OPTIMAL ADOPTION OF GREEN ROOFS: HYDROLOGY AND PUBLIC FINANCE APPLICATIONS

THESIS

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Abstract

New growth within established communities puts undue pressure on existing infrastructure which in turn, drives tax rate increases for all residents to cover. However, there are sustainable methods that municipalities can turn to that diminishes the local impacts of new growth on the community. Based on the absorptive nature of green roofs, the delayed release of stored rainfall volume diminishes the instances of combined sewer outflows as well as reduces the need for increased infrastructure to convey and treat stormwater discharge. A municipality can introduce planned percentages of green roof coverage which will diminish infrastructure improvement costs over time and increase the population's sustainable footprint. By employing the curve number method for determining runoff volumes from specific rain events and attaching cost-per-unit increase values to the interacting variables, the runoff-cost model produces cost curves in relation to the percentages of green roof coverage. From this runoff-cost model, (based on a specific area), a calculated 40% green roof coverage can be fully reimbursed to the builders through tax abatements, eliminating the perceived cost premium of green over conventional roofs.

Acknowledgments

I would like to thank Dr. Michael Hicks, Col Jeffery Smith, Dr. Alfred E. Thal Jr., Capt John Volcheck, and Mr. Preston Rufe for their guidance and support in investigating and researching the various components of economic theory and its interaction with green roofs. Without their help, this would have been a horrible, painful mistake, which I would be paying for throughout the rest of my career.

Luke D. Stumme

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OPTIMAL ADOPTION OF GREEN ROOFS: HYDROLOGY AND PUBLIC FINANCE APPLICATIONS

I. Introduction

Background on Impact Fees and Tax Abatement

New growth within established communities puts undue pressure on existing infrastructure and services which, in turn, drives tax rate increases for all residents to cover. However, there are tax-reducing methods that municipalities can turn to that diminishes the local impacts of outside growth on the community. The two most common methods are impact fees and tax abatements.

In municipalities across the United States, impact fees are applied to new construction wherein the developer pays for necessary upgrades and installations of new infrastructure that would impact the local public services. By applying these fees to the incoming growth, the existing community is not burdened with the increase in individual taxes which would pay for the increase in needed services and infrastructure based on the growth of the new construction. The types and land uses vary for impact fees, but are usually assessed against increases in road usage, water usage, wastewater production, increased site drainage, redevelopment of parks, extensions of libraries, fire and police department expansions, impacts on general government services, and school expansions (Mullen, 2007).

Tax abatement, on the other hand, provides post-construction tax reductions to the developer or land owner in exchange for the developer's investment in the construction of the new infrastructure and/or service increase. By deferring or lowering the taxes owed by the new land owner, the municipality benefits from the new infrastructure and the developer saves on taxes for a determined amount of time after construction is complete. This method is also used to spur business and growth in a local economy.

Both of these methods can be used to counter the influence that new construction will have on local taxpayers. However, these methods do have distributional effects which can be detrimental to the community. For example, one study found that for every $1.00 of impact fee assessed, there was a $.60 increase in the price of the home (Ihlandfeldt & Shaughnessy, 2004). These increases in property values decrease home-owning affordability for low-income residents, introduce transitional unfairness in regards to taxation, and could introduce "rent-seeking" by the current residents (Been, 2004).

As will be discussed further in Chapter II, new developments do indeed increase the burden on infrastructure and public services. However, if the developer were to limit the burden on certain infrastructure types and services, in theory, the impact fees could be reduced or the tax abatements could be increased based on the savings provided to the municipality. Two major infrastructure influences that a new development has on a municipality are in stormwater distribution network enhancements and the capacity increase of wastewater treatment plants. One way to diminish these influences is through the utilization of green roof technologies.

A green roof, also called a vegetative roof, is a predesigned system consisting of a waterproofing membrane, soil layer, and a vegetative layer that work together to enhance or replace a current roofing system. There are many monetary benefits to installing green roofs, which will be covered in Chapter II, but there also exist high costs for installation and materials.

Research Objectives

The purpose of this thesis is to identify to what extent green roof technology can inhibit and reduce the potential increases in infrastructure for both stormwater distribution networks and wastewater treatment plant capacities. First, the percentage of green roof coverage within a set geographical area that provides the greatest public benefit will be identified. Second, the dollar amount of benefits that the determined amount of green roof coverage will provide the public, based on Combined Sewer Outflow (CSO) reduction will be identified. Finally, various tax measures that a municipality could initiate to introduce green roofs as an attractive cost saving measure for both the public and private sector will be discussed. By creating this development model, assessing various levels of green roof coverage with associated rain events that cause runoff, and answering the research questions, a calculated percentage of green roof coverage will result in lower infrastructure redevelopment costs.

Methodology

A representative community model will be developed using existing US Census Bureau as well as current satellite images of Beavercreek, Ohio. With the structural development of the model, various inputs for rain events, construction costs, hydrologic soil properties, and other pertinent data and equations will be entered to provide realistic outputs.

Next, representative storm sewer and wastewater treatment plants will be designed. The designs will be estimated using current cost-estimating software and guides. Existing construction data will also be used to verify the correctness of the cost estimates.

Finally, by implementing the USDA's TR-55 "Urban Hydrology for Small Watersheds," the runoff values based the modified curve numbers will be determined and entered into the representative community model. Tables of cost data will be produced based on the rain events, construction costs, and percentages of green roof coverage.

The overall concept behind the model is that with a calculated percentage of green roofs installed on the new development's structures, the stormwater and runoff impacts on the potential infrastructure expansions could decrease the probable impact fees or increase the probable tax abatements, which would provide the needed increase in initial capital to the developer to install the green roofs to begin with.

Assumptions/Limitations

Some assumptions and limitations for this study do apply. First, because this model is based on a representative community, no measurements or data were collected from an existing green roof community. All calculations and benefits were based on secondary data and current design standards from the built model to provide an accurate representation of the potential costs and savings based on a specific geographical area.

Secondly, although the determined values are specific to the thesis' area of interest, the methodology and process of determining inputs can be repeated for any location. Finally, all the calculations are based on the USDA's TR-55 model, which include specific guidelines on design capacities and values used.

Implications

The results found in thesis will have impacts on both city planners and developers. Devising a clear public benefit and cost analysis of the green roof coverage options will provide both parties information to foster green roof growth while simultaneously saving both the municipality and developers money. For the United States Air Force, being able to plan and program for reduced runoff and increased energy savings within the planning phases of construction would provide great benefits. While energy savings and other private benefits have been discussed previously in other research, other benefits do exist. Exhaustive public relations exposure as well as the potential to sell environmental credits to other non-Department of Defense entities for profit based on runoff reductions could also be investigated.

II. Literature Review

Introduction

The emergence of "green" technologies has entered the world's buying conscience in day-to-day market choices from food and construction, to energy and transportation. Market demands for green products increase worldwide on a daily basis and currently account for 9% of all new-product launches in the United States (Marmor, 2007). Consumers are paying increased price premiums for green items, even though comparable, cheaper, non-green versions are equally available. One of the reasons for this, according to Andreoni, (1990), is that consuming items with environmental attributes is gratifying or gives a "warm glow" to the consumers. This means that environmental attributes are a desirable product quality in market goods that can be measured through revealed preference or market evaluation data. Therefore, there exists a willingness-to-pay premium for green or environmentally friendly items (Hamilton & Zilberman, 2006).

However, even though this "warm glow" feeling contributes to purchases that tend to violate the theory of near perfect substitutes, which is the idea that consumers will always choose what is of greater utility to them, most people still choose what is cheaper in overall price. Given this argument, if two products, one green and one conventional, were of equal cost to the consumer and both provided fairly equal benefits, what would keep the consumer from choosing the conventional one over the green one? If the price difference between the green and conventional products were eliminated, thereby reducing the option to which product gave the most benefits, the green one would most likely be chosen.

Background

Within the green movement is the increased interest in the construction segment of environmental consciousness. While the green movement has flooded into the new construction and urban development sectors, thus forcing developers and contractors to adopt energy efficient, recyclable, and overall green elements, according to a Wall Street Journal article dated 30 May, 2007, there has been pushback by consumers to the increased price-premium on these features. Ultimately, price conscience consumers are closely considering what green features they can afford, how quickly the technology will pay for itself in the near future, and how much these green modifications can add to the health and happiness of their families' lives. Ultimately, the consumer wants to know: Which green technologies will maximize their personal utility?

By using the representative consumer theory (the idea that each person will maximize their utility, which can represent the entire population of study), one can find the willingness to pay (WTP) of a community for a certain benefit such as a green roof (Smith & Haefen, 1997). However, rather than focus on individual choices which could be used to determine the community's choice, this thesis will focus on the community as a whole in making these choices. To focus this argument, the overall utility gained by the community will be investigated by removing the financial impact of building the roofs on the municipality by reimbursing the builder 100% of the cost. Also of note, throughout the rest of the thesis, “public benefits” will refer to the benefits seen by the tax payers of the municipality. This would include reduction of utility and service costs that the tax payers would normally pay for as well as non-market items such as cleaner air, water, and increased biodiversity. “Private benefits” will refer to those items that an individual member of the community would gain, that the remainder of the community would not.

This direction in public policy economics combined with engineering economic calculations will be applied to a representative neighborhood and municipality in order to determine the benefits and costs associated with green roofs, impact fees, and taxes. However, we must understand what constitutes a green roof, as well as which benefits are supplied and what costs are incurred by installing these roof types.

History and Definitions of Green Roof Types

Green roofs have been adopted throughout history based on their ease of construction and availability of resources all over the world. In the United States, sod roofs were utilized by settlers on the American Prairies in the mid to late 1800s (Morgan, 2004). For over 60 years, green roofs have populated many international urban centers such as Berlin, Madrid, London, New York City, and Chicago. The popularity of the green movement, coupled with the shrinking of public green spaces, has ushered in a desire to install green roofs in more urban areas. Because of this increasing popularity, there has been an influx of studies discussing the benefits and costs of installing and maintaining green roofs (e.g., Wong, (2003), Acks, (2005), and Kosareo, (2006).

The term "green roof" refers to the external membrane of soil, vegetation, and other support components that rest on or are adhered to the top of an existing roof. The soil layer can range from one to five inches of depth for the extensive type, and from six inches up to a foot or more of depth for intensive types of green roof (Morgan, 2004). The intensive type of vegetative roof tends to contain a larger variety and more sizable selection of plants than the extensive type roof. Intensive type roofs tend to weigh in the neighborhood of 80-150 lb/ft^2, whereas the extensive roofs tend to weigh in the area of 10-50 lbs/ft^2 (Morgan, 2004). Extensive green roofs will be the focus of this study as the majority of the research uses extensive green roofs for their data.[1]

Why Green Roofs?

Although the focus of installing green roofs was based initially on financial savings from reduced energy usage, green roofs have also been applied to reduce stormwater runoff during rain events (Kibert, 2005). One of the green movement's most publicly beneficial areas lies in Low Impact Development (LID) (EPA, 2000). This area of technology reduces storm water runoff and its increased pollutant-carrying potential. LID includes the technology of green roofs, rainwater storage barrels, and other pervious surface materials which reduce water volume and pollution in our public waters and estuaries (Montalto, 2007). Green roofs have also been shown to create other benefits,

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[1] More about green roofs can be read in Morgan's 2004 thesis regarding green roof construction, types, and history.

such as cleaner air and reduced energy use for the surrounding area residents and users (Banting et al., 2005).

Even though both private and public benefits exist for green roofs, as can be seen in current research, there is still hesitancy among consumers and developers to include such technology in new construction. The burden of financing these new infrastructure concepts is the main reason that developers are slow to adopt radical, expensive means of reducing footprints of development. In Germany, however, tax incentives and subsidies have made green roof technologies more available and financially acceptable in the German housing market. However, in the United States, only larger metropolitan areas, such as Portland, have made such LID technologies monetarily attractive to consumers through construction offsets and tax credits (Kibert, 2005). The next section will describe the benefits found by other studies that green roofs provide.

Background Benefit Studies

Green technologies provide both public and private benefits. One Ryerson University study showed that green roofs could potentially provide initial cost savings to the City of Toronto (public benefit) of $313.1 million and an annual cost savings of $37.1 million based on air quality improvements, urban heat island reductions, and storm water runoff savings (Banting et al., 2005). The private benefits found were due to the insulating properties of the green roof. Individual household energy usage could be reduced by as much as 4.15 kilowatt hours per meter squared per year, ($kWh/m^2/yr$), which would result in energy savings of about $21 million total for the residents of

Toronto which had installed green roofs (Banting et al., 2005). These private and public benefits are discussed in the following studies.

Roof Costs and Benefits

Both intensive and extensive roof types have various benefits that are easily found in market research. Most vegetative roofs, when installed correctly, tend to extend the life of the roof by up to three times that of a normal built-up roof (Perry, 2003). This longevity tends to be attributed to the protection of the waterproof membrane from hail, ultraviolet rays, and sudden changes in temperature (Scholz-Barth, 2001; Liu, 2003). Due to the various initial costs and benefits of having a green roof, both the initial cost of purchasing and installing a green roof as well as the life-cycle costs of both the conventional and green roofs must be examined.

Wong et al. (2002) determine both the initial and life-cycle costs of the three main roof types. The initial cost was $\$89.86/m^2$ and \$178.93/m2, respectively, for an extensive roof system and an intensive roof system without trees. This is compared to the initial costs of $\$49.35/m^2$ and $\$131.60/m^2$, respectively, for flat roofs and built up roofs. However, Wong et al. (2002) determined that the initial construction costs of green roofs had a larger variance in price as compared to conventional roof installations. This was due to the different types of green roofs, drainage systems, structural support, and the variety of trees and broad diversity of vegetation installed. However, the only roof type that had a positive net savings over the life of the roof, or positive life-cycle cost, was the extensive green roof (the shallower, less maintenance-intensive of the two), with an annual energy savings of $4773.40, or $190,936 over the 40-year life span of the modeled green roof.

The next study showed the comparative environmental life-cycle assessment of green roofs. Kosareo and Ries (2007) investigated three types of roofs: intensive green roof, extensive green roof, and conventional built-up roof. The report found that although the energy reduction was not substantial, in terms of the overall energy use of the facility (in Pennsylvania), it was still a significant amount of savings, and reduced the green roof's environmental impact over the life of the roof (from the roof's production, installation, maintenance, deconstruction, and eventual disposal) more so than that of a conventional roof.

In another study, the Department of Energy (2007) discussed the "promising" technology of energy-efficient roofs by studying various categories of vegetative roofs, the reduction of heat absorption, the filtering and delayed runoff of rainwater, and the photosynthesis process that reduces greenhouse gas emissions. The report states that green roofs maintained a 95% reduction in heat gain, a 26% reduction in heat loss, and a 47% overall reduction in total heat flow. These numbers would translate into energy savings or money saved by the consumer who had a green roof rather than the standard asphalt roof, or a private benefit.

Another part of the Department of Energy study found that green roofs absorb, filter, and retain about 75% of the precipitation that falls on the roof. This finding could be described as a reduction of non-permeable surfaces that leads to a decreased rain water runoff, which would lead to a combined sewer overflow event (the combination of storm sewers and sanitary sewers referred to as the CSO). This reduction of non-permeable surface area, while increasing the permeable surface area, would ensure delayed release of stored rainwater. This would effectively "hold" the runoff and release it over time, which would allow the sewers time to transport the excess water away from the building. As a result, the municipality, and in turn the taxpayers would save money by not having to enlarge the storm and sanitary sewer systems to handle large water events. This savings would also include the reduction of construction and operations of river filtration systems to clean the runoff as it washes toxins and other harmful solutions into the local rivers and lakes.

Carter and Jackson (2007) used the curve number method of calculating stormwater runoff to calculate the potential reduction and management of storm water runoff in Atlanta, Georgia. They found that green roofs in an urban setting can effectively be used to reduce peak runoff rates during small storm events by up to 26%. However, the authors concluded that green roofs themselves cannot solely provide stormwater management in an entire watershed. Other rain-gathering technologies such as rain-barrels, porous-pavements, and retention tanks should be used to minimize the runoff caused by rain events.

Other studies also found that green roofs reduce the CSO of the entire surface area of the building footprint by 40%. With this reduction, one can assume that if all structures in the representative neighborhood have this technology, a 40% reduction in total flow could be implied. CSO reduction also translates into a reduction in water pollution costs, which has been found to be around $2,560/ha of green roof/year

(Montalto et al., 2007). In addition to the reduction in CSO and water cleanup costs, green roofs have also been shown to reduce energy usage per household due to the insulating properties of the green roof. The energy reduced was found to be as high as 4.15 kWh/m^2/year (Banting et al., 2005).

These benefits and costs, both private and public, can be combined with current construction data and impact fee statistics to show the reduction of civic taxes and developer impact fees which can be realized with proper research and utilization of LID technologies. With these stated market benefits, there also needs to be a discussion of the public nonmarket benefits that can be realized.

Nonmarket Valuation Benefits

Because the owner of a green roof can realize the market costs and savings of a green roof, it is easy to assign a value or benefit to them. However, there are public and indirect values that can be realized, such as cleaner water and cleaner air. These indirect values can be estimated, but should be measured using nonmarket valuation techniques such as surveys.

The nonmarket value portion of green roof cost analysis has not been deeply analyzed to date. It has been mentioned in various papers as one of the continuations of research needed to be addressed for complete green roof analysis. One study in particular addresses this concern by stating that “although there are many benefits of green roofs, the value of green roofs are underestimated and therefore not accurate based on indirect benefits.” (Kaufman, 2007)

To begin with, one must determine the immeasurable, or nonmarket, qualities that a green roof provides which are not purchased, traded, nor sold on the open market. Acks (2005) examined differing tiers of market and nonmarket benefits. The first tier is called "private benefits and costs." This category assigns monetary values to the market items that the owner would realize, such as reduction of heat island effects, reduction of storm water runoff payments, installation and maintenance costs, and program costs. However, the next tier of "public" or "common good" categories refer to items that are not market measurable, at least directly. They include sound reduction, aesthetic benefits, food production, and health savings. Although Acks (2005) mentions these categories as nonmarket, it assigns somewhat arbitrary values to the public's willingness-to-pay for varying levels of each and assumes certain values without in-depth data analysis.

Getter and Rowe (2006) also discussed the various indirect benefits of a green roof. These include many of the aforementioned categories, but also include the nonmarket categories of increased plant biodiversity and habitat, improved aesthetics, noise reduction, and mitigation of air pollution.

Impact Fees and Tax Abatements

One reason that green roof technologies have not been widely accepted in the United States residential housing markets has been the up-front costs imparted on the consumer. These up-front costs, or impact fees, charged by the local municipality on the housing developers (which could potentially include green roofs) are so large that the developer must cut costs to make a profit. These cuts usually include removing large, non-required cost items, such as a green roof, from the construction budget.

These impact fees, also known as commuted sums, are fees accessed on newly constructed buildings, within a governance, that would potentially have a negative monetary impact on public services such as police, fire, library, sewer systems, and wastewater treatment due to the amplified pressure of an increased population. The fee is calculated to offset the increases required in each publicly provided service. The fees charged to the developer are usually invested in a bond which is ultimately used to offset a future municipal utility program increase.

Since public benefits can stem from building a green roof, and because the local municipalities attempt to cover the increases in their municipal utilities with impact fees, a study should be conducted to evaluate the interaction of both LID technologies and the reduction of impact fees. This paper will show that by introducing green roofs to a newly constructed community, the reduction of impact fees or increase of tax abatements can be assessed as the public's benefits increase. With this information, economists, developers, home-builders, and governments can realize a more accurate value for green roofs; they may even be able to foster the growth by understanding and advertising the benefits, both market and nonmarket.

III. Methodology

Chapter Overview

This chapter will discuss and layout the development of the runoff cost model. Involved in the construction of the model are three parts. The first part focuses on the representative community and its representation of what is common in the area of interest (AOI). This portion of the overall runoff cost model is the most modifiable section. The user can change the various building types and sizes, to correspond with an actual area of development or potential construction area. The second part of the model determines the runoff rates from rain event data, percentage green entries, and calculated curve number values. By entering historical rain events for the AOI, the model will project runoff values based on the modified curve numbers and percentage of green roof coverage for the AOI. Finally, the runoff values will be associated with costs to the builder and savings to the municipality. These costs are dependent on geographic construction costs and present value green roof costs.

From the literature review, one can see that there are very few studies that investigate the use of green roofs to mitigate storm water runoff and the associated public benefits of reduced taxes. As shown previously, green roofs do mitigate stormwater runoff. By linking the mitigation of stormwater runoff to the costs of increased capacity and operations of a wastewater treatment plant (WWTP) as well as the storm water distribution systems (SS), one can view green roofs as an infrastructure cost-saving measure applied to the monetary impacts on a municipality.

Representative Community

The mixed-use community data is entered into the runoff cost model using the concept that a representative community can be built to characterize a newly constructed area within a municipality that contains mixed-use buildings, open-space, and roads. By varying the size and lot-layout of each type of zone, the representative community can mirror existing or proposed actions within a community. The specific representative community used in this thesis was measured and planned using existing satellite images, as well as current United States Census data provided by a 2003 survey.

The US Census data was combined with the acreage ratios of the mixed-use area (multi-family, single-family, landscaping, and commercial areas) to create a representative community that would be the model for the imperviousness ratios and curve numbers. Below, Figure 3.1 represents a visual breakout of the mixed-use areas based on the US Census data, while Figure 3.2 is a satellite image with the areas and acreages broken out.

The image of a newly constructed mixed-use area in Beavercreek, Ohio was used to estimate the acreage ratios as well as identify where soil data and rainfall measurements would need to be collected and used in calculations. One reason this area was chosen was due to the minute elevation changes across the actual AOI; the actual geographic area proves to be an ideal model candidate by limiting drainage and velocity calculations based on elevation changes.

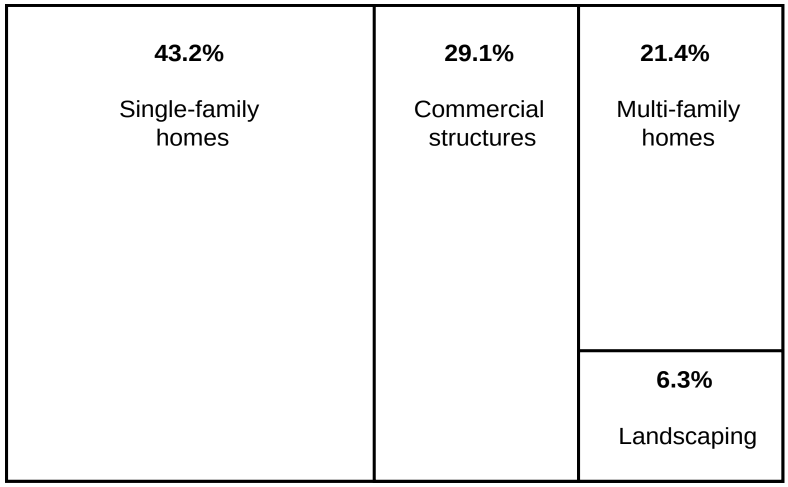


Figure 3.1: Visual percentage breakout of the AOI based on US Census data.

Figure 3.2: Satellite image of area of interest (from Google Maps, 2007)

All the geographic model information was measured and entered into a Microsoft Excel spreadsheet that combined and iterated the various values of curve numbers, rainfall events, percentages of impervious surface, square footage, and percentages of green roof. The next step in the representative community model was to determine the impervious roof areas as potentially pervious due to the addition of green roofs. Figure 3.3 shows the breakout of the impervious roof percentages based on the design of the community and the US Census data.

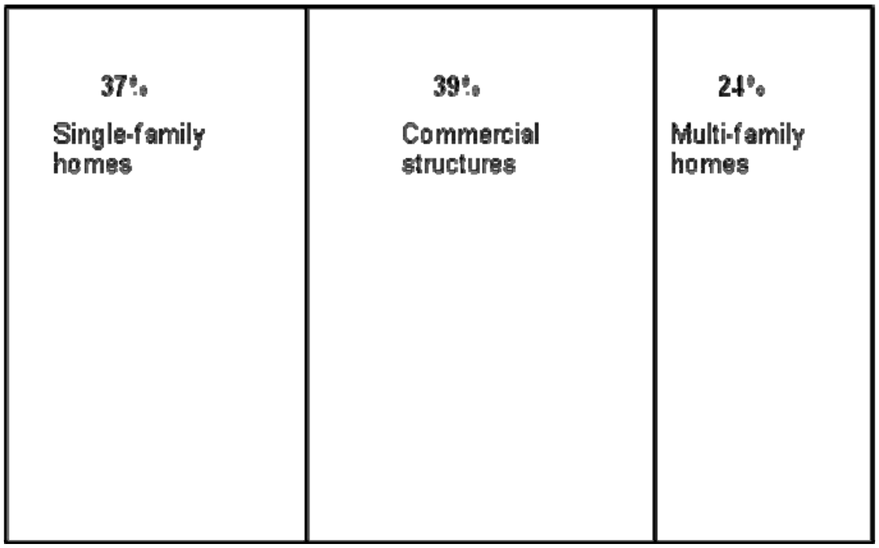


Figure 3.3: Percentage of impervious/pervious roof areas based on design

Runoff Calculations

The runoff cost model is built around the concept of rainfall intensity being translated to direct runoff based on pervious and impervious surface areas. The Society of Soil Conservation (SCS) curve number (*CN*) method for estimating runoff, used by the United States Department of Agriculture (USDA) in the TR-55 manual (Urban Hydrology for Small Watersheds), will be applied in this model to determine various runoff scenarios (USDA, 1986). The TR-55 utilizes the SCS runoff CN equation:

$$Q_{design} = \frac{(P - 0.2S)^2}{(P + 0.8S)} \qquad (3.1)$$

Where: Q_{design} = runoff (in)
P = rainfall (in)
S = potential maximum retention after runoff (in) begins

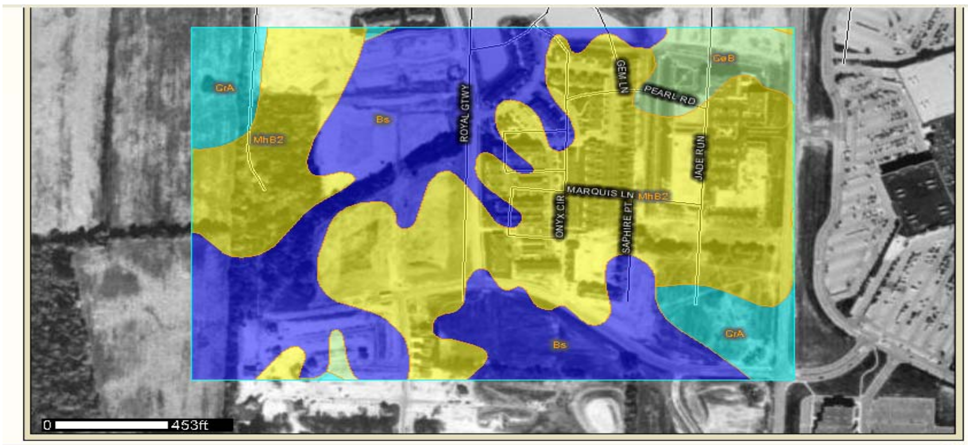
Because the S value is related to the combination of the vegetative coverage and soil conditions of the area of interest, the following equation is used to determine its S value:

$$S = \frac{1000}{CN} - 10 \tag{3.2}$$

Where: CN = Curve Number with a range from 0 to 100

The CN is calculated through various equations based on hydrologic soil groups (HSG), cover types, treatments, hydrologic conditions, and antecedent runoff conditions (ARC) (USDA, 1986). By initially using the pre-construction soil types (which translate to curve numbers which indicate imperviousness ratios during rain events) and utilizing rain event records (the "P (in)" value in equation 3.1) from the National Oceanic and Atmospheric Administration's (NOAA) database for the area of interest, the runoff volume (Q_{design}) in inches can be calculated (Bonin et al., 2004).

For this particular model, the AOI measurements and geographic data, as well as the soil and drainage types (Figures 3.4 and 3.5), were determined and entered from a custom soil resource report for Green County, Ohio from the United States Department of Agriculture and Natural Resources Conservation Service website. (http://websoilsurvey.nrcs.usda.gov, accessed 22 October, 2007) By utilizing these soil classifications, the distinct curve numbers for the different soil types were entered into the TR-55 model using Table 2-2c, “Runoff curve numbers for other agricultural lands” (pg 2-7 of TR-55), and Table 2-2a, “runoff curve numbers for urban areas” (pg 2-5 of TR-55) (USDA, 1986).



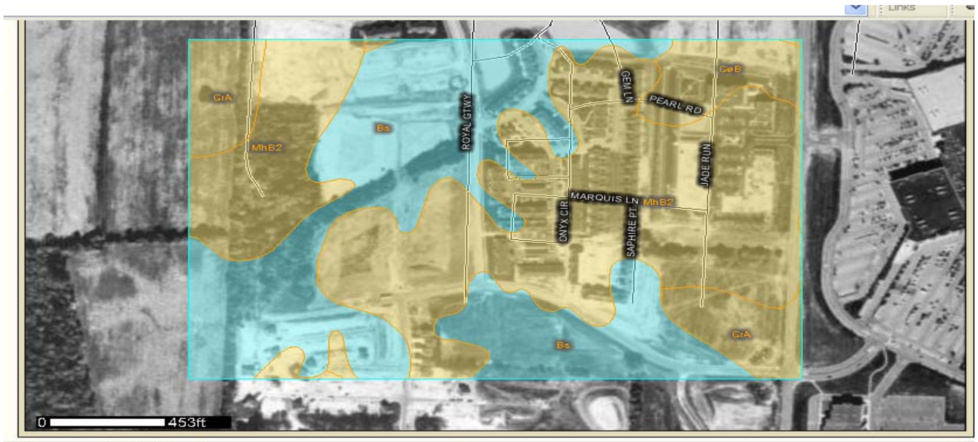
Tables — Drainage Class — Summary By Map Unit

Summary by Map Unit — Greene County, Ohio

Map unit symbol	Map unit name	Rating	Acres in AOI	Percent of AOI
Bs	Brookston silty clay loam	Very poorly drained	34.6	36.9%
CeB	Celina silt loam, 2 to 6 percent slopes	Moderately well drained	4.8	5.1%
CrA	Crosby silt loam, 0 to 2 percent slopes	Somewhat poorly drained	7.4	7.9%
CrB	Crosby silt loam, 2 to 6 percent slopes	Somewhat poorly drained	0.1	0.1%
MhB	Miamian silt loam, 2 to 6 percent slopes	Well drained	0.0	0.0%
MhB2	Miamian silt loam, 2 to 6 percent slopes, moderately eroded	Well drained	46.8	49.9%
Totals for Area of Interest (AOI)			**93.7**	**100.0%**

Description — Drainage Class

Figure 3.4: Soil types from USDA report for Area of Interest (AOI)



Tables — Hydrologic Soil Group — Summary By Map Unit

Summary by Map Unit — Greene County, Ohio

Map unit symbol	Map unit name	Rating	Acres in AOI	Percent of AOI
Bs	Brookston silty clay loam	B/D	34.6	36.9%
CeB	Celina silt loam, 2 to 6 percent slopes	C	4.8	5.1%
CrA	Crosby silt loam, 0 to 2 percent slopes	C	7.4	7.9%
CrB	Crosby silt loam, 2 to 6 percent slopes	C	0.1	0.1%
MhB	Miamian silt loam, 2 to 6 percent slopes	C	0.0	0.0%
MhB2	Miamian silt loam, 2 to 6 percent slopes, moderately eroded	C	46.8	49.9%
Totals for Area of Interest (AOI)			**93.7**	**100.0%**

Figure 3.5: Hydrologic Soil group report from USDA for AOI

The curve numbers from the USDA charts were used in calculating the modified curve number values used in the model for the pre-construction runoff and the post-construction runoff tables. The modified curve number values used in the calculations in the model were varied using the assumptions made below.

Because conventional roofs have a curve number of 98 (pg 2-5 of TR-55) and green roofs have an estimated curve number of 86 based on experimental data (Carter & Jackson, 2007), the curve number per each mixed-use acreage was estimated through interpolation by finding the ratio percentage between *CN* 98 and *CN* 86 based on percentage green (0% green is *CN* 98, 100% green is *CN* 86). Further, because a conventional roof has a *CN* of 98, it is understood that the curve number is not representative of the entire mixed-use lot type (i.e., single-family housing, multi-family housing, or commercial) having the same curve number. What is calculated however, based on individual lots, is the percentage of roof area in a lot, combined with impervious pavements and landscaping area that needs to have an adjusted curve number assigned.

For example, from the model, a commercial site is estimated to have 40,000 square feet of roof space per unit, (based on 13 units from the US Census percentages of commercially mixed areas in an urban area, which is 29% of the total mixed-use area). The roof area curve number is then adjusted based on the green percentage of the roofs. However, the rest of the commercial area must be accounted for based on the remainder of the acreage being pavements and landscaping. However, because the entire commercial lot area is a combination of roof, pavements, and landscaping, the roof curve number is only a portion of the modified curve number calculated previously. Therefore, an adjusted curve number for 100% green roof is calculated, (based on 15,000 square feet of impervious pavements per unit of commercial construction) at 90. A 50% green roof area would have an estimated curve number of 94, and a 0% green roof area would have a curve number of 98. By varying the adjusted curve numbers per mixed-use area, a more concise and correct value of runoff is calculated. The adjusted *CN* is then calculated by combining all the variables of each individual mixed-use area of interest using an Excel version of the TR-55's "Worksheet 2: runoff curve number and runoff" (USDA, 1986).

Next, after finding the proper curve numbers for each percentage of green and zoned property, the model required the input of the rain events. Although there are varying intensities of rain events, lasting from seconds to days, only one-hour rain event intensities were used. This was based on page 1-1 of the TR-55, where it is stated that the design equations were based on the one-hour duration of the event rather than a 24-hour event sometimes used in other design equations (USDA, 1986).

By using the same process for determining the initial value of runoff (Q_{design}), a post-construction runoff value (Q_1) can be calculated using the same area ratios and post-construction curve numbers based on the newly constructed surfaces. Also, by subtracting the pre-construction runoff values (Q_0) from the post-construction runoff values (Q_1), the newly calculated runoff value (Q_{diff}) would be the new construction runoff volume difference.

$$Q_{Diff} = Q_1 - Q_0 \tag{3.3}$$

Where: Q_{diff} = Runoff difference based on new construction and old construction (in)
Q_1 = Post-construction runoff (in)
Q_0 = Pre-construction runoff (in)

One of the main ideas behind the runoff cost model is that by incrementally increasing the percentage of green roof area from 0.0% green roof coverage to 100.0% green roof coverage in the representative community, the post-construction runoff volume can be proportionally lowered, which would create a lower design runoff volume (Q_{diff}). This lower Q_{diff} would then translate into a reduced cost associated with the expansion of existing infrastructure and treatment capacity. One note in this calculation is that Q_{design} is not the same as Q_{diff}. Q_{design} is the actual volumetric flow of storm water outflow that is used to calculate the overall costs of expanding both infrastructure and treatment capacity. Q_{diff} is the subtracted volumetric flow used to delineate the differences between doing no green (100% impervious roof areas) and total green (100% pervious roof areas).

Cost Modeling

The final step in the runoff cost model is the costing portion. To determine the costing portion, construction costs, life-cycle costs, and investment rates must be identified. Each portion of the WWTP and the SS expansion were designed and priced according to labor rates in the Dayton, Ohio area.

The wastewater treatment costs were determined from actual operating, maintenance, and labor costs gathered from various sources of municipal and county wastewater treatment plant cost data[2]. By multiplying the "per gallon" cost of increased capacity with the runoff volumes from the construction (calculated previously in the model), a present value cost of wastewater treatment plant expansion per gallon was found. Although more modern municipal wastewater treatment plants have the ability to "absorb" increased runoff volume from new development in an area due to good design foresight, it was assumed that the local plant would need to account for every increase to the current treatment capacity. This can be clarified as either a direct expansion cost to the plant before construction is begun or a lump-sum investment made to the municipality-managed fund for future expansion to the existing plant. These costs were

[2] Because expansion costs vary greatly across the United States, only Ohio municipal WWTP expansion costs were used in the calculated average.

then figured for each level of green roof coverage and the individual rain events. The costs to expand the WWTP became a "linear-curve" function of runoff.

As with the wastewater treatment plant expansion costs, the storm sewer expansion costs depend primarily on the stormwater runoff volumes. The pipe sizes for the distribution system must be sized to the appropriate runoff or discharge (Q). By utilizing the Q values in cubic feet per second (cfs) for each green percentage and rainfall event, tables from Appendix 5A (Haan et al., 1994) were examined to determine the appropriate size of pipe. In some instances, more flow did not translate into a larger sized pipe.

By utilizing the Parametric Cost Engineering System (PACES)[3], the cost of demolishing and removing the old distribution system and installing the new system (including all labor rates, equipment, taxes, and mobilization fees) was calculated as a per foot cost based on each change in pipe size. Although the demolition, pavement, landscaping, and various other costs would remain constant no matter what size pipe was installed, the actual construction costs of each assorted sized pipe was what varied the cost across the different storm water runoff volumes. The costs to increase the SS expansion became a "step-wise" function of runoff.

With the majority of the infrastructure costs accounted for, the installation and maintenance costs are then added. Because green roofs cost on average almost two times as much as conventional roofs to install initially, the life-cycle costs must be examined.

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[3] Cost analysis software used by the Army Corps of Engineers, the United States Air Force, and other Federal agencies was developed by Earth Tech. (http://talpart.earthtech.com)

From various studies addressed in the literature review, the cost of a green roof used in the model was \$190/square meter installed over a 36-year life span, with maintenance accounting for 1% of the initial installation cost per year (Montalto et al., 2007). For the conventional roof, a cost of \$92/square meter over a 12-year life span with maintenance accounting for 1% of the initial installation cost per year. In the model, these costs were determined over the 36-year life of the green roof, discounted at a 4.8% interest rate based on the September 18, 2007, Federal Reserve interest rate.

Using engineering economics calculations for deferred annuities for the conventional roof, and then converting those payments to a present value, the model is able to estimate the per square meter cost of the conventional roof at time zero. (Eschenbach, 2003)

$$(P/A,i,N) = \frac{[(1+i)^N - 1]}{[i(1+i)^N]} \tag{3.4}$$

$$(P/F,i,N) = (1+i)^{-N} \tag{3.5}$$

Where: P = present value
A = annuity payment
i = interest rate
N = number of payments

In this same vein, the model could calculate per square meter cost of the green roof at time zero using equations (3.4) and (3.5). The green and conventional cost per square meter values were converted to cost per square foot values and then multiplied by the square footage of green roof coverage and conventional roof coverage over the entire

AOI as determined by the percentage "green" established by the model user. Although the model assumes a "per meter" installation cost regardless of roof size, in reality, the larger the square footage per unit, the cheaper installation costs will be per unit. In other words, a 3,000 square foot house green roof installation project will cost much more per square foot to install than a 40,000 square foot warehouse.

Benefit Equation

From the methodology, a public benefit equation can be investigated as a function of the following:

$$\Psi = f(S, W_c, Q_e, I_{cn}) \tag{3.6}$$

Where: Ψ = Public Benefit
S = Percentage of green roof
W_c = Combined costs of WWTP and SS updates
Q_e = Water volume based on rain event
I_{cn} = Area coefficient

The following general relationships are estimated through trends of holding all other variables constant while adjusting the investigatory variable and observing the public benefit changes.

First, as S increases, Ψ increases to a certain value. After the minimum point on the runoff cost curve is reached, Ψ then decreases proportionally. Second, as W_c increases, Ψ decreases. Third, as Q_e increases, Ψ increases as shown on the runoff cost curves based on the entire range of S values. Fourth, as I_{cn} increases, the Ψ decreases significantly. I_{cn} can be defined further as the following:

$$I_{cn} = f(\alpha, \beta, \delta, \varepsilon, \phi, \lambda) \tag{3.7}$$

Where: I_{cn} = Area coefficient
α = Building type ratios
β = Area of investigation
δ = distance to catchment
ε = elevation changes in the AOI
ϕ = conventional/green roof ratio
λ = pervious/impervious ratio

Model Review

To determine the monetary benefit of a green roof, the model includes a present worth analysis based on the values found in the current literature. The assumptions made and the costs associated with these assumptions are in the following table.

Table 3.1: Table of model inputs

Item	Cost
Green Roof (installation)	$190/m^2
Conventional Roof (installation)	$92/m^2
O&M (green & conv)	1% of installation
Wastewater treatment plant construction costs	$4.28/gal increase
Rate of Return	Principle on 30-yr bond invested at 4.8%

The model created for this thesis was designed to be dynamic to accommodate changes in various values and costs over time as well as different geographic regions. The overall calculations gathered from the model are a combination of values from rain event data from NOAA, curve number calculation data and soil specific drainage properties from the USDA, wastewater treatment plant costs from average construction costs in Ohio, storm sewer distribution network construction data from PACES, green roof and conventional roof construction costs from various peer-reviewed studies, and demographic housing and commercial property data from the US Census Bureau. With those set values, the user can vary the percentages of green roof coverage, ratios of construction type, and acreage investigated in the AOI. Overall, this model is both dynamic and flexible enough to be used anywhere in the United States that construction, rain event, demographic, and cost data are available.

IV. Results and Analysis

Chapter Overview

This chapter discussed the model results and analyzes the gathered data to show trends or patterns within the area of interest. As mentioned in the beginning of Chapter III, the ten levels (0.0% through 100.0% in 10% increments) of green roof coverage were input into the model, curve numbers were calculated, and volumetric flow potentials were produced. Concurrently, the ten historic measured rain flow events for the area of investigation (AOI) were entered into the model, which produced volumetric discharges (Q) that were run against cost data for construction and expansion of new and existing stormwater infrastructure.

Because the model was robust enough to handle various iterations of data changes, various scenarios were entered based on findings from different papers. Initially, both the curve number method (Carter & Jackson, 2007) for volumetric discharge (gallons per hour), as well as the rational number method (Montalto et al., 2007) for time variable flows (acre-in/hour), were used to calculate the discharges separately for comparison purposes. However, after reviewing various Environmental Protection Agency (EPA) and United States Department of Agriculture (USDA) reports on small-area watershed calculations and reviewing the rational number method and outputs used by Montalto et al., (2007) it was decided that the curve number method was more appropriate for the AOI and data used as well as for ease of modeling.

The data produced was organized into tables of costs as related to green percentage and rainfall event. Next, the costs were graphed against the percentage green, per rain event. Each cost curve for each rain event was the sum of a number of curves. The "water costs" curve was the sum of the wastewater treatment costs and the expansion of the storm sewer infrastructure costs per percentage green. The "roof costs" were the sum of initial green and non-green construction costs as well as the replacement and maintenance costs for roofs, both green and conventional per percentage green.

The "water costs" added to the "roof costs" become the "combined costs." This "combined costs" line is then overlaid on the "non green costs" line. The "non green costs" line is the sum of all wastewater treatment plant expansion, storm sewer infrastructure expansion, and all conventional roof costs with no percentage of green roof coverage, or the status quo. Below are the 25-year rain event curves for each percentage of green.

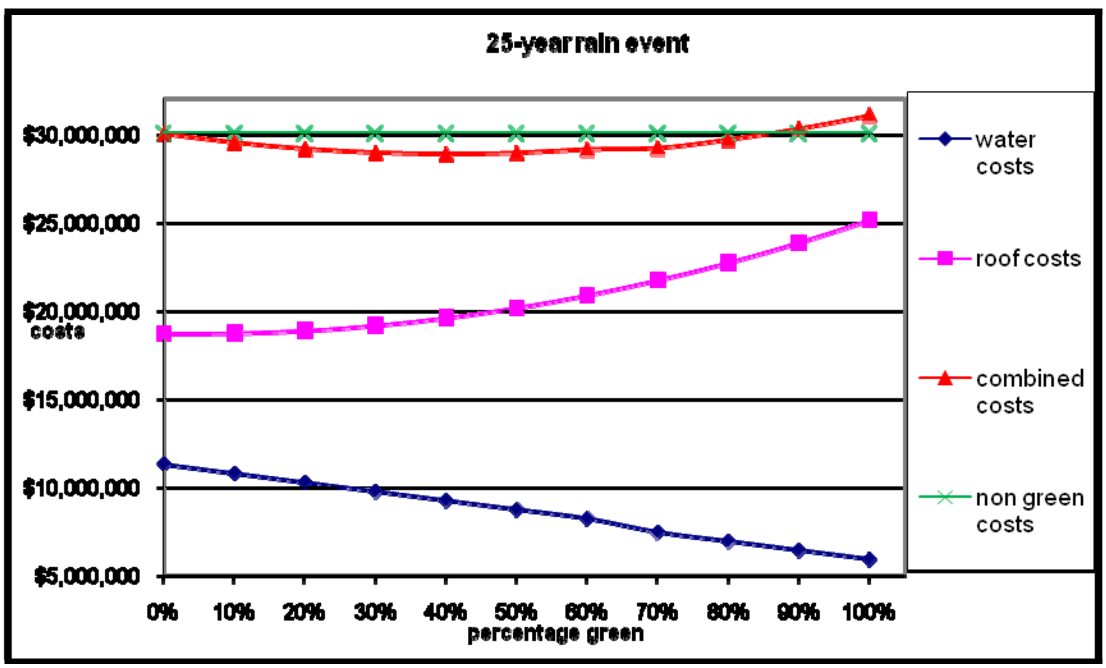

Figure 4.1: 25-year Rain Event Cost Curves

As seen from the Figure 4.1, a green coverage of 40% will provide the minimum cost (US$28,904,828) to the developer, while maximizing the benefits to the community. Although design events vary from municipality to municipality, the standard event is between a 10-year event and a 25-year event. Because of this range, the model will use the greater design standard of the 25-year event (ASCE, 1998). Next, by combining every rain event's combined cost curve into one graph (Figure 4.2) the user can see a trend of zero slope curves rising from 20% (for a 1-year rain event) to 80% (for a 1000-year rain event) green roof coverage. The graph also shows that as rain events increase in year-size, the percentage green that corresponds to a zero-slope on the curve also increases.

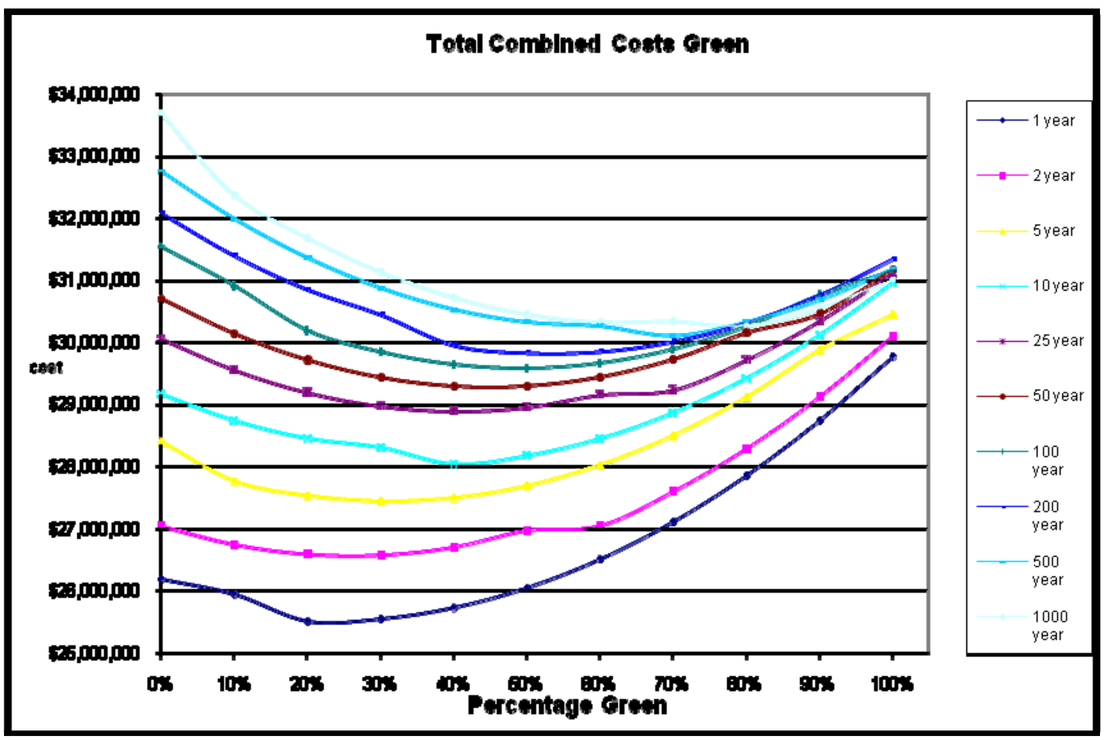

Figure 4.2: Overall graph of curves for costs verses rain events.

From Figure 4.2, one can interpret that costs are dependant on the rain event. At the beginning of each curve (0.0% green), there is a slight decrease in slope, or drop in cost, as the percentage of green rises. At 0% green roofs, there exists no public benefit, while costs to the developer are only the minimum expenditures on infrastructure construction. As the percentages of green increase (according to each rain event), the curves approach a slope of zero (between the 20.0% and 80.0% percentage green) and the construction costs are minimized. This correlates to the developer installing some green roofs, at a higher premium, which in turn, provide some public benefit that could be, in theory, reimbursed to the developer. After the slope has gone to zero, each curve rises again as the costs of green surpass any public savings that may be realized by the developer based on the reduction of runoff. Therefore, based on rain event, geographic area, hydrologic soil properties, and other discussed model attributes, there is an actual percentage of green roof coverage for the area that would be the most cost effective. In our case, by designing to the 25-year rain event, as many municipalities do, the most cost effective green roof percentage is 40%.

Sensitivity

A formal sensitivity analysis was not accomplished due to complexity of the model; however, various ranges of input data were entered in each variable category to visually distinguish what influenced costs on the curve plots. Although most of the data changes showed little influence (less than a 5% change on the cost curves), there was one item that dramatically changed the curves based on minute changes in the initial data. As the per-square-foot cost of conventional roof replacement went down (based on the present value calculated cost of conventional roofs), the zero-slope on the individual rain event curve moved left, corresponding to a lower percentage of green coverage. For example, when the replacement cost for the conventional roof was at $76.51 a square foot, (time-zero cost of the three life-time replacements at 4.0% interest rate), the zero-slope point for the percentage green on the 25-year rain event cost curve was minimized at 50% green. However, when that same replacement cost was changed to $54.26 (time-zero cost of the three life-time replacements at a 5.0% interest rate), the zero-slope point for the percentage green on the 25-year rain event cost curve was minimized at 40% green. This sensitivity to interest rate and cost of replacement should be actualized either in future research or more precisely to geographic area of construction. These differences could provide large varying percentages that could skew actual savings. However, because of the aggregate view taken by this model, the interest rate used and cost of replacement roof are particular to this version of the runoff cost model.

V. Conclusions and Recommendations

Chapter Overview

In this chapter, the results from the model are discussed in accordance with the savings that can be realized and the percentages of green roof to be built. Next, the various options of green roof coverage on the area of interest will be discussed. Also, the methods of encouragement from the municipality will be discussed as how to encourage the developer to build green. Finally, the significance of this thesis and ideas for future research are discussed.

Percentages of Green Roof

From Chapter IV, it was shown that, based on the 25-year rain event, the percentage of green coverage to minimize costs was 40%. From the model's geographic area of interest (AOI), this would account for approximately 559,000 square feet of overall roof space to be green roof space. This would then leave approximately 838,000 square feet as conventional roof space.

These percentages could be viewed in three different ways. First, 40% green roof space on 100% of the single-family houses would result in only 519,000 square feet of green roof. This is only 92.8% of the needed green roof coverage which would produce less estimated savings to the municipality as projected by the runoff model. Because of individual small roof areas (2,469 sf/unit), the installation costs could be much higher per square foot than if installed on fewer roofs with a much larger area. This would also mean that there would be much higher instances of maintenance or repair issues due to the volume of green roofs installed on such small, individual areas (210 units). Finally, because of economies of scope, the savings realized by the owners on an individual, energy-saving level would be much less than on a larger building with a green roof.

The second way this could be viewed would be to mix the percentages of green roof covering area for both the larger single family houses and the entirety of the multi-family houses. Therefore, the smaller amount of individual roofs would provide a cheaper installation cost to the developer, as well as a smaller sample of potential maintenance issues. However, with 100% of the multi-family houses having installed a green roof, only 359,000 square feet of roof could be covered in green roof, leaving 200,000 square feet of single-family houses to be covered with green roofs. This would mean that in total, 16 multi-family houses, and 82 single-family houses would need to be green roofed. This is reminiscent of the first option; the more roofs that must be covered, the higher the cost per square foot. Additionally, with a smaller roof area, the building owner will see fewer savings. This option would also require tax code changes in most of the nation's municipalities, more that 25,000 nationwide, to implement the impact fee reduction for the building of the green roofs for the residential areas. This will be discussed later in the chapter.

Finally, the most cost-effective option would be to cover the entirety of the commercial structures. Commercial structures tend to be the larger in square footage which translates to a larger roof area per unit. Although the commercial roof area only corresponds to 29.1% of the area of interest, this still provides 520,000 square feet of roof space, which amounts to 93.4% of the area needed to be green roofed. With this volume of units (13 buildings), two additional multi-family structures, or 16 additional single-family houses, would result in the calculated savings from the runoff model. The commercial building green roof coverage option would be the highest ratio of square footage to unit number of any option and would result in the lowest cost per square footage installed. This option would also provide potential tax abatement savings to the businesses that build the green roofs and operate the commercial facilities based on municipal policy. Additionally, tax abatement policies are currently in place in most states that allow firm negotiations regarding rates and specifics between the municipalities and commercial businesses, furthering the concept that green roof based commercial tax abatements could easily be entered into practice. As noted previously, the 520,000 square feet is 39,000 square feet less than the 559,000 required for the 40% green roof coverage to meet the "low cost" point of the curve. However, the 520,000 square feet of green roof coverage does fall very closely within the area of percentage green that will still realize the majority of the savings (93.4% rather than the 100% green roof coverage needed for 559,000 square feet).

Putting into Practice and Significance of Research

The cost-runoff model was primarily directed towards capturing the public savings associated with green roofs, or more precisely, the public sector cost savings due to the water systems. It was found was that green roofs can reduce the public costs of stormwater distribution networks and wastewater treatment expansions. However, the introduction of green roofs will probably raise private sector costs, both in maintenance and installation.

The lowering of public and private sector costs vary with both residential and commercial activities. The two options most readily available to lower these costs are reduction of impact fees for residential buildings and tax abatements for commercial construction. In locations without impact fees, a portion of the property taxes are dedicated to the wastewater treatment and distribution. However, private sector adoption can be very costly, administratively.

Both residential and commercial areas of construction were investigated in the model. What was found was the commercial roof area most closely matches the desired green percentage with the smallest number of structures to be covered. In addition, the high administrative costs of residential adoption, coupled with the more established tax abatement codes for commercial construction establishes that the commercial building option should be investigated further. Although the "warm glow" has an effect on building green as mentioned in Chapter II, installing a green roof for the consumer comes down to the bottom line of installation costs compared to conventional roof costs. As stated previously, green roofs are not as cheap, initially, to install as conventional roofs. However, the monetary benefits provided, both private and public, outweigh the cost difference.

Because the large commercial structures are built by either the developer, or a builder that will do more than just one structure in an area, cost-saving measures are of interest. A builder desires to minimize construction costs so as to increase profit on the sales price of the facility. Choosing a green roof over a conventional roof will lower the builder's profit margin or, when the cost is passed on to the buyer, will raise the sales price and make it less competitive in the commercial real estate market. However, by adopting tax abatements or a reducing impact fees, the up-front costs can again become negligible.

In this model, to lower the impact of building a green roof on the builder and buyer, the municipality could offer a tax abatement to offset the cost of the green roof. The length or amount of tax abatement would be dependent on the situation, but using the current model, the difference in price per square meter based on the life cost of the roof should be the starting point. For example, because the difference in the installed cost of the first green roof compared to the three roof installations of the conventional roof is $3.76 per square foot, and the square footage of the development is 559,000 square feet, the amount to be reimbursed by the tax deferments would be the price difference multiplied by the green roof area. The value from this example iteration from the model is $2,101,840. Because this amount would be tax deferred to the builder, this could be considered a lost income potential to the municipality.

However, this can be shown as a wise investment for the municipality. By strategically allowing deferment over a set period of time for a predetermined amount, the municipality can recoup its lost value by not having to invest property taxes into the current water treatment systems. It should be noted that the costs of wastewater treatment plant expansion and storm sewer infrastructure expansion would be primarily a public cost, financed through property taxes. Although the point of impact fees is to cover those costs, some portion is still the responsibility of the municipality.

In the runoff cost model, the Table 5.1 is an example of the public costs associated with the 40% green roof coverage verses the status quo of conventional roofs.

Table 5.1: Public Costs

Public Item	*Conv. Roof (0%)*	*Green Roof (40%)*
Tax Abatement	$0	$2,101,840
WWTP Costs	$9,011,287	$6,956,744
SS System Costs	$2,559,738	$2,326,518
Total	**$11,571,025**	**$11,385,102**

Based on the 40% green roof coverage for the model area of interest, and utilizing the difference between green and conventional roof prices tax abatement, the public infrastructure costs alone will save the municipality $185,923. However, more creative investments and tax abatements can be investigated to provide an even greater savings.

In a more aggregate view (combining ratios of green and conventional roof building), the overall public and private savings associated with constructing the 40% green roof coverage is between $800,000 to $3,324,000 (based on rain event design). What are not captured in this runoff-cost model are the other externalities and private benefits that increase the value of this technology. Reduced energy costs, cleaner runoff, cleaner air, reduction of the heat island effect, increased biodiversity, and other non-market items could potentially be captured to show an even greater value to the public.

Recommendations for Action

The runoff model and associated discussion proposes the adoption of this model for communities that are facing infrastructure cost problems as well as communities that are interested in fostering sustainable developments within its area. This would permit a community to vary the impact fees or offer tax abatements to sustainable-designed developments based on the public cost savings of both infrastructure expansion and continuous water treatment operations. This model differs from existing research and cost models in that it explicitly addresses the cost of the private investment over the lifetime of both roof types and includes the potential public savings realized by the municipality. What is not included, but that can be inferred from current research, are the potential private savings realized by the building owners themselves, in both yearly energy savings and maintenance cost reductions.

Although this runoff cost model was based on the geography and specific hydrological soil data for a specific area, it could be altered and applied to any municipal region in the World interested in developing cost models to stimulate sustainable development. In many cases, green roofs will not be a cost effective choice based on both rain events and geography. However, by entering the data for the area into the runoff model, the magnitude of cost and saving margins can be calculated which could be used to encourage further investigation.

Recommendations for Future Research

Future research should be focused on identifying weaknesses in the model and verifying the data produced through actual studies. By investigating deeper the hydrologic equations, areas of watershed, and various other calculations in the model, more precise values could be attained.

Another area of future research is the various geographic regions and weather zones throughout the world. These areas could be tested to see if they agree with the findings in this thesis. Those inputs could be used to create a more universal model containing more significant variables relating to elevation changes, temperature extremes, and other significant implications.

Finally, other environmentally-friendly technologies should be researched as to their investment potential for municipal applications. Green roofs may have been the focus of this thesis, but other "green" technologies could be thoroughly investigated in other runoff-cost type models to determine the investment and cost savings potential. The more research that is done as these green technologies advance, the more cost efficient and available they will become.

In addition to the sensitivity of the interest rate varying the cost curves, the private benefits of green roof construction were not entered into the runoff-cost model, which very well could vary the thresholds of cost effectiveness. This model was focused primarily on public benefits, rather than private.

Appendix

Please see attached CD-ROM disc for the cost-runoff model, results, and graphs.

Bibliography

Acks, Kenneth. 2005 "A Framework of Green Roof Cost-Benefit Analysis: Initial Estimates." *Green Roofs in the New York Metropolitan Region: Research Report I,* (eds) Rosenzweig, C., Solecki, W. and C. Cheney, in press.

Andreoni, James. 1990 "Impure Altruism and Donations to Public Goods: A Theory of Warm-Glow Giving." *The Economic Journal*, Vol. 100, No. 401 (Jun., 1990), pp. 464-477

ASCE (American Society of Civil Engineers), WEF (Water Environment Federation). 1998 "Urban Runoff Quality Management." *ASCE Manual and Report on Engineering Practice No. 87, and WEF Manual of Practice No. 23*

Banting, Doug., Doshi, Hitesh., Li, James., Missios, Paul. 2005. "Report on the Environmental Benefits and Costs of Green Roof Technology for the City of Toronto." Report prepared for the City of Toronto, October 31, 2005.

Been, Vicki. 1991. "Exit" As a Constraint on Land Use Exactions: Rethinking the Unconstitutional Conditions Doctrine. *Columbia Law Review* 91:473.

Carter, Timothy., Jackson, C. Rhett. 2007. "Vegetated Roofs for Stormwater Management at Multiple Spatial Scales." *Landscape and Urban Planning*, No. 80 (2007) 84-94.

Eschenbach, Ted. 2003. *Engineering Economy, Applying Theory to Practice,* New York: Oxford University Press, Inc.

Getter, Kristen L., Rowe, D. B. 2006. "The Role of Extensive Green Roofs in Sustainable Development." *HortScience*, Vol. 45, No. 5, pp. 1276-1285.

Google Maps. 2003. Image of Beavercreek, Ohio development accessed from www.maps.google.com on 7 October, 2007. Modified with outlines and text by Luke Stumme on 12 October, 2007.

Haan, Charles T., Barfield, B. J., Hayes, J. C. 1994. *Design Hydrology and Sedimentology for Small Catchments*, San Diego: Academic Press, Inc.

Hamilton, Stephen F., Zilberman, David. 2006, "Green Markets, Eco-Certification, and Equilibrium Fraud." *Journal of Environmental Economics and Management,* 52 (2006) 627-644.

Ihlandfeldt, Keith R., Timothy M. Shaughnessy. 2004. "An Empirical Investigation of the Effects of Impact Fees on Housing and Land Markets." *Regional Science and Urban Economics* 34 (2004) 639– 661

Kaufman, Andrew., Cox, Linda, J., Muira, Tomaoki., Easterday, Dawn. 2007. "The Potential for Green Roofs in Hawai'i." *Resource Management*, RM-15, February, 2007

Kibert, Charles J. 2005. *Sustainable Construction: Green Building Design and Delivery*, Hoboken: John Wiley & Sons, Inc.

Kosareo, Lisa., Ries, Robert. 2006. "Comparative Environmental Life Cycle Assessment of Green Roofs." *Building and Environment*, Vol. 42 (2007), pp. 2606-2613.

Laurence, Michael. 2003. "Square Footage Measurements and Comparisons: *Caveat Emptor*." *2001 Residential Energy Consumption Survey*, Published 2003 by the Energy Information Administration under the United States Department of Energy

Marmor, Jessica. 2007. "Pound by Pound, Dollar for Dollar, the Complicated Equation for Going Green." *Wall Street Journal,* April, 20 2007.

MDE (Maryland Department of the Environment) WWTP fact sheet (25 Oct 2005): www.mde.state.md.us/assets/document/BRF-Attach2WWTPFactSheets101905.pdf accessed 1 December, 2007.

Montalto, Frank., Behr, Christopher., Alfredo, Katherine., Wolf, Max., Arye, Matvey., Walsh, Mary. 2007. "Rapid Assessment of the Cost-Effectiveness of Low Impact Development for CSO Control, *Landscape and Urban Planning,* No. 82 (2007) 117-131.

Morgan, Ben. 2004. "An Evaluation of Vegetated Roofing Technology: Application at Air Force Plant Four, Building 15." Graduate Thesis, Air Force Institute of Technology.

Mullen, Clancy. 2007. "National Impact Fee Survey: 2007." Published by Duncan Associates on August 22, 2007 in Austin, TX.

Bonnin, G.M., Martin, D., Lin, B., Parzybok, T., Yekta, M., Riley, D. NOAA, National Weather Service. 2004. *Point Precipitation-Frequency of the United States* NOAA Atlas 14, Volume 2, Version 3. From the Xenia Treatment Plant, Ohio (33-9357). Extracted 23 Oct 2007.

Perry, Michael. 2003. "Green Roofs Offer Environmentally Friendly Alternatives." *Plant Engineering Magazine*, 2003. Article. 20 Aug 2003.

Pollack, Wendy. 2007. "Few Homebuyers Pay Up for Green Features." *Wall Street Journal,* February 2, 2007.

Scholz-Barth, Katrin. “Green Roofs: Stormwater Management From the Top Down,” *Environmental Design and Construction*, January 2001.

Smith, Kerry., Haefen, Roger., “Welfare Measurement and Representative Consumer Theory.” Resources for the Future Discussion Paper, Published April 1997

U.S. Department of Agriculture. 1986. “TR-55, Second Edition”, *Urban Hydrology for Small Watersheds*, Published June 1986 by the United States Department of Agriculture, Natural Resources Conservation Service, Conservation Engineering Division

U. S. Environmental Protection Agency. 2000. “Low Impact Development (LID), A Literature Review”, EPA-841-B-00-005, Published October 2000 by the EPA, Office of Water

Wong, Nyuk H., Tay, Su F., Wong, Raymond., Ong, Chui L., Sia, Angelia. 2002. “Life Cycle Cost Analysis of Rooftop Gardens in Singapore.” *Building and Environment*, Vol. 38 (2003), pp. 499-509.

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Captain Luke David Stumme grew up in Boulder, Colorado and graduated from the Colorado School of Mines in December 2001 with a Bachelor of Science degree in Engineering, Civil Specialty. He worked as a civil engineer for Rocky Mountain Consultants and as a research assistant in the Biomechanics laboratory at the University of Colorado Health Sciences Center before entering the US Air Force through Officer Training School in September 2003. Since commissioning, Luke has served as a project engineer, SABER chief, and programmer at the 89th Civil Engineer Squadron, Andrews Air Force Base, Maryland. He was also deployed to the 506th Expeditionary Civil Engineer Squadron in support of Operation Iraqi Freedom in January 2005 to May 2005. He currently is attending the Air Force Institute of Technology as a Master's student in the Graduate Engineering Management program.

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New growth within established communities puts undue pressure on existing infrastructure which in turn, drives tax rate increases for all residents to cover. However, there are sustainable methods that municipalities can turn to that diminishes the local impacts of new growth on the community. Based on the absorptive nature of green roofs, the delayed release of stored rainfall volume diminishes the instances of combined sewer outflows as well as reduces the need for increased infrastructure to convey and treat stormwater discharge. A municipality can introduce planned percentages of green roof coverage which will diminish infrastructure improvement costs over time and increase the population's sustainable footprint. By employing the curve number method for determining runoff volumes from specific rain events and attaching cost-per-unit increase values to the interacting variables, the runoff-cost model produces cost curves in relation to the percentages of green roof coverage. From this runoff-cost model, (based on a specific area), a calculated 40% green roof coverage can be fully reimbursed to the builders through tax abatements, eliminating the perceived cost premium of green over conventional roofs.

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