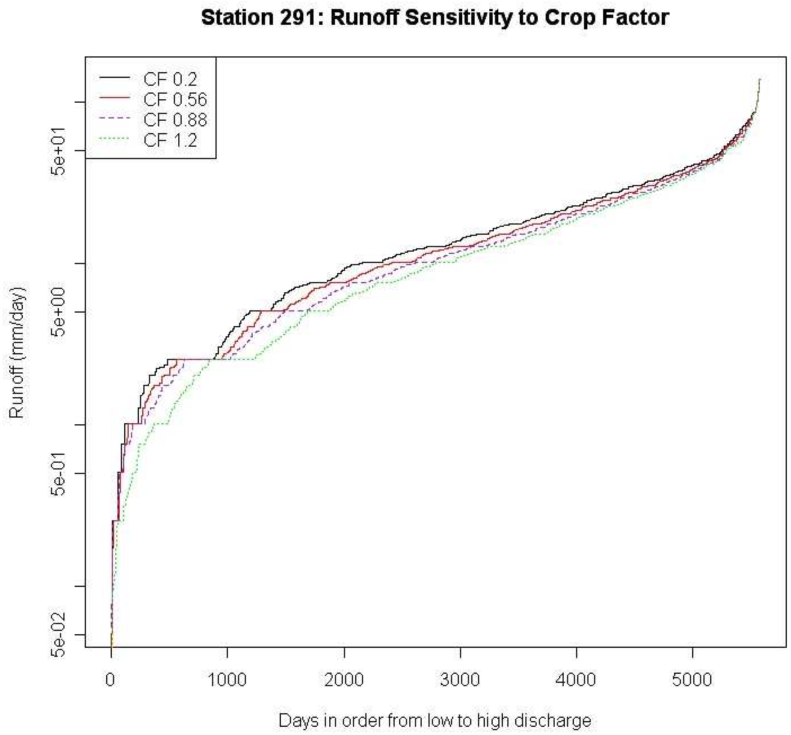
The boxplots show the full range of data in a given subset. For example, for a boxplot showing runoff sensitivity to substrate depth, for all runoff from a roof modeled with 2 inches substrate depth and globally varying field capacity and crop factor, we see the range in runoff in mm in the dotted line running between the thin horizontal black bars at the two ends of the dotted line. The box itself represents the first to third quantiles of the data and the black bar represents the median value of the data. Dots outside of the range of data are outliers to the mean quantiles generated. Each set of three pages represents all of the sensitivity analysis for each parameter range for each station.

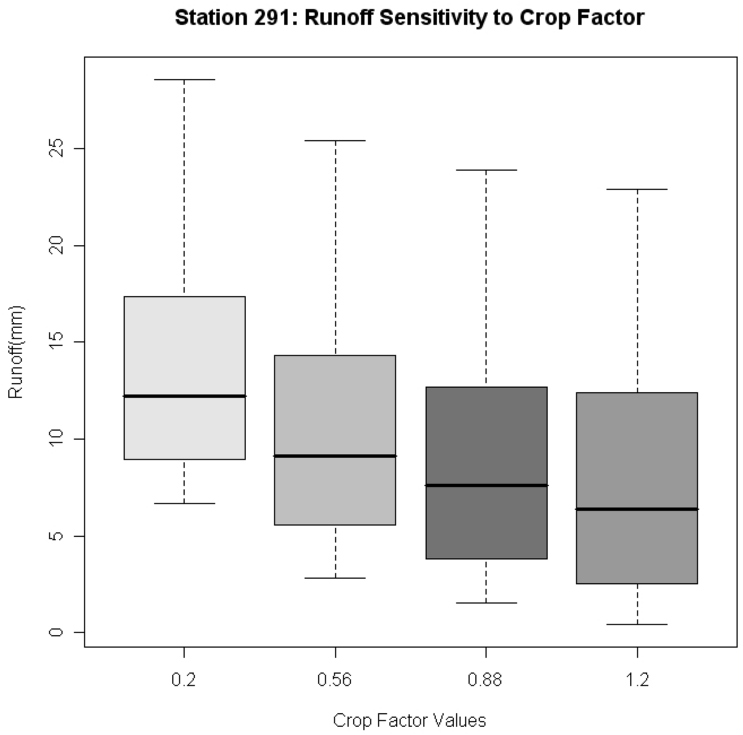

Station 291: Runoff Sensitivity to Substrate Depth

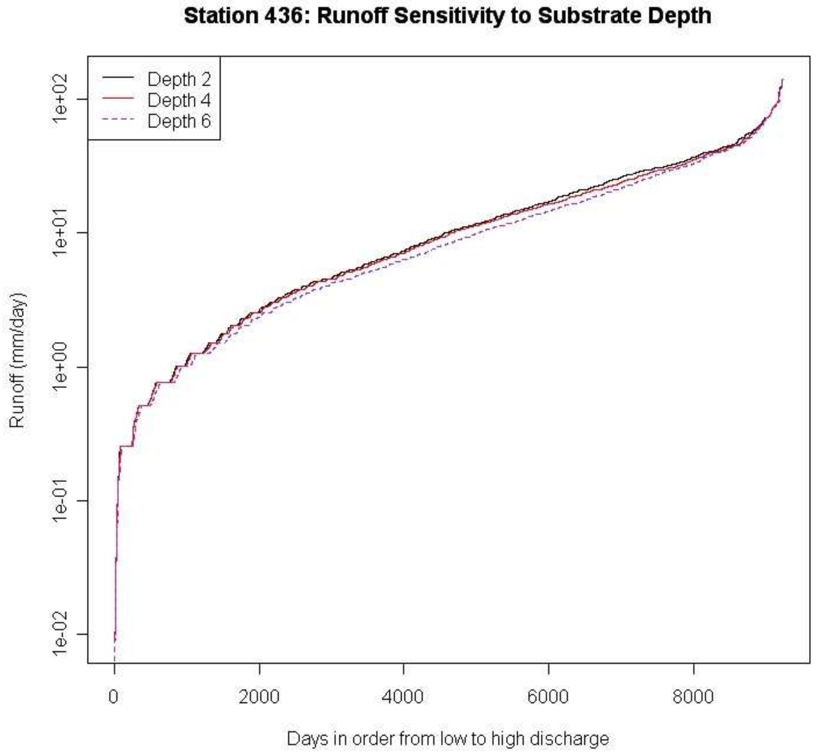

Station 291: Runoff Sensitivity to Substrate Depth

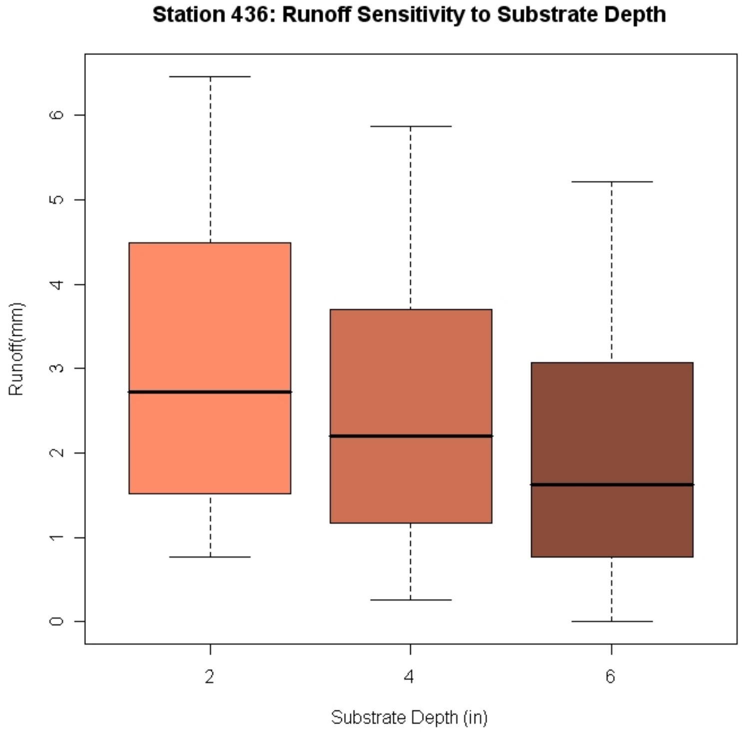

Station 291: Runoff Sensitivity to Field Capacity

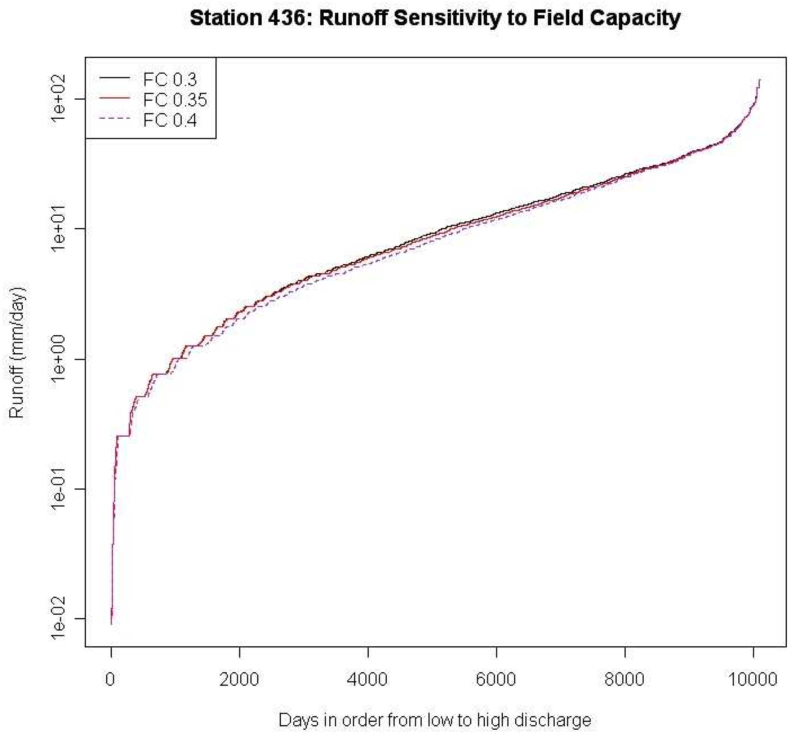

Station 291: Runoff Sensitivity to Field Capacity

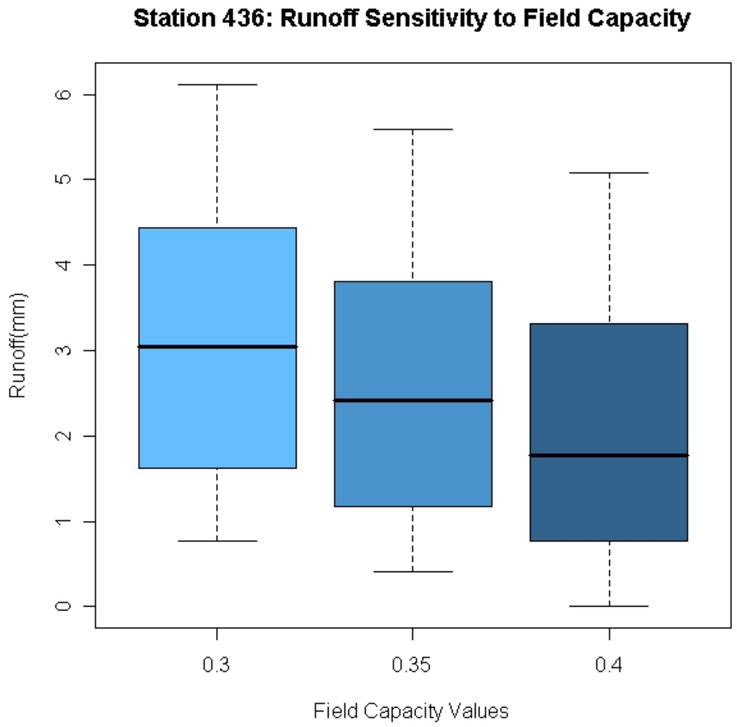

Station 291: Runoff Sensitivity to Crop Factor

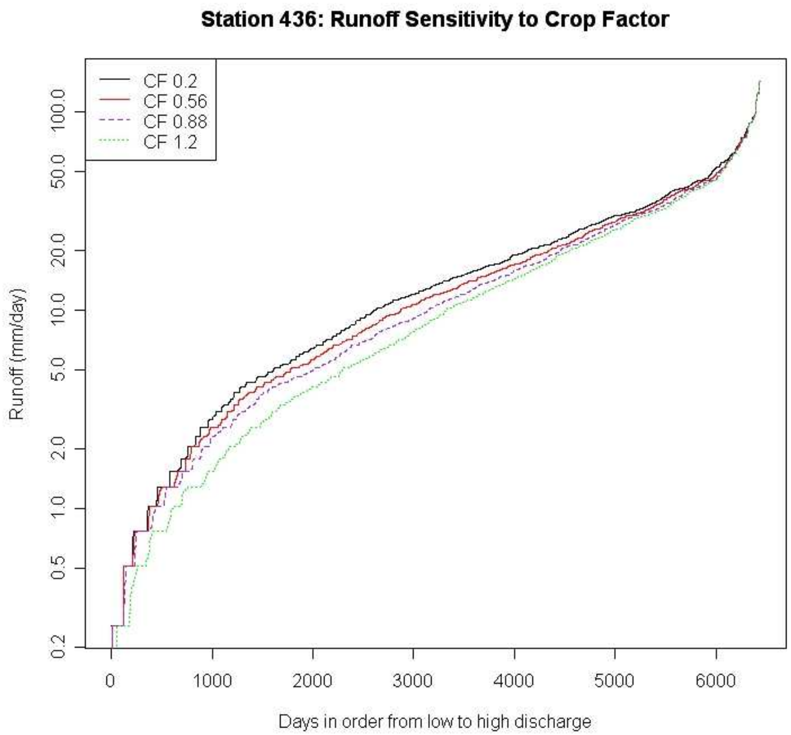

Station 291: Runoff Sensitivity to Crop Factor

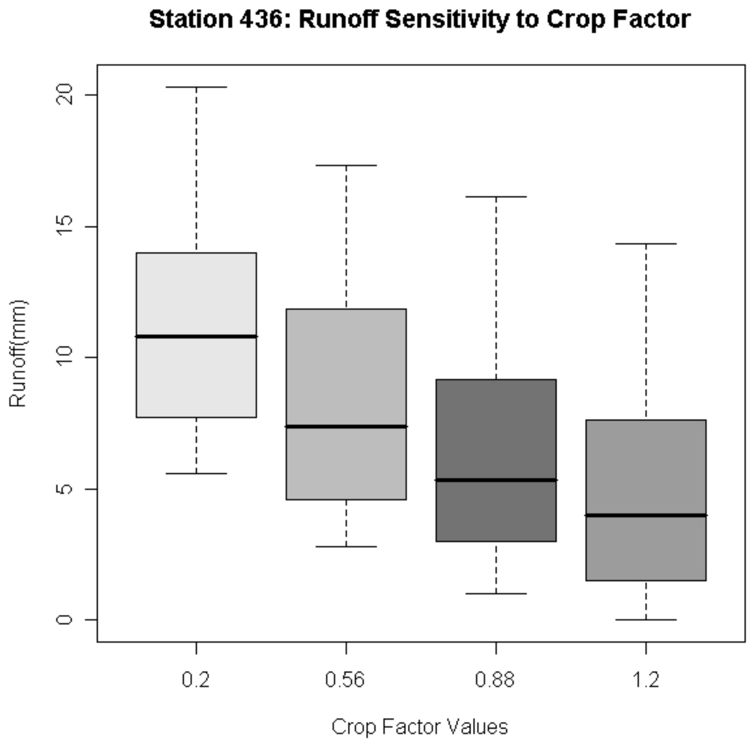

Station 436: Runoff Sensitivity to Substrate Depth
Depth 2
Depth 4
Depth 6
Runoff (mm/day)
1e-02
1e-01
1e+00
1e+01
1e+02
0
2000
4000
6000
8000
Days in order from low to high discharge

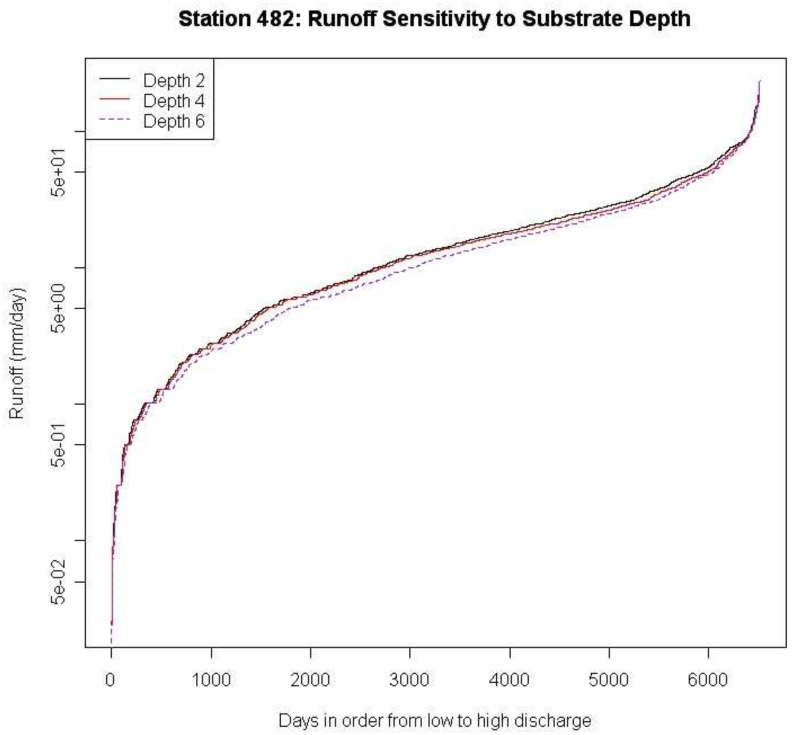

Station 436: Runoff Sensitivity to Substrate Depth
Runoff(mm)
0
1
2
3
4
5
6
2
4
6
Substrate Depth (in)


Station 436: Runoff Sensitivity to Field Capacity
FC 0.3
FC 0.35
FC 0.4
Runoff (mm/day)
1e-02
1e-01
1e+00
1e+01
1e+02
0
2000
4000
6000
8000
10000
Days in order from low to high discharge

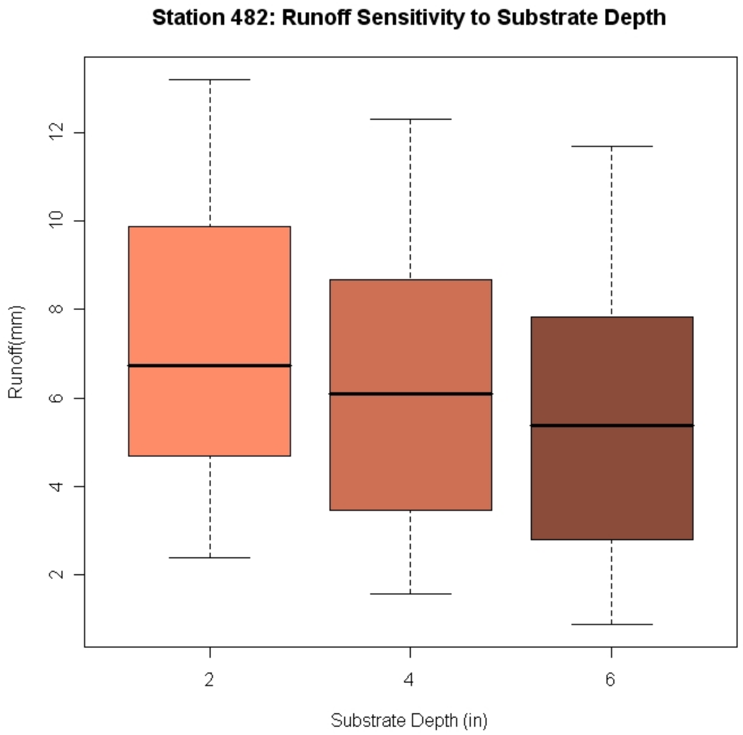

Station 436: Runoff Sensitivity to Field Capacity
Runoff(mm)
0
1
2
3
4
5
6
0.3
0.35
0.4
Field Capacity Values


Station 436: Runoff Sensitivity to Crop Factor

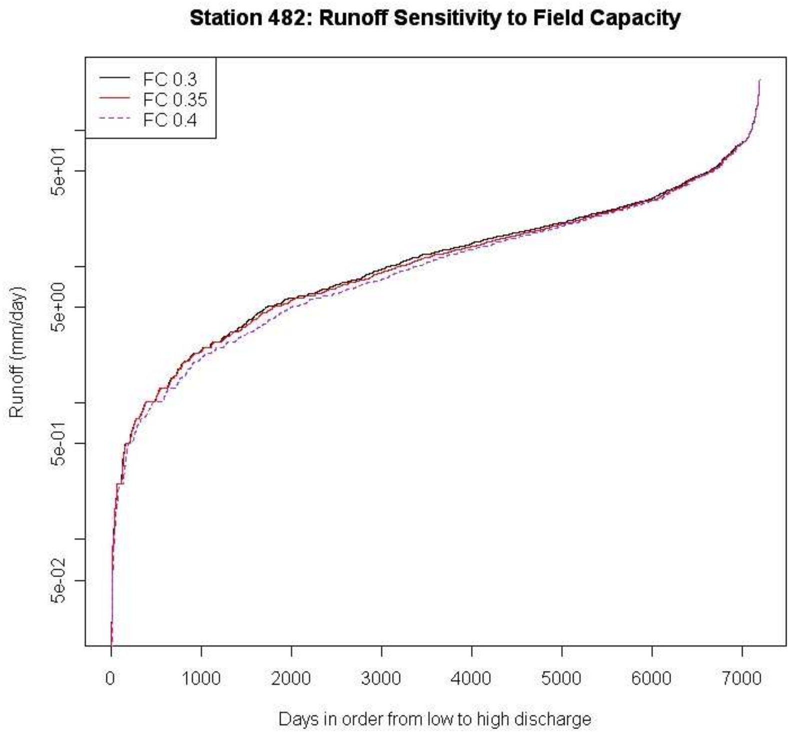

Station 436: Runoff Sensitivity to Crop Factor

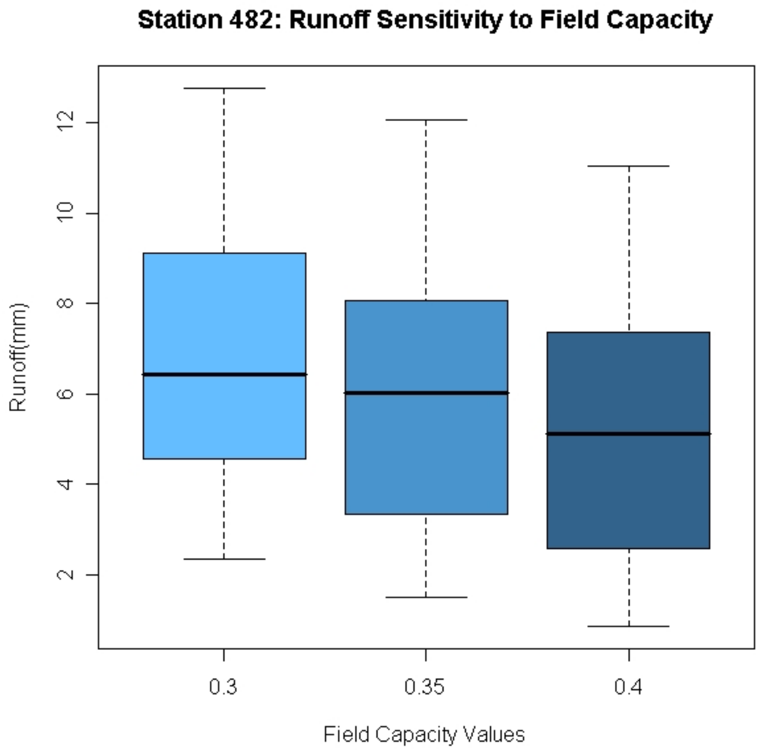


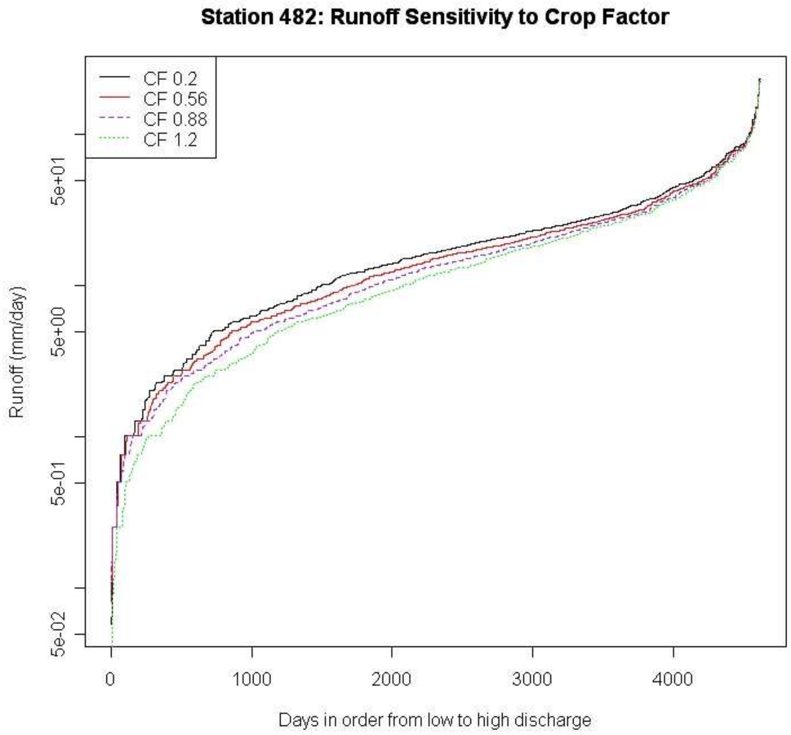
Station 482: Runoff Sensitivity to Substrate Depth

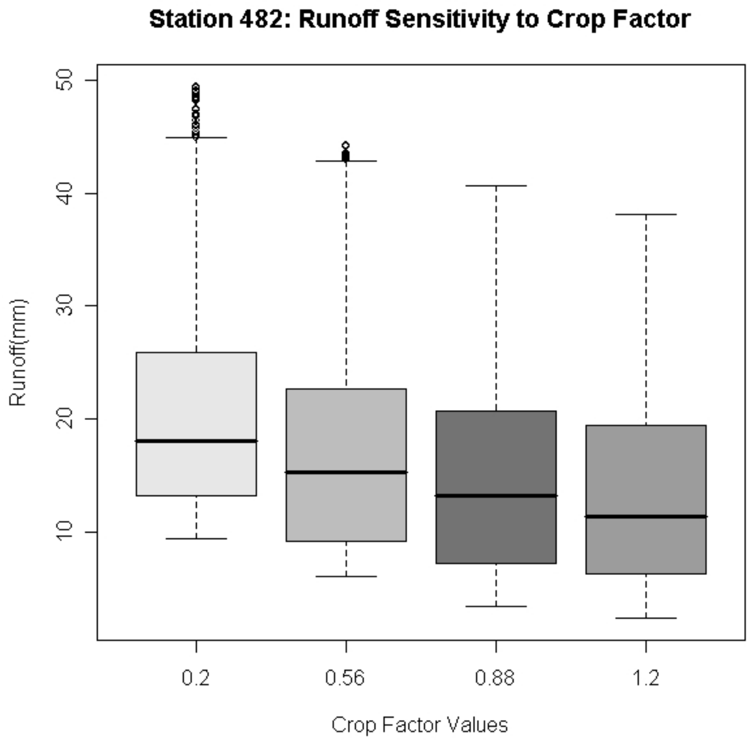


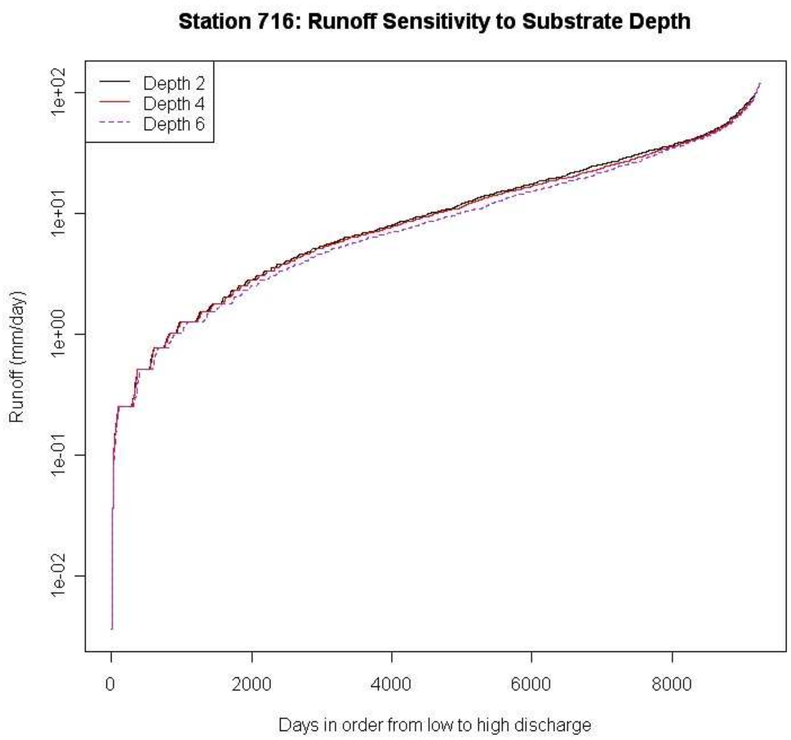
Station 482: Runoff Sensitivity to Substrate Depth


Station 482: Runoff Sensitivity to Field Capacity

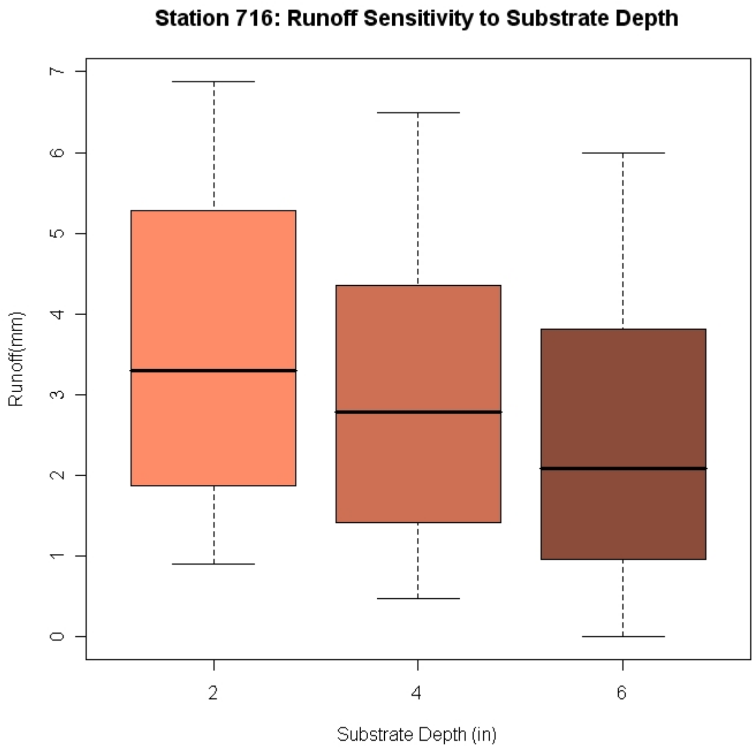

Station 482: Runoff Sensitivity to Field Capacity


Station 482: Runoff Sensitivity to Crop Factor
CF 0.2
CF 0.56
CF 0.88
CF 1.2
Runoff (mm/day)
5e+01
5e+00
5e-01
5e-02
0
1000
2000
3000
4000
Days in order from low to high discharge

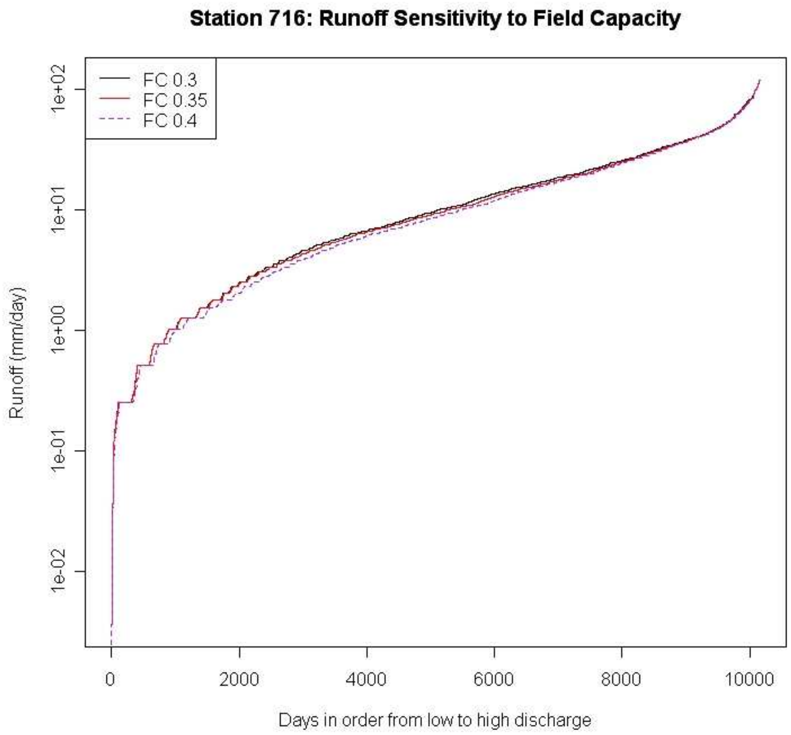

Station 482: Runoff Sensitivity to Crop Factor
Runoff(mm)
50
40
30
20
10
0.2
0.56
0.88
1.2
Crop Factor Values

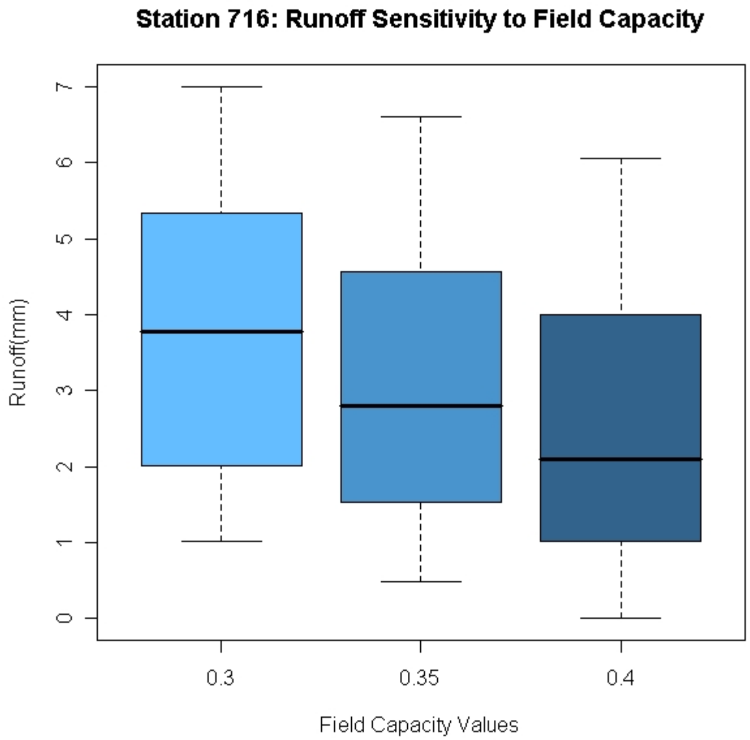


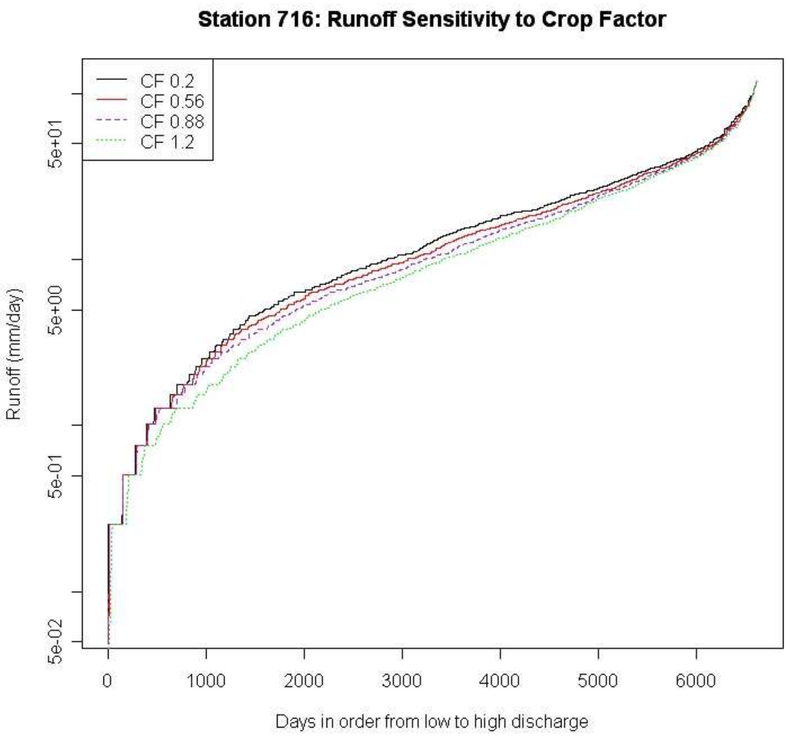
Station 716: Runoff Sensitivity to Substrate Depth

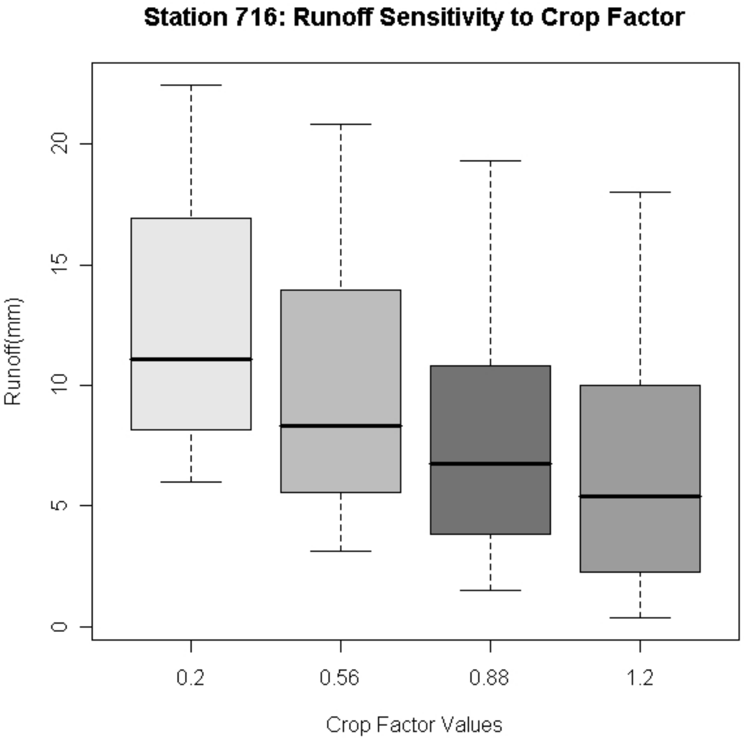


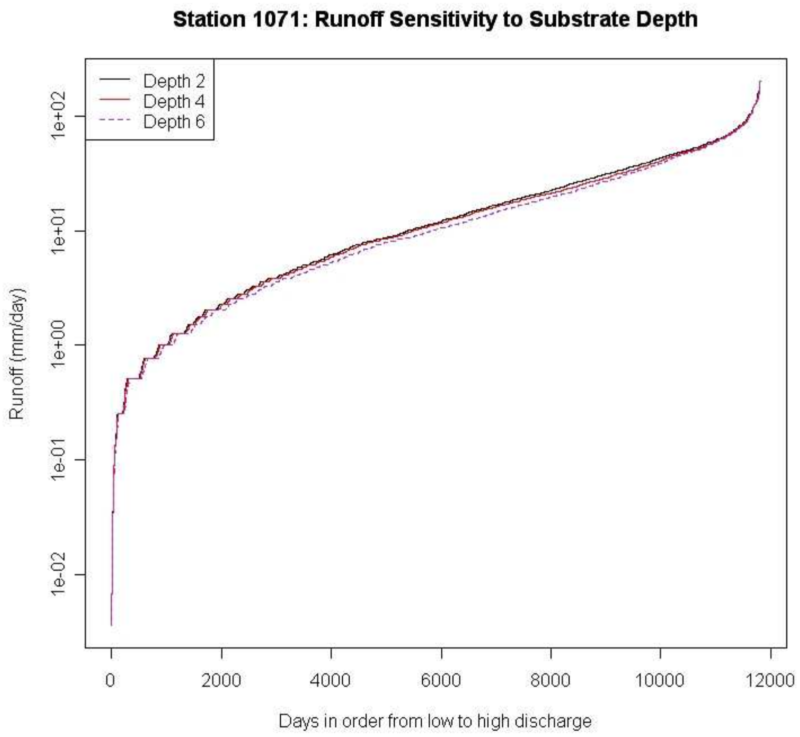
Station 716: Runoff Sensitivity to Substrate Depth

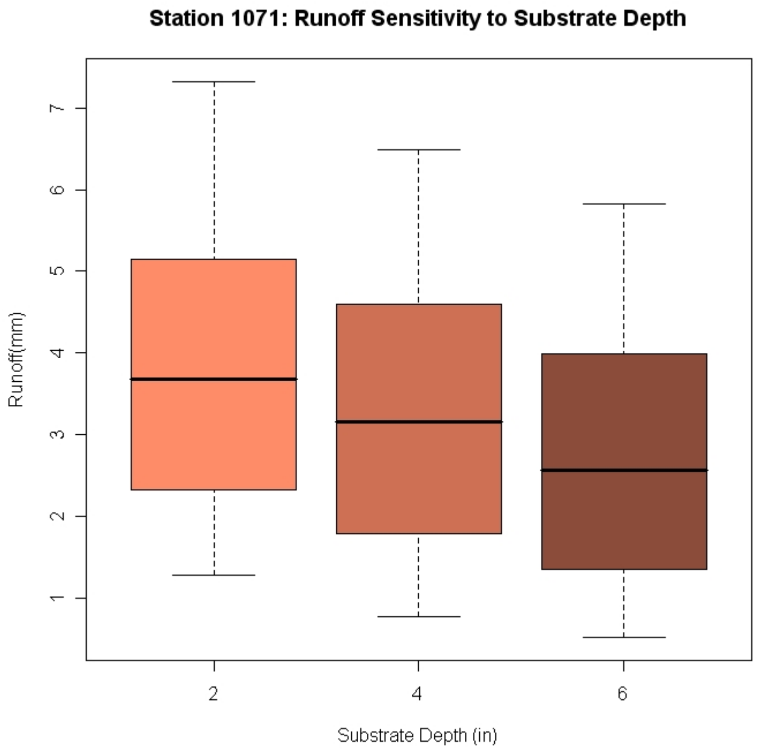

Station 716: Runoff Sensitivity to Field Capacity
FC 0.3
FC 0.35
FC 0.4
Runoff (mm/day)
1e+02
1e+01
1e+00
1e-01
1e-02
0
2000
4000
6000
8000
10000
Days in order from low to high discharge

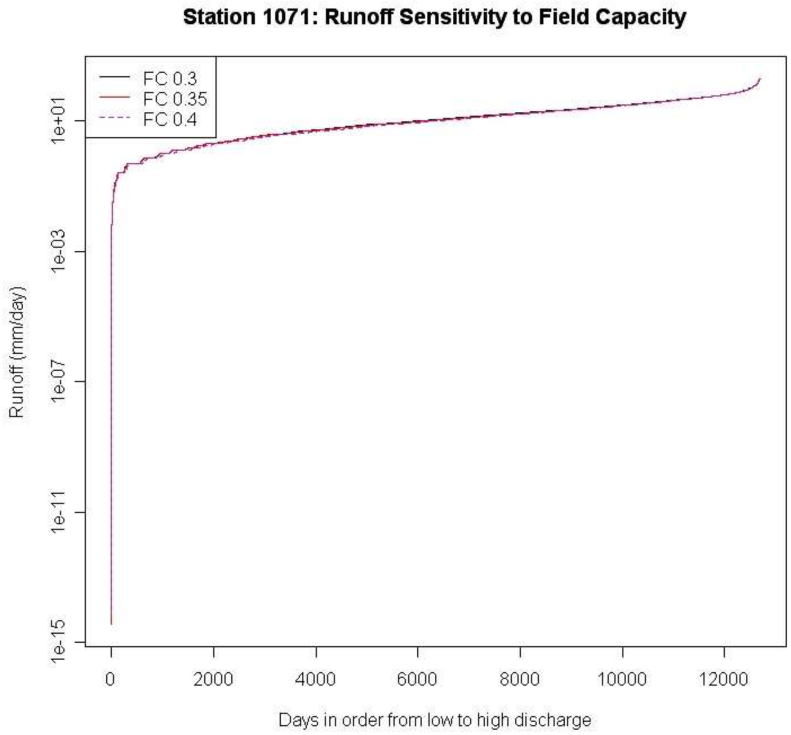

Station 716: Runoff Sensitivity to Field Capacity
Runoff(mm)
0
1
2
3
4
5
6
7
0.3
0.35
0.4
Field Capacity Values

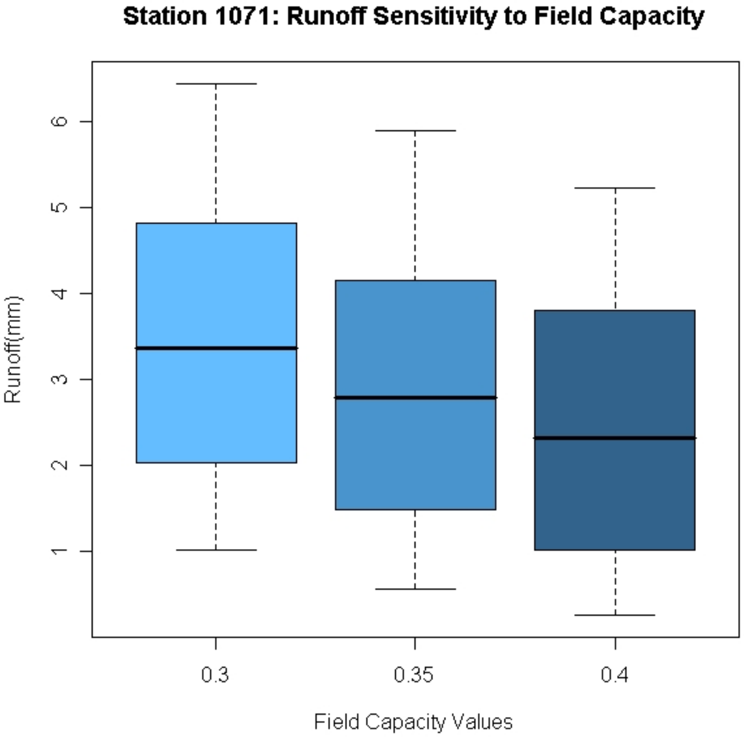

Station 716: Runoff Sensitivity to Crop Factor
CF 0.2
CF 0.56
CF 0.88
CF 1.2
Runoff (mm/day)
5e-02
5e-01
5e+00
5e+01
0
1000
2000
3000
4000
5000
6000
Days in order from low to high discharge

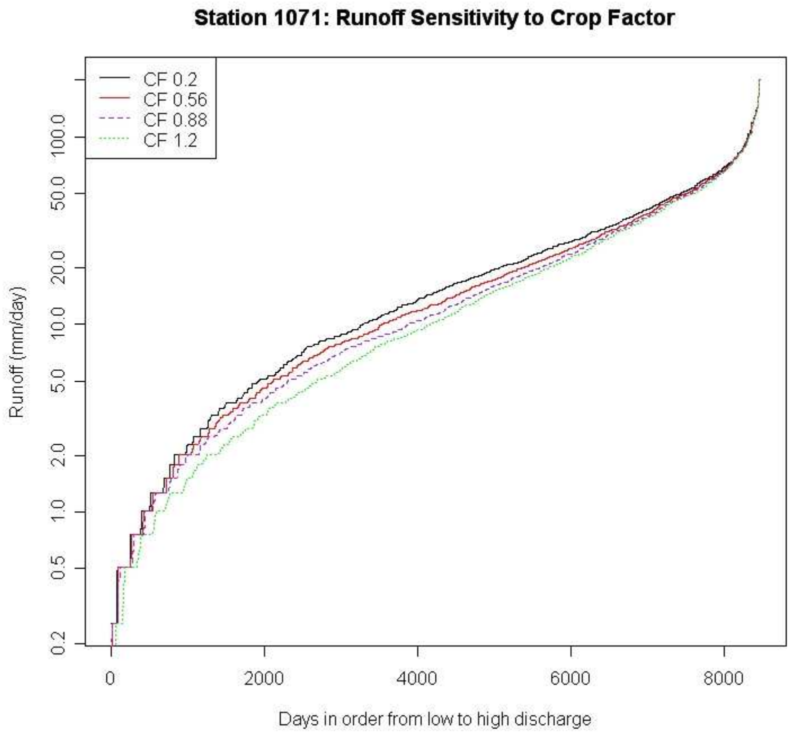

Station 716: Runoff Sensitivity to Crop Factor
Runoff(mm)
0
5
10
15
20
0.2
0.56
0.88
1.2
Crop Factor Values

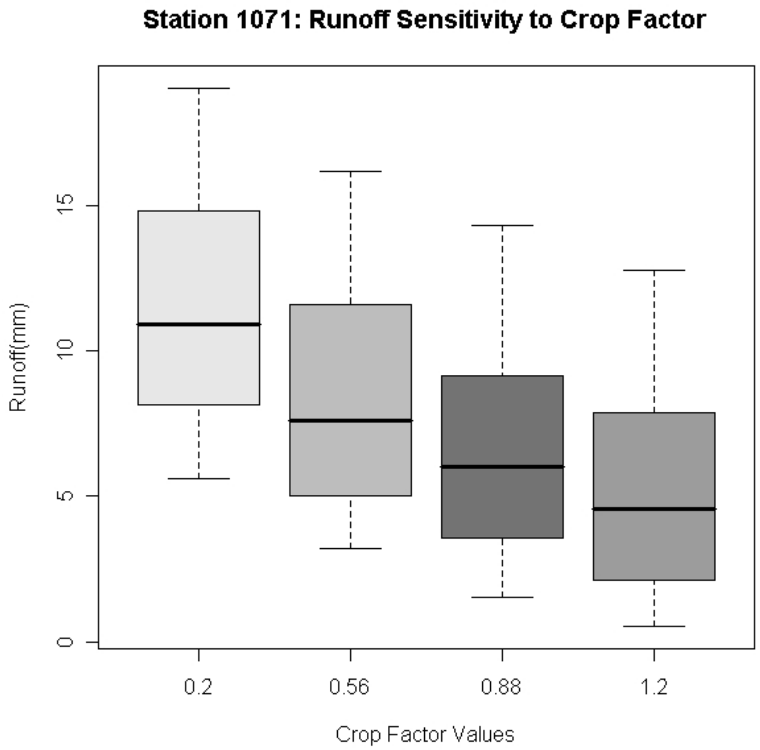

Station 1071: Runoff Sensitivity to Substrate Depth
Depth 2
Depth 4
Depth 6
Runoff (mm/day)
1e+02
1e+01
1e+00
1e-01
1e-02
0
2000
4000
6000
8000
10000
12000
Days in order from low to high discharge


Station 1071: Runoff Sensitivity to Substrate Depth
Runoff(mm)
7
6
5
4
3
2
1
2
4
6
Substrate Depth (in)


Station 1071: Runoff Sensitivity to Field Capacity
FC 0.3
FC 0.35
FC 0.4
Runoff (mm/day)
1e+01
1e-03
1e-07
1e-11
1e-15
0
2000
4000
6000
8000
10000
12000
Days in order from low to high discharge


Station 1071: Runoff Sensitivity to Field Capacity
Runoff(mm)
6
5
4
3
2
1
0.3
0.35
0.4
Field Capacity Values


Station 1071: Runoff Sensitivity to Crop Factor
CF 0.2
CF 0.56
CF 0.88
CF 1.2
Runoff (mm/day)
0.2
0.5
1.0
2.0
5.0
10.0
20.0
50.0
100.0
0
2000
4000
6000
8000
Days in order from low to high discharge


Station 1071: Runoff Sensitivity to Crop Factor
Runoff(mm)
0
5
10
15
0.2
0.56
0.88
1.2
Crop Factor Values