Spring 2014

# Retrofiting LID Practices into Existing Neighborhoods: Is it Worth It?

Timothy Wright
*Purdue University*

## Recommended Citation

Wright, Timothy, "Retrofiting LID Practices into Existing Neighborhoods: Is it Worth It?" (2014). *Open Access Theses*. 282.
https://docs.lib.purdue.edu/open_access_theses/282

Graduate School ETD Form 9
(Revised 01/14)

# PURDUE UNIVERSITY
## GRADUATE SCHOOL
## Thesis/Dissertation Acceptance

This is to certify that the thesis/dissertation prepared

By Timothy John Wright

Entitled
Retrofitting LID Practices into Existing Neighborhoods: Is It Worth It?

For the degree of Master of Science

Is approved by the final examining committee:

Dr. Bernie Engel

Dr. Natalie Carroll

Dr. Larry Nies

To the best of my knowledge and as understood by the student in the *Thesis/Dissertation Agreement. Publication Delay, and Certification/Disclaimer (Graduate School Form 32)*, this thesis/dissertation adheres to the provisions of Purdue University's "Policy on Integrity in Research" and the use of copyrighted material.

Approved by Major Professor(s): Dr. Bernie Engel

Approved by: Dr. Bernie Engel 04/24/14

Head of the Department Graduate Program Date

# RETROFITTING LID PRACTICES INTO EXISTING NEIGHBORHOODS: IS IT WORTH IT?

A Thesis

Submitted to the Faculty

of

Purdue University

by

Timothy J Wright

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science

May 2014

Purdue University

West Lafayette, Indiana

In memory of my Mom

&

For Nina and her Family

# ACKNOWLEDGEMENTS

I would like thank the following people for making this possible:

Dr. Laurent Ahiablame, his research with the L-THIA LID model provided a foundation for mine and his insights helped me though many issues

Dr. Bernie Engel, for guiding me throughout this process

Dr. Natalie Carroll and Dr. Larry Nies, for agreeing to be on my graduate committee and for their insights and suggestions

Sarah Wright, for her work in editing the many drafts of this document

# TABLE OF CONTENTS

# LIST OF TABLES

Table Page

Appendix Table

# LIST OF FIGURES

Figure Page

Figure Page

Figure Page

Figure Page

Appendix Figure

# ABSTRACT

Wright, Timothy J. M.S., Purdue University, May 2014. Retrofitting LID Practices into Existing Neighborhoods: Is It Worth It? Major Professor: Bernard Engel.

Low impact development (LID) practices are gaining popularity as a way to manage stormwater close to the source. This reduces infrastructure requirements and helps to maintain hydrologic processes close to predevelopment conditions. Studies have shown LID practices to be effective in reducing runoff and improving water quality. However, little has been done to aid decision makers in selecting the most effective practices for their needs and budgets.

To this end, the L-THIA LID model has been applied. Using readily available data sources, multiple scenarios can quickly be examined, and then analyzed to determine the cost of implementation and the approximate period needed to see a return on the investment. This has been demonstrated by modeling four neighborhoods in greater Lafayette, Indiana using the L-THIA LID model to estimate the levels of runoff reduction that could be achieved through retrofitting LID practices. Based on LID practice cost of implementation, the payback period was determined for each practice. Depending on the LID practice and adoption level, 10 to 70 percent reductions in runoff volumes could be achieved. Cost per cubic meter of runoff reduction was highly variable depending on the LID practice and the land use it was applied to, ranging from around $3.00 to almost $600.00. In some cases the savings from reduced runoff volumes paid back the LID practice cost with interest in less than 3 years, while in other cases it was not possible to generate a payback. This information can help decision makers establish realistic goals and make informed decisions regarding LID practices before moving into detailed designs, thereby saving time and resources.

# CHAPTER 1. INTRODUCTION

## 1.1 Introduction

Low impact development (LID) practices for stormwater management have gained popularity as a cost-effective alternative to meet increasingly strict requirements for water quality and controlling runoff volumes on new construction. As a result, there has been a large body of scientific literature published detailing the effectiveness, benefits, and uses of individual methods in new construction or test bed settings. Some of the known benefits associated with LID practices include filtering out pollutants, decreasing urban heat island effects, and allowing increased infiltration (Dietz 2007). One of the major benefits of LID methods is the decreased volume of runoff, as many of the methods are designed to capture or allow stormwater to infiltrate into the soil (Davis 2005).

Stormwater is particularly a problem in urban areas where high percentages of impervious surfaces can generate large volumes of runoff (Ando and Freitas 2011). Traditionally, the method for dealing with this water has been to get rid of it as quickly as possible using drains and pipes to move it to the nearest body of water. The problem with this method is that many older developed areas used combined sewer systems, in which the same pipe network is used to carry both storm and waste water (USEPA 2004).

There are two problems with these systems. First, both municipal waste water, which needs to be treated, and stormwater, which does not need treated, are delivered to the treatment plant; requiring larger treatment plants to accommodate the volumes generated by these combined flows. The second major problem is that during intense storms, the volume of stormwater can exceed the capacity of the system, causing a mixture of water and municipal waste to discharge into rivers or lakes, an event known as a combined sewer overflow (CSO) (Gunderson et al. 2011). An overflow event occurs when the treatment facility is overwhelmed, causing the system to overflow through an outlet structure and dump a mixture of stormwater and raw sewage into the local waterways (USEPA 2004). These systems often have an emptying time of about 12 hours, meaning that when a series of storms moves through, the system does not have its full capacity available, thus increasing the likelihood of an overflow event (Vaes and Berlamont 2001). Overflow events can also lead to large fines for cities (Buranen 2013).

The alternative to a combined sewer system is a sanitary sewer system. In a sanitary sewer system, municipal wastewater is collected and transported through a network of pipes to the water treatment plant (USEPA 2004). With these systems only small amounts of water infiltrate into the system from the ground or stormwater (USEPA 2004). Municipalities with these systems often use a separate storm sewer system to convey runoff and snow melt to local water bodies (USEPA 2004). This poses some environmental concern, because urban runoff can contain many pollutants (Makepeace et al. 1995), which in a separated storm sewer may not receive treatment.

Sanitary sewers can still overflow releasing raw sewage into the environment (USEPA 2004). These events are known as sanitary sewer overflows (SSO) and are typically caused by insufficient capacity, failures, or damage to the system (USEPA 2004). These SSOs are generally controlled through proper design and maintenance of the system (USEPA 2004).

In a retrofit situation, it appears LID practice adoption has the potential for significant savings and to improve water quality (Gunderson et al. 2011; USEPA 2007). This is especially true in areas that are part of a CSO. Traditional approaches for CSO management typically involve separating the conveyance systems for municipal wastewater and stormwater, constructing large underground storage tunnels, and upgrading existing treatment facilities to handle increasing volumes (Gunderson et al. 2011). While these approaches are effective in controlling CSO events, they are also very expensive (Gunderson et al. 2011). Locally, the city of Lafayette, Indiana, completed an $18.5 million CSO storage tunnel in the summer of 2009 (TunnelTalk 2009).

LID practices offer an alternative to these traditional methods for stormwater management by reducing the volume of stormwater entering the system, focusing instead on onsite storage, treatment, and infiltration (USEPA 2007). With this reduction in runoff, it is possible that overflow events can be avoided. It is also possible that cost savings could be seen through less need for pipes, drains, and smaller treatment plants (Gunderson et al. 2011).

Little information is readily available to allow decision makers to accurately evaluate the effects of retrofitting these LID practices into existing neighborhoods.

These retrofit projects generally focus on reducing stormwater runoff volumes, reducing the likelihood of CSO events, and improving water quality in local water bodies. With this goal, a system is needed that will allow decision makers to quickly and easily use readily available data to estimate existing runoff volumes and the amount of reduction that can be achieved by various LID practices. Through estimating levels of runoff reduction, it should be possible to approximate the type, amount, and cost of implementing LID practices needed to achieve a desired level of reduction. This information will make it possible to make informed decisions and set realistic goals for projects.

Costs of retrofitting LID practices are an area where there is little information readily available and much of what is available is presented on a citywide level or is tied to the costs of building a new development using LID versus without. There is little information available on how the costs of retrofitting LID methods relate to the benefits that are being achieved. Does this relationship increase or decrease with the adoption level? How does it compare with traditional methods for dealing with stormwater runoff? Perhaps most importantly, do the benefits outweigh the upfront costs of LID implementation?

To address these questions, there are two hypotheses that will be tested in this project:

- The amount of runoff will decrease in proportion to the surface area treated with LID practices and LID practice adoption rate.

- The reduction in runoff will provide a monetary savings that will offset or surpass the cost of implementing the selected practice.

The objectives of this project are to:

- Estimate the amount of runoff reduction that can be achieved in existing neighborhoods by retrofitting LID practices at varying levels of adoption.
- Estimate the cost of using LID practices to achieve various levels of runoff reduction.
- Demonstrate methods for estimating LID practice cost using assumptions made in the L-THIA LID model and published price information.

For the purposes of this research, the dependent variable that was used to determine the benefits of implementing LID measures was runoff volume, because a decrease in runoff volume should correlate to a decrease in pollutants being carried to surface water or treatment facilities (USEPA 2003). With this focus, the Long-Term Hydrologic Impact Assessment (L-THIA) LID (Engel and Ahiablame 2011) model was selected to estimate the effects that common LID methods have on a series of neighborhoods in the Greater Lafayette area and the cost of implementation.

# CHAPTER 2. BACKGROUND

## 2.1 Background

The LID methods which have been considered for this study are green roofs, bioretention, pervious pavement, and rain barrels or cisterns. These practices were selected to represent some of the more common LID practices for stormwater management. They were also selected because it is thought that it would be possible to retrofit them into a wide range of land use settings. Each of these practices have been widely researched and examined on multiple criteria and conditions, and a brief overview of some of these studies is presented here.

## 2.2 Green Roofs

Green roofs, also known as vegetated roofs, come in three basic forms: extensive, simple intensive, and intensive. These are defined by the thickness of the system: extensive roofs are less than 15 centimeters; simple intensive roofs are between 15 and 25 centimeters; and intensive roofs are over 25 centimeters thick (Mentens and Hermy 2003). The vegetation that can be used on the roof also varies between these types, extensive roofs are typically planted with varieties of sedum; increasing to herbs and grasses on simple intensive roofs; and intensive roofs that can include shrubs and small trees (Mentens and Hermy 2003). Aside from the thickness and vegetation, all three types of green roofs are similarly constructed. All three have a layer of substrate, which serves as the growth media for the vegetation and provides temporary water storage during storms (Mentens and Hermy 2003). Under the substrate layer is a filter layer, which prevents the substrate from washing into the drainage layer and inhibiting function (Mentens and Hermy 2003). The drainage layer creates space for water to drain off the roof and prevents water logging and crop stress (Mentens and Hermy 2003). Beneath the drainage layer is an impervious membrane that protects the roof from water damage and prevents leaks (Mentens and Hermy 2003).

Green roofs are useable in many situations. They can be included with new construction or as part of retrofit projects (USEPA 2008), and can also be adapted to commercial, industrial, or residential structures (USEPA 2008). Installation can be accomplished either as an integrated design (custom-building the system on the roof) or through the use of a modular prefabricated tray system (USEPA 2008). There are a few structural requirements for the use of green roofs; the roof must be able to support the additional weight of the system and the slope of the roof should be less than 20 percent (USEPA 2008). These requirements may restrict the ability to retrofit green roofs onto some structures.

Stormwater management is one of the major functions of a green roof. Studies have shown that green roofs can successfully reduce peak flows and reduce total runoff volumes. This is largely due to the retention capabilities of the green roof increasing the time needed for runoff to start, reducing the total volume that can runoff, and increasing the time over which water is released (Mentens et al. 2006). They have been shown to achieve peak flow reductions of approximately 57 percent (Stovin 2010). This in part seems to correspond to the retention capabilities and total reduction in runoff (Stovin 2010). Integrated green roofs have been shown to be capable of averaging just under a 78 percent retention rate (Carter and Rasmussen 2006). Results for modular systems indicate slightly lower retention rates than the integrated system with an average rate of approximately 67 percent (Carter and Butler 2008). Retention rates for green roofs vary seasonally, with the highest retention rates being recorded in warm summer months (Berghage et al. 2009). The ability of green roofs to retain stormwater is also dependent on the depth of the substrate media and the slope of the roof, with thicker substrates and shallower roof slopes retaining more water (VanWoert et al. 2005).

Green roofs receive mixed reviews when it comes to water quality. Berghage et al. (2009) found that runoff from the green roofs developed a distinct yellow-brown color after passing through the media. Higher levels of phosphorous have also been seen in the runoff from green roofs (Berghage et al. 2009; Kok et al. 2013). Levels of Cu (copper) and Al (aluminum) have also been reported as high in discharges from green roofs (Vijayaraghavan et al. 2012), although it is thought that many of these issues will decrease as the roof ages (Berghage et al. 2009; Kok et al. 2013).

Green roofs have been shown to have a balancing effect on the pH of stormwater, bringing it close to neutral (Berghage et al. 2009; Kok et al. 2013; Vijayaraghavan et al. 2012). They also reduce the amounts of heavy metals in the discharge (Vijayaraghavan et al. 2012). Green roofs are also effective at reducing the amount of total suspended solids (Kok et al. 2013). Berghage et al. (2009) reported that the total volume of nitrates discharged from green roofs was lower than from asphalt roofs. However, both Berghage et al. (2009) and Vijayaraghavan et al. (2012) noted that concentrations of nitrates were higher from green roofs, possibly due to the small amount of water being discharged.

When considering green roofs, there are other factors to consider beyond runoff and water quality as they can have a much broader impact on the environment. Some of these factors include the addition of green space, creation of habitat, reduction of urban heat island effects, improved air quality, increased thermal insulation and efficiency, and lifespan and durability over conventional roofs (Banting et al. 2005; Carter and Butler 2008; USEPA 2008; Rowe 2011; Bianchini and Hewage 2012). Traditional roofs are a dead space that serve only a utilitarian function, while green roofs in contrast can provide a green amenity to the occupants of the building (Banting et al. 2005). Similarly, the green space created on the roof provides a habitat for birds, spiders, beetles, and other invertebrates (Carter and Butler 2008). The addition of green space also helps to decrease the urban heat island effect by decreasing the amount of solar radiation stored by the roof and through the cooling effects of evapotranspiration from the plants (Banting et al. 2005; Carter and Butler 2008; Rowe 2011; Bianchini and Hewage 2012). The plants also serve to improve air quality by absorbing $CO_2$ and other pollutants and releasing oxygen into the environment (Banting et al. 2005; Rowe 2011).

The thickness of the green roof system functionally increases the amount of insulation on the roof of the building, increasing its thermal efficiency (Banting et al.

2005; Carter and Butler 2008; Rowe 2011; Bianchini and Hewage 2012). Carter and Butler (2008) found that in the climate of Atlanta, Georgia, the cooling demand for a “big-box” commercial building could be reduced by approximately 12 percent, and heating demand could be reduced by almost 32 percent. This additional thickness also increases the lifespan of the roof membrane, allowing green roofs to last much longer than the typical 20-year lifespan of conventional roofs (Rowe 2011). In a survey of several studies, Bianchini and Hewage (2012) found that the lifespan of a green roof was between 40 and 55 years depending on maintenance, weather, and type of roof. Rowe (2011) reports as an example of the exceptional lifespan of green roofs that the roof on the Zurich, Switzerland, water treatment facility was repaired for the first time after 91 years of service; it was installed in 1914.

## 2.3 Bioretention

Bioretention areas, sometimes referred to as rain gardens, are landscaping features that are designed to provide on-site treatment and storage for stormwater runoff (USEPA 2005). This is achieved by mimicking hydrologic processes found in upland regions (ESD DER 2007). Generally, bioretention areas are shallow depressions that have been placed in order to use the site’s topography to collect runoff (ESD DER 2007). These areas will typically be constructed out of an engineered soil media between 0.8 to 0.9 meters deep and covered with 3 to 8 centimeters of bark mulch (Davis 2007). They are then planted with a variety of grasses, perennials, shrubs, and trees that are water tolerant (Davis 2008). In areas where the native soil types have low infiltration rates, an underdrain constructed of perforated plastic pipes may be installed below the soil media to allow the bioretention facility to properly drain (Davis 2007). An overflow drain may also be installed in the bioretention area to prevent flooding the surrounding areas during heavy rainfall events (ESD DER 2007). In both cases these drains will usually be connected to a storm sewer system (ESD DER 2007).

Bioretention has proven to be an effective method for managing stormwater runoff volumes, peak flow rates, and improving water quality. Runoff volumes and flow rates are reduced because bioretention systems provide extra storage space allowing the water to collect and pool (Davis 2008; Hunt et al. 2008). Once the water has been collected in the system, it infiltrates into the soil, is absorbed into plants, or evaporates back into the atmosphere (ESD DER 2007). In order to avoid standing water, these systems are designed to remove ponded water in 4 to 6 hours (Davis 2008).

Ponding also helps to improve water quality by providing time for sediments and other solids to settle. Bioretention has shown the capability to be able to reduce the levels of total suspended solids by approximately 98 percent (Glass and Bissouma 2005). In addition to filtering out solids, infiltration through the mulch layer and soil media has been shown to be effective in removing metals like copper, lead, zinc, and arsenic (Davis et al. 2001; Glass and Bissouma 2005; Davis 2007). Bioretention also works to remove nutrients, such as nitrogen and phosphorus, from the collected stormwater. This is accomplished through anaerobic processes within the bioretention media as part of the infiltration process (Davis et al. 2006), and by the plants incorporated into the system absorbing and using the nutrients to fuel their growth (ESD DER 2007). Other pollutants, such as oil and grease (Hong et al. 2006), or bacterial contaminates, like E. coli and Fecal coliform, can also be reduced (Hunt et al. 2008). Water quality improvements can be increased further by selecting plants for the bioretention system that will break down or assimilate pollutants (ESD DER 2007).

Besides enhancing water quality and reducing runoff and peak flows, bioretention systems can provide other benefits. As landscape elements, bioretention areas can aesthetically enhance the site (USEPA 2005), and when native plants are used, they can provide a habitat for wildlife (ESD DER 2007). Bioretention areas are multifunctional elements that can be used to achieve credit towards both landscaping and stormwater requirements (ESD DER 2007). This allows for some savings when developing a new site. An EPA study found that the cost of retrofitting a bioretention area into an existing site was approximately one-third the cost of installing a proprietary system sized to treat runoff from the same area (USEPA 2000). Bioretention is also low maintenance and is maintained similarly to the rest of the site's landscaping (ESD DER 2007). This negates the cost of the extra maintenance that would be required to keep proprietary systems functioning (USEPA 2000).

## 2.4 Pervious Pavement

There are several different products that are typically thought of when talking about pervious pavement, including porous asphalt, porous concrete, and permeable interlocking concrete pavement (PICP). Porous asphalt is similar to standard hot-mix asphalt except it is formulated with less sand and fines to allow for the formation of interconnected open pores, creating voids for water to flow through the surface (USEPA 2009b). Porous concrete, similar to porous asphalt, is a typical concrete mix that contains less sand and fines, which allows for the formation of interconnected stable air spaces that water can flow through from the surface (USEPA 2009c). PICP is based around impervious manufactured concrete units, which are designed to create permeable joints between the individual units (USEPA 2009d); these joints, which comprise between 5 and 15 percent of the surface area, are typically filled with crushed stone and provide channels for the water to infiltrate through the pavement (USEPA 2009d).

All three of these methods are similar in that they are constructed on top of an open-graded aggregate base that serves as a reservoir (NCSU 2008; USEPA 2009b; USEPA 2009c; USEPA 2009d). This reservoir space serves to store stormwater until it can infiltrate into the native soil (NCSU 2008). In areas where the soils have a low infiltration rate, an underdrain system is typically installed to drain the system into a municipal storm sewer system (NCSU 2008). A geotextile fabric is placed under the base to prevent soil from migrating into the aggregate (NCSU 2008).

Pervious pavement has shown to be an effective method for managing stormwater, having been shown to greatly reduce, or even eliminate runoff (Bean et al. 2007). On impervious surfaces, the amount of runoff closely follows precipitation rates during a storm event (Brattebo and Booth 2003). In contrast, pervious surfaces have the potential to infiltrate most of the water generated during a storm event (Brattebo and Booth 2003). The capability to reduce runoff has also been demonstrated on heavy clay soils with low infiltration rates. In studies by Dreelin et al. (2006), plus Fassman and Blackbourn (2010), observed flow rates from the underdrain systems of permeably paved parking lots were found to be significantly lower than runoff rates from similar asphalt parking lots. Research is also finding that pervious pavements, when properly designed and installed, will continue to properly function in cold climates (Cahill et al. 2003; Dietz 2007; Roseen et al. 2012).

Water quality can also be improved through the use of pervious pavement systems. As water infiltrates through the pavement material and the aggregate base, many pollutants are filtered out (Bean et al. 2007; Brattebo and Booth 2003; Tota-Maharaj and Scholz 2010; Pagotto et al. 2000). These pollutants are held mainly within the pavement structure and in the base, with little or no contamination occurring in the underlying soil (Legret et al. 1996; Legret and Colandini 1999). It has been demonstrated that pervious pavement systems are capable of achieving total pollutant retention rates exceeding 99 percent (Fach and Geiger 2005).

Studies have demonstrated that pervious pavements are capable of significant reductions in the amount of solids present in discharged stormwater (Bean et al. 2007; Tota-Maharaj and Scholz 2010; Pagotto et al. 2000). Pagotto et al. (2000) reported approximately a 77 percent decrease in total suspended solids compared to what was observed in runoff from traditional asphalt. Metals, most notably lead (Pb), copper (Cu), cadmium (Cd), and zinc (Zn), are also greatly reduced in stormwater discharges from pervious pavement systems (Bean et al. 2007; Brattebo and Booth 2003; Legret et al. 1996; Legret and Colandini 1999; Pagotto et al. 2000). Pagotto et al. (2000) reported reductions in metals from 15 percent (for dissolved Cu) up to 83 percent (for particulate Pb). Nutrient loading has also been found to be significantly lower for pervious paving systems than traditional asphalt (Bean et al. 2007; Pagotto et al. 2000). Tota-Maharaj and Scholz (2010) found that pervious pavement systems removed or degraded almost all microbial contaminants, total coliforms, E. coli and fecal streptococci. Removal efficiencies for these contaminants were found to always exceed 90 percent with a mean removal efficiency around 98.6 percent (Tota-Maharaj and Scholz 2010).

Hydrocarbons, such as motor oil, are also removed or broken down in the pervious pavement structure at high rates (Pagotto et al. 2000). Part of this efficiency in dealing with hydrocarbons is due to microbial communities that form in the pavement and aggregate base, functionally creating a bioreactor (Newman et al. 2002). These microbial communities grow and develop naturally over time without the need to add commercial oil degrading microbe mixtures into the system (Newman et al. 2002).

Maintenance of pervious pavements can be slightly more intense than traditional impervious surfaces. Pervious pavements should be visually inspected to ensure that the system is functioning properly and not becoming clogged (NCSU 2011). It is recommended that a street sweeper be used at least twice a year to maintain the maximum efficiency of the system, although more frequent sweeping may be needed in some cases (Cahill et al. 2003; NCSU 2011). Without sweeping pervious pavements will still maintain some permeability, even after 35 years of simulated sediment loading (Pezzaniti et al. 2009). For PICP systems, it is also necessary to ensure that the gaps stay filled with crushed aggregate in order to avoid the formation of tripping hazards (NCSU 2011). Any vegetation that begins to grow in the system should also be removed when it is found (NCSU 2011).

In colder climates pervious pavement systems may require less maintenance than impervious pavements in winter months (Cahill et al. 2003; NCSU 2011; Roseen et al. 2012). Cahill et al. (2003) reports that snow melts faster and that ice is less likely to form on the surface of pervious pavements since melt water infiltrates into the system before freezing, possibly creating some maintenance cost savings due to less plowing and salting (UNHSC 2009). Sand or gravel, used to enhance vehicle traction, should only be applied when necessary to avoid clogging the system (UNHSC 2009; NCSU 2011).

In addition to possible savings on winter maintenance, there are other economic factors to study when considering pervious pavements. The reduction in runoff provided by pervious pavements may reduce or eliminate the need for a traditional drain and pipe storm system. Additionally, because they are constructed on top of a reservoir structure, pervious pavements can double as onsite detention (Cahill et al. 2003), eliminating the need for large detention ponds and possibly increasing the total space that can be developed (Cahill et al. 2003).

## 2.5 Rain Barrels and Cisterns

Rain barrels and cisterns are ancient and relatively simple concepts that represent a range of structures capable of gathering, collecting, and storing water to be used later (Boulware 2004). In modern terminology, rain barrels and cisterns refer to different systems that accomplish the same goal. Both systems collect and store rainwater from the roof of a structure. A rain barrel is the simpler of the two methods and can be made up of a simple barrel with a screen on top to keep out debris and are placed under a downspout (IASWCD 2012). Most commonly, these barrels are made of plastic, preferably opaque to limit algae growth, with a spigot near the bottom to allow for the connection of a hose. Barrel systems can increase in complexity, adding more complex filtration systems, improving connection with the downspout, and linking multiple barrels together to increase capacity. However, they tend to remain relatively small and are usually based around 208 liter (55 gallon) barrels and generally only used to store water that will be used on landscaping (IASWCD 2012). Cisterns, on the other hand, are constructed in multiple ways; they can be built as free standing structures, underground, or internally within buildings. They can also be constructed in a variety of capacities allowing them to be more precisely tailored to the building and intended use (Boulware 2004). Cistern systems can then be connected to systems that do not require water of drinkable quality (Boulware 2004).

The main reasons that rain barrels have been encouraged by many conservation groups is because they provide a way to keep water out of the sewer system, decrease demand on infrastructure, and manage stormwater at the source (Gunderson et al. 2011). The City of Chicago is estimated to have diverted almost 8.3 million gallons of water from its sewer system through the use of rain barrels and downspout disconnection (Gunderson et al. 2011). A rain barrel represents one option for detaining this water, allowing it to be released later at a slower rate. Even without their full capacity available, a well-designed rain barrel or cistern system can significantly reduce the peak rate of flow in the sewer system (Vaes and Berlamont 2001).

The water that is captured during rainfall events can be used in place of tap water for some applications, allowing for savings on water bills. The most common use for rain barrels is as a source of water for landscaping, which produces several benefits. It is better for some plants since rainwater lacks the chlorine that is commonly added to treat water (IASWCD 2012), it conserves drinkable water, and it helps reduce water bills. According to Master Gardener Paul James, during the summer in Indiana, 40 percent of the average household's water usage is used on their lawn (IASWCD 2012). Cisterns that are capable of storing more water can be used for other applications beyond landscaping, such as fire suppression or flushing toilets. In some cases they can even be attached to additional filtration systems and used to supply drinkable water (Boulware 2004).

By modeling the retrofit of these practices, it is anticipated that a relationship will be seen between the area being used for LID practices, the cost of implementing the changes, and the amount of runoff reduction. By determining and understanding these relationships, it should be possible to make recommendations on the adoption of LID methods. Insight should also be gained into the usefulness of L-THIA LID (Engel and Ahiablame 2011) as a tool for decision makers and planners to evaluate LID use on a project by project basis.

## 2.6 L-THIA LID

The L-THIA LID model (Ahiablame et al. 2012; Ahiablame et al. 2013) is an upgraded version of the original L-THIA LID model (Engel and Hunter 2009). The Engel and Hunter (2009) model added the capability of modeling effects of LID practices into the original L-THIA model (Engel 2001), which was developed in response to the needs of decision makers for a simple, easy-to-use tool capable of assessing the impacts of land use changes (Harbor 1994). L-THIA combines the Curve Number method (NRCS 1986) with soil, land cover, and long-term climate data for the area of interest in order to estimate long-term average annual runoff (Engel 2001). The model has the capability to estimate non-point source pollutants using the event mean concentration (EMC) (Baird et al. 1996).

The L-THIA models are easy to use tools that allow for the quick assessment of multiple scenarios across scales ranging from a single lot to entire watersheds (Ahiablame et al. 2012). Based around the widely used Curve Number method, L-THIA offers a simplified alternative to other more complicated hydrologic models (Ahiablame et al. 2012). One benefit to the simplicity of the model, besides ease of use, is that it does not rely on intensive datasets that are not always readily available (Ahiablame et al. 2012). Instead, it makes use of nationally available datasets from the USGS, USDA, and NOAA for land cover, soils, and rainfall information.

The model is also highly adaptable and configurable, allowing a wide range of studies to be conducted using the model. For example, Tang et al. (2005) used the model to study the impacts of urbanization and land use change on a Michigan watershed. They found that urbanization had a significant impact on long-term annual runoff in subcoastal watersheds and that it would also impact the types and quantities of nonpoint source pollutants (Tang et al. 2005). The impacts of urban sprawl and large surface parking lots was explored in a paper by Davis et al. (2010). They demonstrated that parking lots are expensive, consume large amounts of space, diminish ecosystem services, and increase both runoff and pollutants (Davis et al. 2010). Ahiablame et al.

(2012) conducted a study of a subdivision comparing pre- and post-development hydrology both with and without LID practices. They found that while development increased both runoff and pollutants, LID practices could be used to bring the site hydrology back to near pre-development conditions. Ahiablame et al. (2013) used a modified version of the model to study the impacts of LID practices on stormwater and base flow for two urbanized watersheds around Indianapolis. They found that LID practices were effective in managing runoff, pollution, and reducing baseflow even though only small reductions were seen in the study (Ahiablame et al. 2013). Gunn et al. (2012) used the L-THIA model to develop a pair of indices that would quantify the impact of land use change on the original site hydrology, and demonstrated the impact that different development strategies would have on runoff and pollution. This adaptability is made possible in part because the Curve Numbers can be created, configured, combined, or calibrated to represent a wide range of situations, practices, and materials using the methods described in TR-55 (NRCS 1986).

L-THIA has proven to be accurate for modeling direct runoff from watersheds throughout the Midwest with little or no calibration (Bhaduri et al. 1997; Grove et al. 2001; Tang et al. 2005; Lim et al. 2006; Choi 2007; Ahiablame et al. 2013). Lim et al. (2006) found that in the Little Eagle Creek watershed in Indianapolis, the L-THIA model estimate for direct runoff was slightly lower compared to the direct runoff volume obtained through baseflow separation. In two watersheds near Indianapolis, Ahiablame et al. (2013) confirmed that the L-THIA LID model tends to provide a conservative estimate for direct runoff, when compared to direct runoff estimates obtained from separated streamflow.

Runoff volume estimates obtained through runoff separation may not be the ideal method for calibrating the L-THIA models, because streamflow data will reflect constantly changing land cover, while L-THIA assumes a constant land cover (Grove et al. 2001). Using short-term data (<15 years) for calibration, in order to minimize the impact of land use changes, can introduce variability due to wet or dry years (Grove et al. 2001). However, because L-THIA is a simple model that calculates direct runoff based on empirical coefficients and does not take into account other processes, such as evapotranspiration, infiltration, or interflow, it can generally be applied without calibration (Choi 2007). Grove et al. (2001) observed that L-THIA predicted trends were consistent with estimates from streamflow data. Comparisons with estimates from streamflow data also show that the uncalibrated L-THIA model provides a reasonable estimate for average annual runoff, although it tends to be conservative (Grove et al. 2001).

With its speed, ease of use, and simplicity, L-THIA LID gives planners, natural resource managers, and decision makers a tool to make high-level decisions before moving into a more detailed design (Ahiablame et al. 2012; Gunn et al. 2012). By requiring simple and accessible datasets, the model allows accurate predictions for the impacts of different development scenarios to be generated and assessed while still at a conceptual planning level (Gunn et al. 2012). This allows informed decisions to be made early in the planning process, aiding in goal setting and saving time as the process moves into more detailed design.

# CHAPTER 3. METHODS

## 3.1 Methods

L-THIA LID (Engel and Ahiablame 2011) was used to model possible retrofitting scenarios for several different development approaches found in the Greater Lafayette area . Many of these development approaches are typical of what is found in towns and cities throughout America. A typical commercial corridor, downtown area, historic residential neighborhood, and a typical subdivision were selected for modeling (Figure 1).

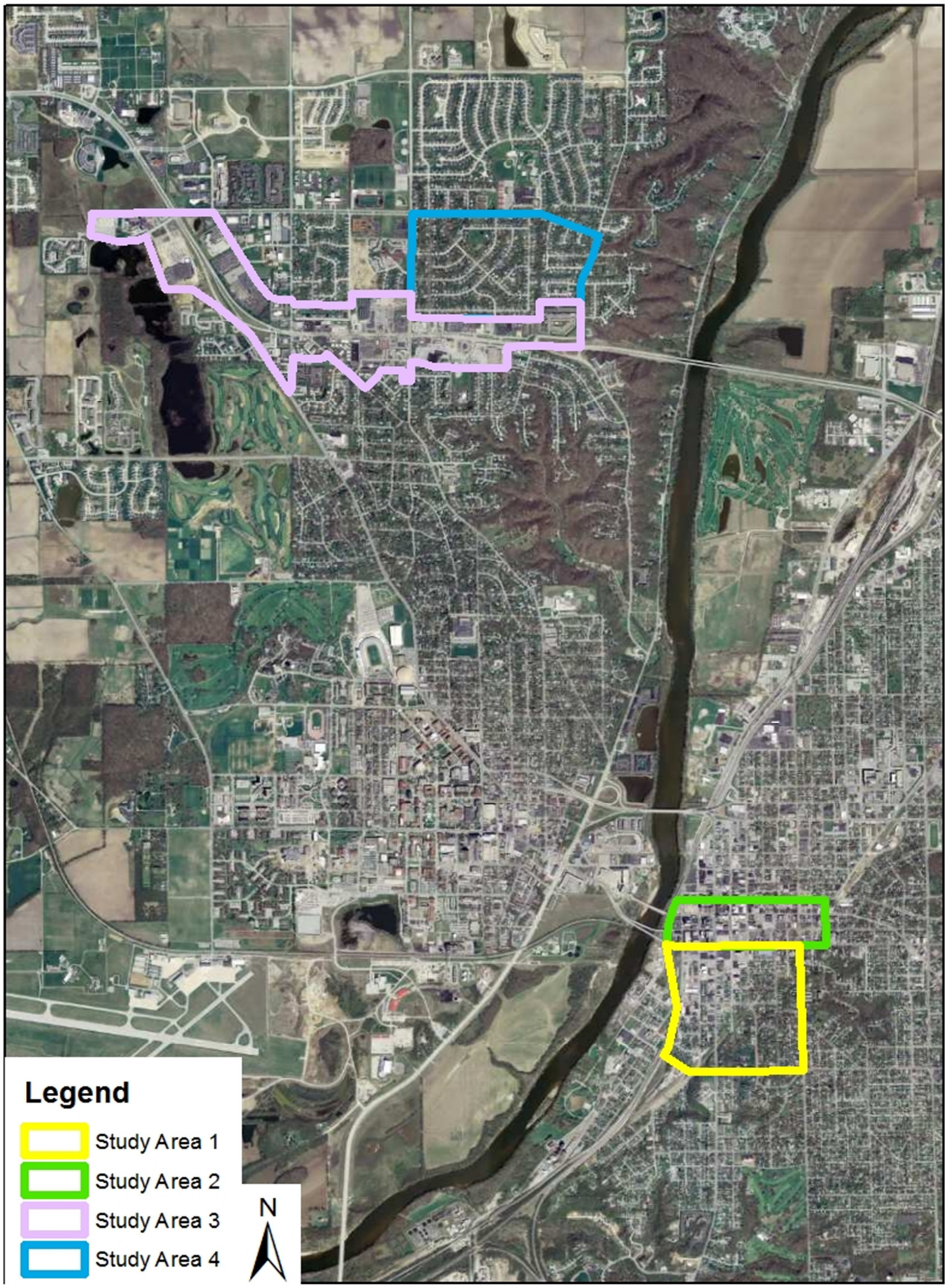


Figure 1: Aerial Photograph Illustrating study areas

The typical commercial corridor selected was the US 52 corridor in West Lafayette from Happy Hollow to Yeager Road. This area is dominated by big-box retail and out parcels surrounded by parking.

Downtown Lafayette has been defined as the area between 2nd and 11th Streets to the east and west and between Ferry and South Streets to the north and south. This area is made up of multistory buildings that serve a mix of retail, office, and residential uses, along with the associated parking lots, streets, and sidewalks. This area is largely covered by impervious surfaces, although a few pervious areas do exist around the courthouse and near street trees.

For the historic neighborhood, the Ellsworth-Romig neighborhood was selected. This neighborhood is defined as the area between South and Kossuth Streets and from the railroad tracks to 8th Street, and is primarily high-density residential with some commercial and industrial uses as the neighborhood transitions into downtown Lafayette. The Ellsworth-Romig Neighborhood also includes South 3rd Street and South 6th Street, which are both local historic districts, and directly adjoins the South 9th Street local historic district. In these districts there are special restrictions for renovations and a Certificate of Appropriateness from the Historic Preservation Commission is required for any changes to the houses that would be visible from the public view. These restrictions eliminate or restrict the use of some LID methods in this neighborhood.

The final area for the study was a typical residential subdivision. For this a group of residential neighborhoods that were developed beginning in the 1970s through early 1980s were be examined. This group of neighborhoods was defined by North Salisbury

Street on the west, Cumberland Avenue on the north, Soldiers Home Road on the east, and the commercial district used in this study to the south.

A combination of L-THIA and GIS were used to categorize the land uses and hydrologic soil types that were present within the study areas. The NRCS Soil Survey Geographic (SSURGO) Database (USDA NRCS 2011) was used to obtain the soil data. Before the SSURGO data could be used for the L-THIA model, preliminary processing was required. The SSURGO data includes dual type hydrologic soils (in example A/D, B/D, or C/D) and the L-THIA model requires single hydrologic soil categories. In order to fit this requirement, all dual type soils were adjusted to a single type. As the areas being examined were urbanized, it was assumed that all soils in these areas have been disturbed and compacted (Lim et al. 2006). Based on this assumption, all dual type soils were classified according to their lower drainage class.

SSURGO does not provide hydrologic soil data for areas that were developed before the survey was conducted. In these areas the worst case was assumed and they were assigned type D (Lim et al. 2006). With these assumptions in place, the SSURGO soil data was loaded into ArcMap and converted to a raster with a 30 meter resolution to match the National Land Cover Database (NLCD) layers.

Finally, the soil raster was compared to aerial photography in order to determine if any areas needed to be reclassified based on development. Two such areas were identified and reclassified to type D. One of these areas was listed as type C, but is now a parking lot, and the other was also type C and consisted of two cells at the edge of Study Area 1 that contained parts of a street, sidewalk, and driveway.

The NLCD impervious surface layer (U.S. Geological Survey 2011) was then used to approximate the types of land uses within the study areas. The process began by using USDA TR-55 Urban Hydrology for Small Watersheds (NRCS 1986) to determine what the impervious cover percentage of the different land uses should be. As TR-55 supplies only a single percentage per cover and the NLCD impervious surface layer is a range from 0 to 100 percent, a range for each of imperviousness was determined by finding the midpoint between each of the uses. The NLCD impervious surface layer was then reclassified to represent these ranges.

The GIS layer attribute tables were then exported to Excel for final analysis. Once in Excel, the raster cell counts were totaled by use categories. The resulting breakdowns of land uses derived by this method are shown in Table 1. Then for each land use category, the cell count was multiplied by 900 to find the area in square meters, since each cell in the raster was 30 meters by 30 meters. The area in square meters was then converted to hectares for use in L-THIA LID. Based on these areas, it was possible to use the abstractions that are already made within the L-THIA LID model to estimate the areas for the open space, roads, roofs, and other impervious surfaces that make up the different use types (USACE 2012).

Table 1: Approximate area in hectares for each study area broken down by land use. The table also displays the percentage range of impervious surfaces that were used to classify the land uses.

| | | Area in Hectares | | | |
|---|---|---|---|---|---|
| Land Use Type | % Impervious | Study Area 1 | Study Area 2 | Study Area 3 | Study Area 4 |
| Open Space | 0-10 | 6.57 | 0 | 1.8 | 7.2 |
| 2-Acre | 10-15 | 3.6 | 0 | 0.36 | 5.04 |
| 1-Acre | 15-21 | 2.43 | 0 | 0.81 | 4.23 |
| 1/2-Acre | 21-26 | 2.16 | 0 | 0.72 | 1.98 |
| 1/3-Acre | 26-33 | 3.24 | 0 | 1.53 | 3.6 |
| 1/4-Acre | 33-50 | 13.77 | 1.35 | 37.8 | 47.97 |
| 1/8-Acre | 50-66 | 13.95 | 2.43 | 21.24 | 1.35 |
| Industrial | 66-77 | 5.22 | 3.96 | 18.09 | 0 |
| Commercial | 77-100 | 16.02 | 21.51 | 32.4 | 0 |
| | Total | 66.96 | 29.25 | 114.75 | 71.37 |

To analyze the runoff generated by the study areas, the L-THIA LID desktop model (Engel and Ahiablame 2011) was used. The model was applied without calibration because it relies on curve numbers which have been empirically determined (NRCS 1986) and because it has already been proven accurate without calibration in similar conditions to those present in the selected study areas (Bhaduri et al. 1997; Grove et al. 2001; Tang et al. 2005; Lim et al. 2006; Choi 2007; Ahiablame et al. 2013). Established curve numbers were used for all land cover types and LID practices in order to ensure that calibration was unnecessary. For this study, all curve numbers for standard land cover types were set to their default values as specified by TR-55 (NRCS 1986). The curve numbers for the LID methods, with the exception of rain barrels and cisterns, were taken from a paper published by Sample et al. (2001). Table 2 provides a complete listing of all curve numbers used in this study.

For the rain barrels and cisterns, the curve number was calibrated to the specific study areas making it possible to calculate the approximate storage volume required to achieve to the results. This was achieved by using the methodology described in TR-55 (NRCS 1986) to calculate the curve number for a selected volume of storage applied to the average roof size in each land use category. The first step was to take the default roof curve number of 98 along with the roof size that was used to calculate that value of 185.8 $m^2$ (Sample et al. 2001) and calculate back to the initial abstraction of approximately 1.04 liters per square meter. The initial abstraction in this case represents the volume of water that will stick to the roof either through surface tension or due to the roughness of the roof.

The average roof size for the land uses in each study area was found in ArcMap from a building footprints layer obtained from the Tippecanoe County GIS Department. The ‘select by attribute’ tool was used to select the appropriate lot type, and then the ‘select by location’ tool was used to select the correct building footprints from the selection set. Finally the statistics tool in the attribute table was used to find the average roof size. The initial abstraction for the default roof was then multiplied by the average roof size for each category to estimate the amount of water that would normally stick to the roof. This volume was then added to storage volume of the rain barrels or cisterns, since it was assumed that adding storage volume will not change the amount of water sticking to the roof.

For residential uses, a storage volume of approximately 832 liters (220 gallons) was used. This represents four of the 208 liter (55 gallon) rain barrels that are sold by the City of Lafayette being installed on the downspouts of the home. For commercial and industrial uses, three storage volumes of cisterns were used: a 1,136 liter (300 gallon) cistern, an 18,927 liter (5,000 gallon) cistern, and a 39,747 liter (10,500 gallon) cistern. All were used to illustrate the wide range of storage volumes that are available in both prefabricated and custom-built cisterns. The volumes used in this study were found through Rain Harvest Systems' website (http://www.rainharvest.com).

Table 2: Curve numbers used in this study (NRCS 1986; Sample et al. 2001).

| | Curve Number | | | | | | | | | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | Study Area 1 | | | | Study Area 2 | | | | Study Area 3 | | | | Study Area 4 | | | |
| Hydrologic Soil Group | A | B | C | D | A | B | C | D | A | B | C | D | A | B | C | D |
| Impervious Surfaces (streets, parking, etc.) | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 |
| Open Space | 39 | 61 | 74 | 80 | 39 | 61 | 74 | 80 | 39 | 61 | 74 | 80 | 39 | 61 | 74 | 80 |
| Bioretention | 35 | 51 | 63 | 70 | 35 | 51 | 63 | 70 | 35 | 51 | 63 | 70 | 35 | 51 | 63 | 70 |
| Impervious Surface with Bioretention | 76 | 85 | 89 | 93 | 76 | 85 | 89 | 93 | 76 | 85 | 89 | 93 | 76 | 85 | 89 | 93 |
| Driveway with Porous Pavement | 70 | 80 | 85 | 87 | 70 | 80 | 85 | 87 | 70 | 80 | 85 | 87 | 70 | 80 | 85 | 87 |
| Sidewalk with Porous Pavement | 70 | 80 | 85 | 87 | 70 | 80 | 85 | 87 | 70 | 80 | 85 | 87 | 70 | 80 | 85 | 87 |
| Street with Curb and Gutter | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 |
| Street with Curb and Gutter and Porous Pavement | 70 | 80 | 85 | 87 | 70 | 80 | 85 | 87 | 70 | 80 | 85 | 87 | 70 | 80 | 85 | 87 |
| Parking Lot with Porous Pavement | 46 | 65 | 77 | 82 | 46 | 65 | 77 | 82 | 46 | 65 | 77 | 82 | 46 | 65 | 77 | 82 |
| Green Roof | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 | 85 |
| Roof with Rain Barrel 2 Ac. Lot | 93 | 93 | 93 | 93 | - | - | - | - | 96 | 96 | 96 | 96 | 92 | 92 | 92 | 92 |
| Roof with Rain Barrel 1 Ac. Lot | 91 | 91 | 91 | 91 | - | - | - | - | 96 | 96 | 96 | 96 | 92 | 92 | 92 | 92 |
| Roof with Rain Barrel 1/2 Ac. Lot | 92 | 92 | 92 | 92 | - | - | - | - | 95 | 95 | 95 | 95 | 92 | 92 | 92 | 92 |
| Roof with Rain Barrel 1/3 Ac. Lot | 89 | 89 | 89 | 89 | - | - | - | - | 94 | 94 | 94 | 94 | 91 | 91 | 91 | 91 |
| Roof with Rain Barrel 1/4 Ac. Lot | 89 | 89 | 89 | 89 | 87 | 87 | 87 | 87 | 90 | 90 | 90 | 90 | 91 | 91 | 91 | 91 |
| Roof with Rain Barrel 1/8 Ac. Lot | 87 | 87 | 87 | 87 | 87 | 87 | 87 | 87 | 92 | 92 | 92 | 92 | 93 | 93 | 93 | 93 |
| Commercial Roof with 1,136 liter capacity | 94 | 94 | 94 | 94 | - | - | - | - | 96 | 96 | 96 | 96 | - | - | - | - |
| Commercial Roof with 18,927 liter capacity | 55 | 55 | 55 | 55 | - | - | - | - | 77 | 77 | 77 | 77 | - | - | - | - |
| Commercial Roof with 39,747 liter capacity | 37 | 37 | 37 | 37 | - | - | - | - | 63 | 63 | 63 | 63 | - | - | - | - |
| Industrial Roof with 1,136 liter capacity | 95 | 95 | 95 | 95 | - | - | - | - | 96 | 96 | 96 | 96 | - | - | - | - |
| Industrial Roof with 18,927 liter capacity | 67 | 67 | 67 | 67 | - | - | - | - | 77 | 77 | 77 | 77 | - | - | - | - |
| Industrial Roof with 39,747 liter capacity | 50 | 50 | 50 | 50 | - | - | - | - | 63 | 63 | 63 | 63 | - | - | - | - |

The last piece of data the model needed was daily precipitation data for the area of interest. For this study, 30 years of precipitation data (1981-2010) were obtained from the National Climatic Data Center (NCDC: http://www.ncdc.noaa.gov) using the West Lafayette 6 NW station (129430). The 30-year time frame was selected because that is what the web-based L-THIA model uses. With all of the necessary data in place, the application was initiated. Each land use type was examined individually by the model using its component parts. This simplified the process of tracking which LID practice was being used, and also helps to determine the cause and effect relationship of any changes in runoff levels. The runoff values from these individual parts were added together to determine the total for the study area.

The model was initially run without any LID practices in place to establish the baseline runoff levels. Then each of the individual LID practices were put into the model and simulated at 10, 50, and 100 percent rates of adoption for each land use category. A preliminary study was conducted, which started at 10 percent of the area and increased by tens to 50 percent, and then increased from there to 75 and 100 percent adoption. In this preliminary study, it was discovered that the model demonstrates linear relationship between the adoption rate and the reduction in runoff volume, and because of this relationship it was possible to reduce the number of levels where the LID treatments were simulated from 7 to 3.

LID practices were examined individually starting with the use of rain barrels or cisterns, then bioretention, followed by porous pavement, and finally green roofs. Each practice was only applied to appropriate land uses. Rain barrels were only applied to residential uses because they lack the capacity for the larger roof areas found in commercial and industrial uses. Similarly, cisterns were only applied to commercial and industrial uses due to concerns over the amount of space available in residential lots. Green roofs were also limited to commercial and industrial use types because it was thought that the roofs on structures in these use categories would be more likely to accept the additional weight. It was also assumed that the roof slopes or neighborhood requirements would further restrict the application of green roofs in residential uses.

The next step was to create an estimate for the costs of implementing the LID practices. This was achieved by multiplying the unit price for a LID practice by the area, volume, or quantity that is being represented in the model. All prices used were taken from published sources (CNT 2009; SEMCOG 2008). Several assumptions needed to be made in order to streamline the process. First, any demolition that would be required to install a LID practice was considered equivalent in cost to demolishing the traditional infrastructure with the intent to replace it with a similar system. For rain barrels, cisterns, or bioretention, it was assumed that no demolition is necessary for their installation. Finally in the case of green roofs, it was assumed that they were only applied to structures that are already capable of supporting the added weight.

Table 3: Cost Range for LID Practices (CNT 2009)(SEMCOG 2008)

| | Price Range | | |
|---|---|---|---|
| Practice | Low | High | **Cost Unit** |
| Rain Barrel | $ 100.00 | $ 380.00 | per Barrel |
| Cistern | $ 0.19 | $ 1.79 | per Liter of Storage |
| Bioretention | $ 37.46 | $ 512.58 | per Square Meter |
| Porous Pavement | $ 15.93 | $ 129.17 | per Square Meter |
| Green Roof | $ 45.75 | $ 261.02 | per Square Meter |

From these assumptions, it was possible to generate a range of costs for the implementation of each practice. The unit prices used for each practice have been converted from dollars per square foot or dollars per gallon into dollars per square meter and dollars per liter and are shown in Table 3 in 2009 dollars. In order to estimate the costs of implementing LID practice adoption, it was necessary to first convert the areas used in the model into the units used for the price. In the case of porous pavement and green roofs, the area was converted from hectares to square meters and then multiplied by the cost per square meter. Bioretention follows a similar procedure, but the cost was based on 15 percent of the area being impacted (Ahiablame et al. 2012). In all three of these cases, once the area was known, it could then be multiplied by unit costs to acquire an estimate of the total cost of implementation.

For rain barrels and cisterns, the process was changed in order to determine the volume storage in liters that was needed in order to estimate cost. To get this volume, the area to which the rain barrels or cisterns were being applied was multiplied by the initial abstraction that was determined when the curve number was calculated. This volume consists of two parts: the roof storage (the amount of water that the roof normally detains) and the additional storage from the rain barrels or cisterns. To separate these two volumes, the treatment area was multiplied by the default initial abstract which was then subtracted from the total storage volume. This leaves only the volume of the rain barrels or cisterns. Finally this volume was multiplied by the cost per liter for cisterns, or divided by 208 liters to determine the number of barrels rounding up to a whole barrel and then multiplied by the cost per barrel for rain barrels.

After running the simulations, the L-THIA LID model (Engel and Ahiablame 2011) provided outputs of total volume of runoff in cubic meters for each year of rainfall data that was input. It would also be possible for the model to provide the output as a monthly or daily total. The yearly totals were then averaged to determine the average annual runoff volume for each land use type. From this volume, it was possible to determine the reduction in runoff both as a volume and a percent. To determine the volume runoff reduction, the volume of runoff with the LID practice was subtracted from the volume that is generated without any LID practices in place. It was then possible to calculate percent reduction of runoff by dividing the volume of runoff reduction from the volume of runoff without LID (volume Runoff Reduction/volume of runoff without LID).

In order to better understand the economics of implementing the selected LID practices, a value for water in the city of Lafayette was established. For this, the user fees for both drinking water and sewer were examined. These fees are based upon the costs of providing and maintaining these services within the city of Lafayette. The fees were converted from dollars per 1,000 gallons into dollars per cubic meter (see table 4), and then multiplied by the amount of runoff reduction. Only ran barrels and cisterns were multiplied by both the water and sewage fee, because they are the only practices examined that both conserve drinking water and prevent stormwater from entering the sewer system. This provided an estimate for the amount of money that could be saved annually as result of reducing runoff volumes.

Table 4: Estimated value of water within the city of Lafayette, Indiana, based on user fees.

| Cost of Water | | |
|---|---|---|
| Type | Price | Unit |
| Drinking water | $ 0.57 | Cubic Meter |
| Waste water treatment | $ 1.32 | Cubic Meter |

The estimated installation costs and savings were then used to approximate the amount of time needed for the LID practices to pay for themselves. This was accomplished using the NPER function in Excel, which returns the number of payments needed to pay off a loan and uses for its inputs: an interest rate, payment amount, and the present value or principle. The rate selected was 4.46% based on the 1-month average for a 30-year fixed rate mortgage according to Bloomberg.com (http://www.bloomberg.com/markets/rates-bonds/consumer-interest-rates/) on October 2, 2013. The amount for the payment was the estimated annual savings from runoff reduction, and the estimated installation cost was used for the principal. The savings was calculated on an annual basis, and as such only one payment was applied per year, rendering an output equal to the number of years needed to pay off the installation cost. This assumes that the annual maintenance expenditure is roughly the same for both the LID and traditional practice, and can be ignored as there is would be no significant difference between the two.

The costs of implementing LID were also examined at as function of the cost per cubic meter of runoff reduction based on an average year. This value was achieved by dividing the cost of implementation by the average annual reduction in runoff volume, which produced an approximate cost for each cubic meter of runoff reduction.

# CHAPTER 4. RESULTS

## 4.1 Runoff

The results for the historic neighborhood, study area 1, show decreasing amounts of runoff as the adoption rates of LID practices increase, as illustrated in Figures 2 through 10. Within the data in these figures, there are several trends that should be noted. The first is that for all land use types, bioretention is the best performer, typically providing between a 60 and 80 percent reduction in runoff at full adoption for each land use type. However, achieving these types of gains means converting large areas of open space into bioretention. For example in commercial areas, 100 percent of the available open space would need to be converted in order to achieve full adoption. Next, with pervious pavement, a relationship can be seen between its effectiveness and the density of the development pattern. With higher density development patterns, pervious pavement will provide more runoff reduction than for lower density development. Finally, the roof top methods for intercepting runoff offer the least reduction in runoff. Rain barrels provided a maximum reduction of almost 20 percent at the highest residential density. With cisterns, a runoff reduction of between 10 and 30 percent was achieved depending on the size of the cistern used. There was little difference between the medium and large cistern sizes in the amount of runoff reduction that they provide at a given adoption level. Green roofs demonstrate only slightly less runoff reduction than the medium and large sized cisterns.

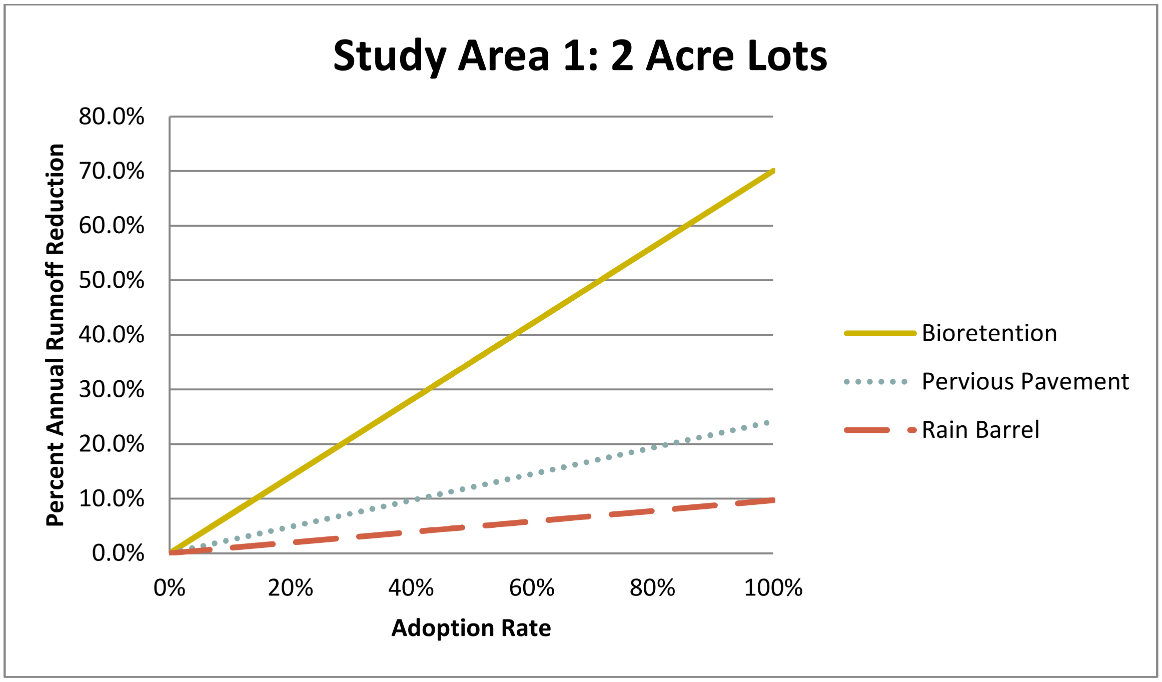


Figure 2: Runoff reduction percentage simulated for each of the LID practices applied to 2-acre lots within study area 1 based on adoption rate.

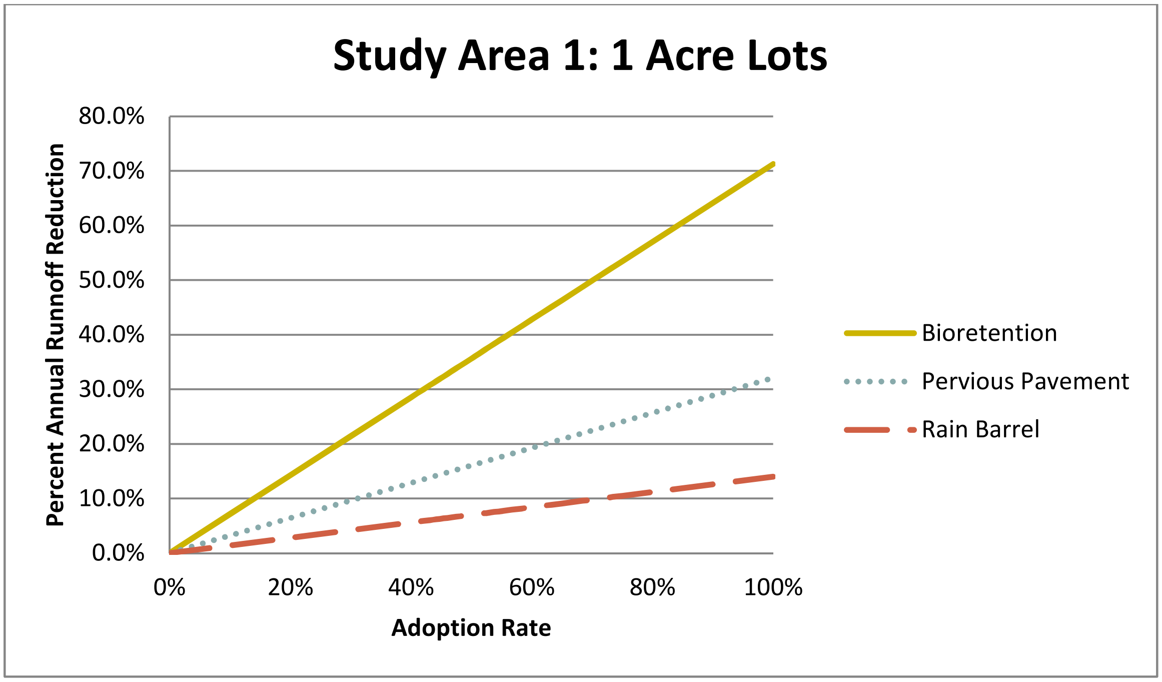


Figure 3: Runoff reduction percentage simulated for each of the LID practices applied to 1-acre lots within study area 1 based on adoption rate.

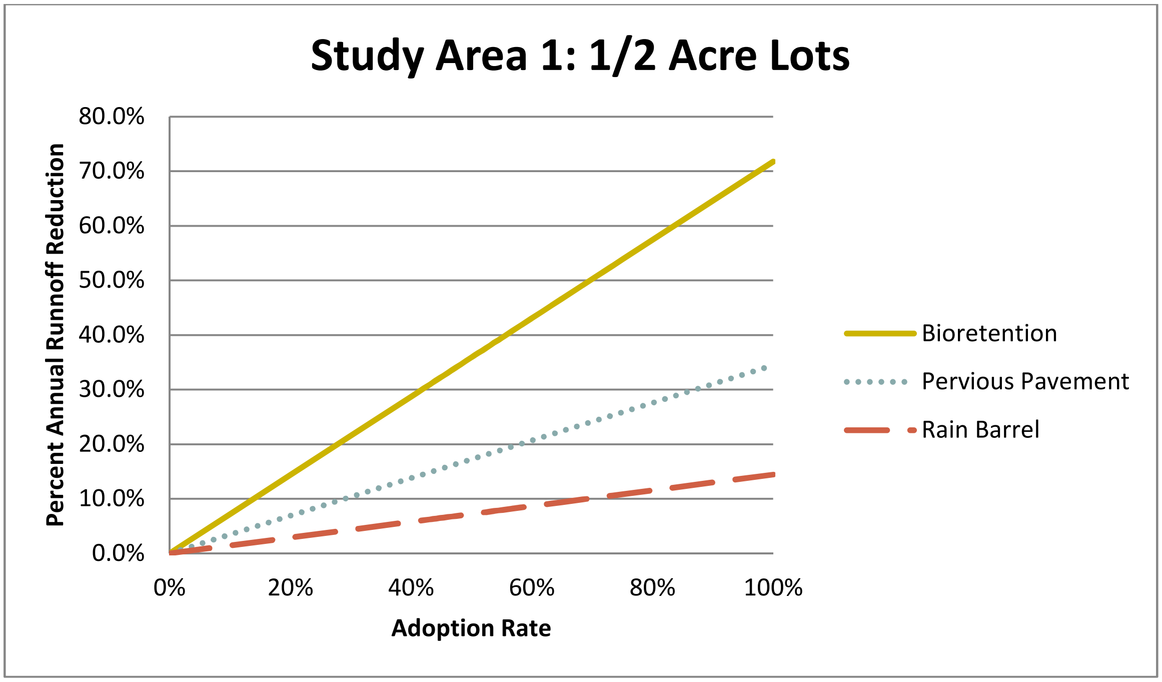


Figure 4: Runoff reduction percentage simulated for each of the LID practices applied to 1/2-acre lots within study area 1 based on adoption rate.

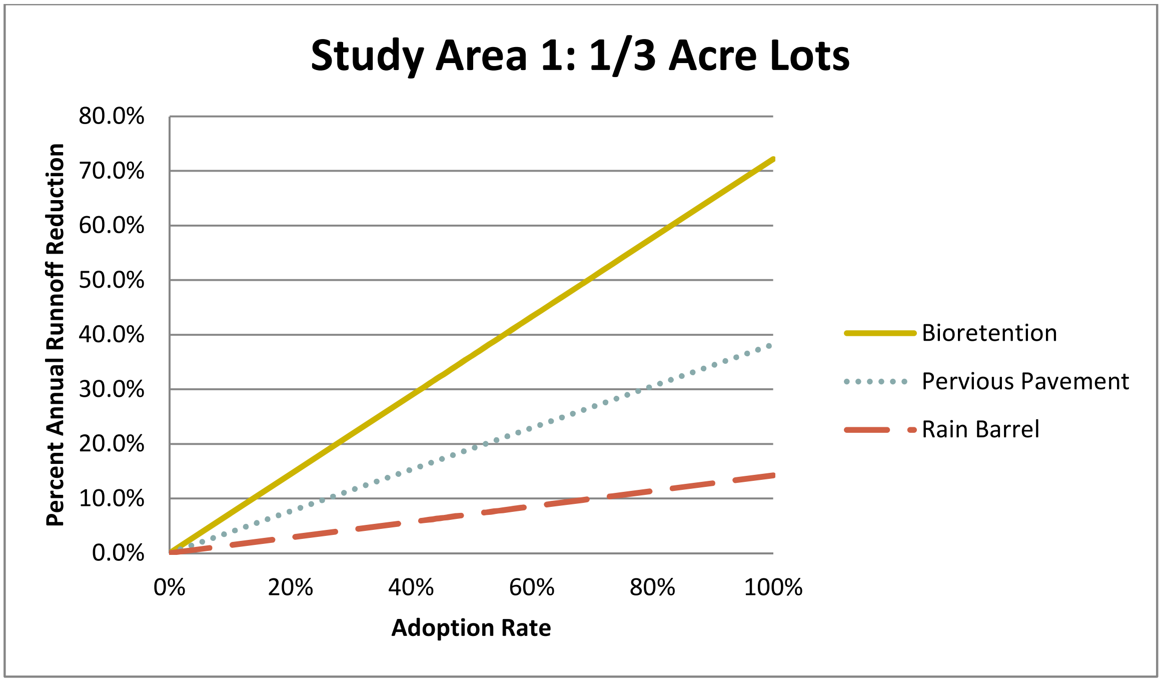


Figure 5: Runoff reduction percentage simulated for each of the LID practices applied to 1/3-acre lots within study area 1 based on adoption rate.

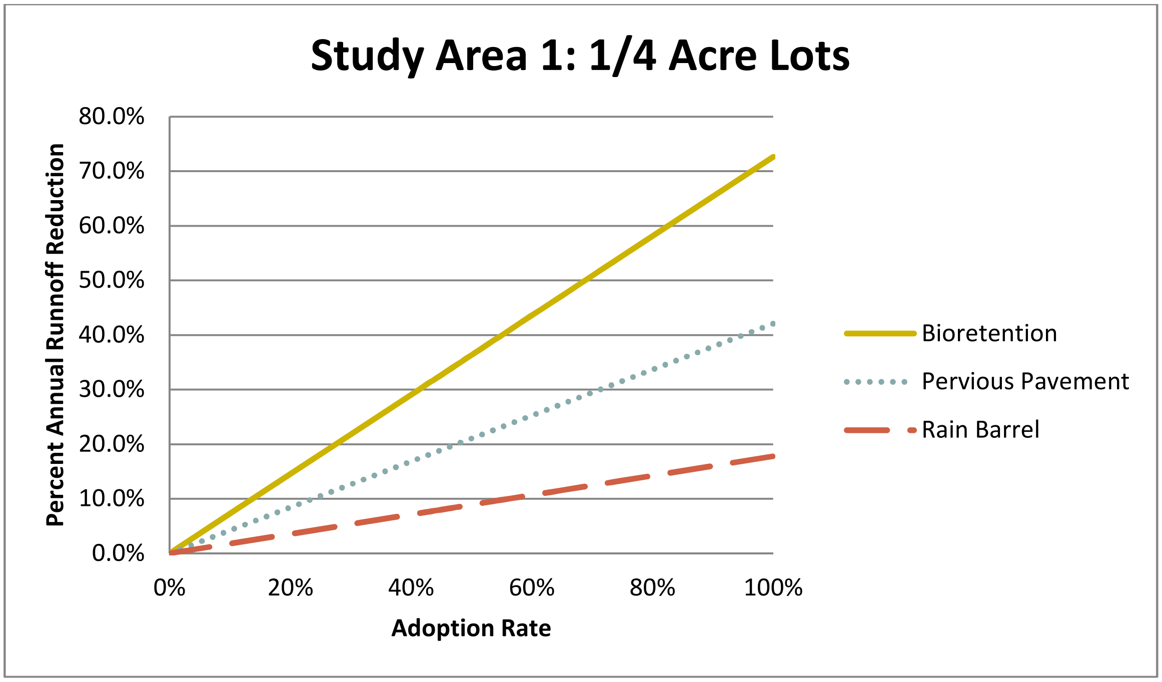


Figure 6: Runoff reduction percentage simulated for each of the LID practices applied to 1/4-acre lots within study area 1 based on adoption rate.

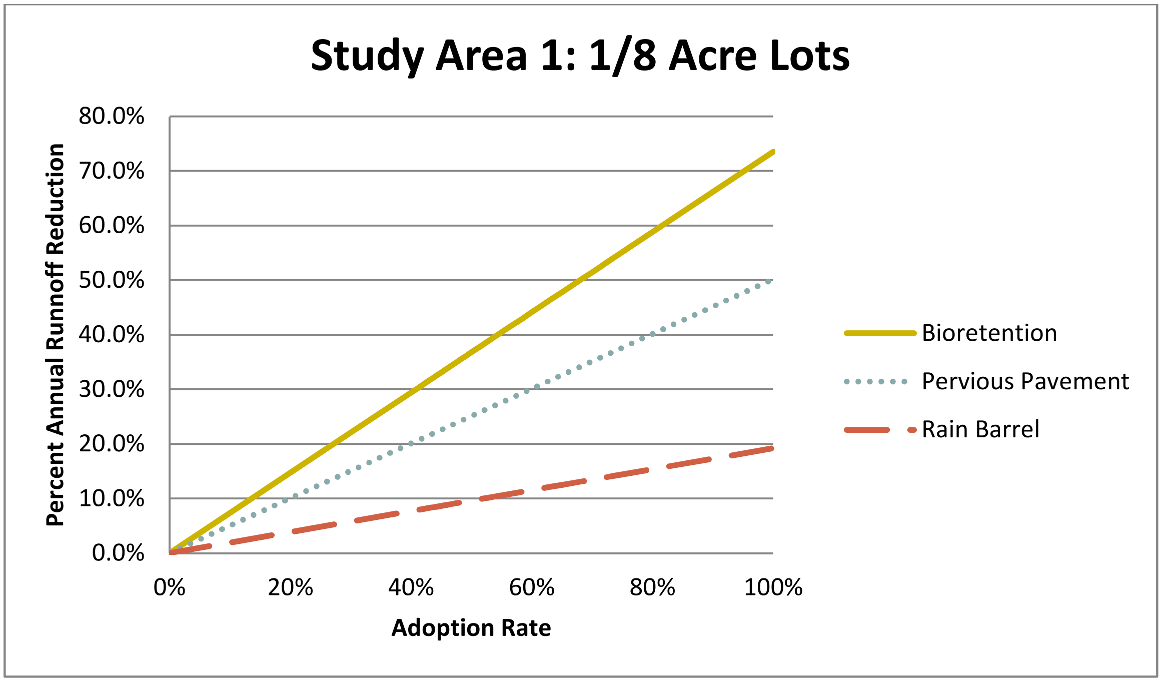


Figure 7: Runoff reduction percentage simulated for each of the LID practices applied to 1/8-acre lots within study area 1 based on adoption rate.

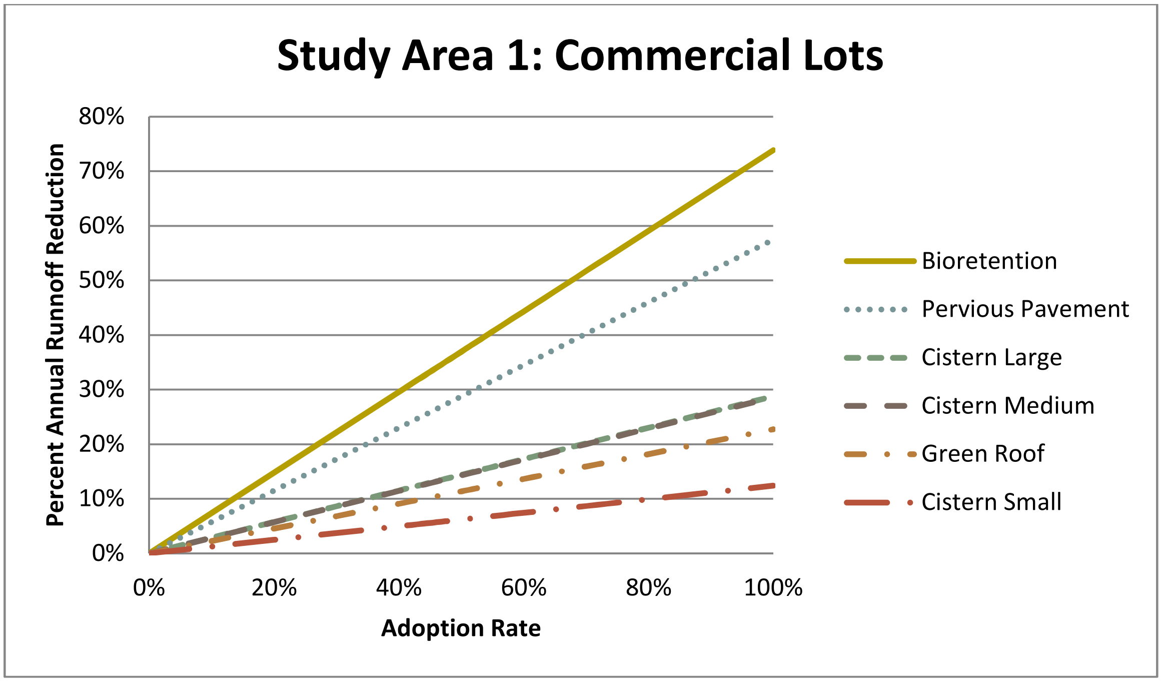


Figure 8: Runoff reduction percentage simulated for each of the LID practices applied to commercial lots within study area 1 based on adoption rate.

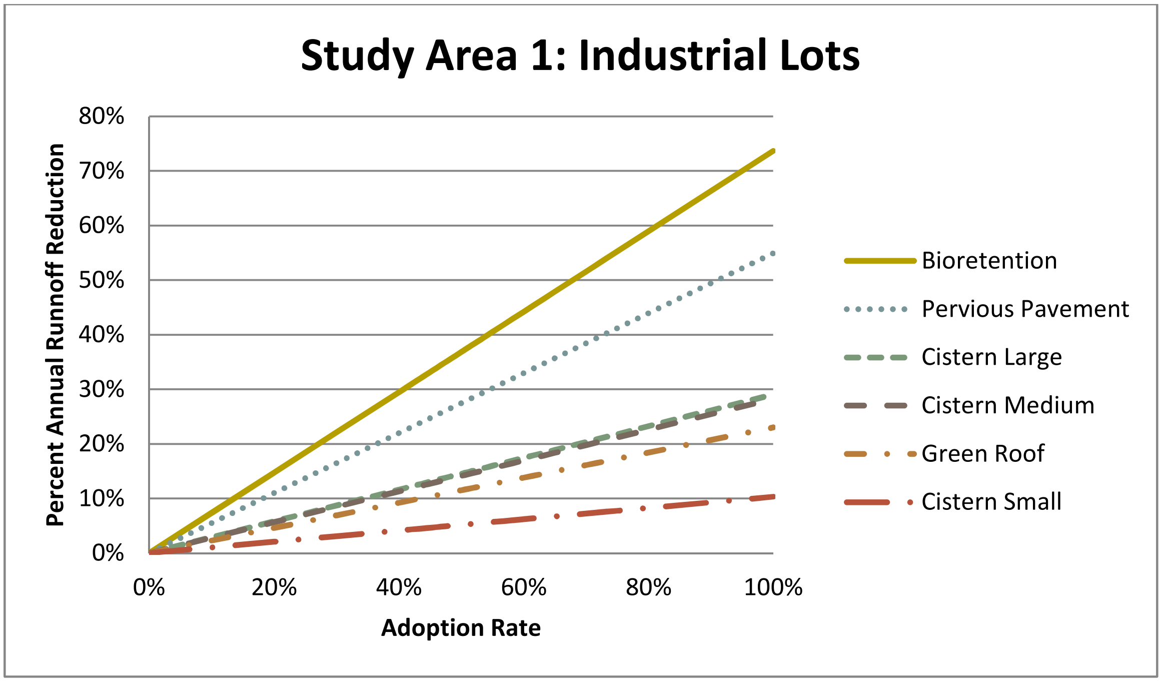


Figure 9: Runoff reduction percentage simulated for each of the LID practices applied to industrial lots within study area 1 based on adoption rate.

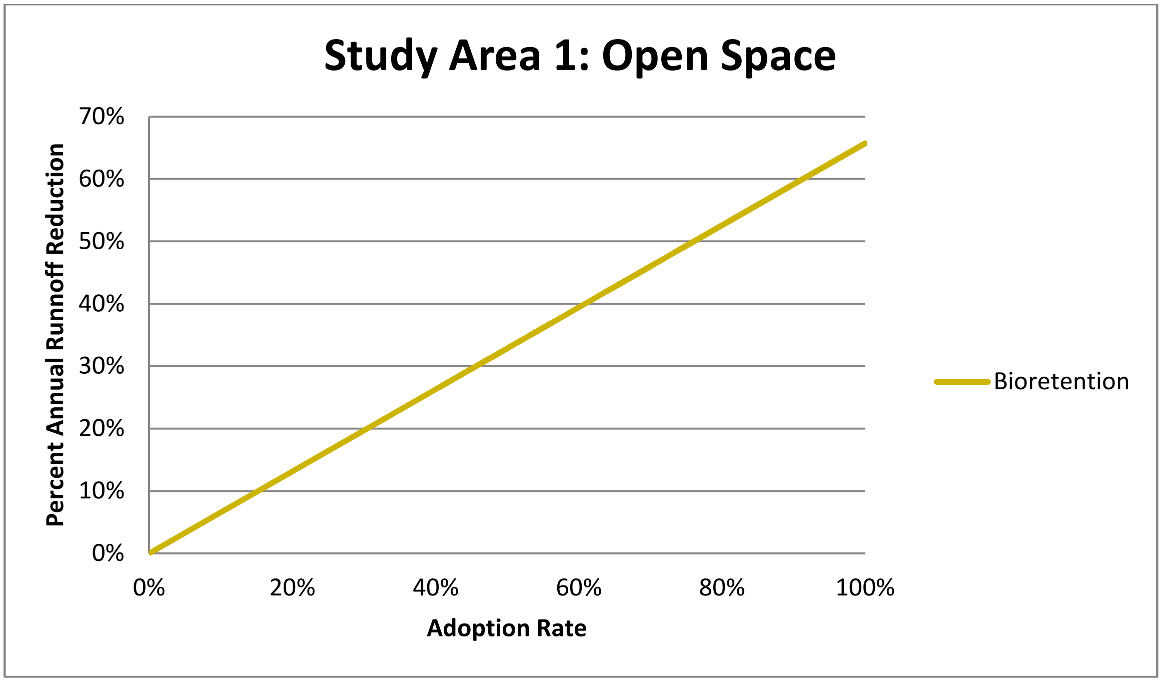


Figure 10: Runoff reduction percentage simulated for bioretention systems in areas of open space. No other LID practices were applied to this land use type.

Finally, when these practices are applied at the same rate of adoption to all appropriate land use types in the study area (Figure 11), the performance of the selected LID practices can be seen for the entire study area. From this stand point, bioretention and pervious pavement provided the greatest volume of runoff reduction within the study area, with pervious pavement being able to provide almost a 50 percent reduction and bioretention providing just over a 70 percent reduction in runoff over the entire study area. Next the medium and large sized cisterns, which were only applied to commercial and industrial uses, provided around a 15 percent runoff reduction across the entire study area. Green roofs, also only applied to commercial and industrial uses, and rain barrels, which were only used on residential uses, both provided approximately a 10 percent reduction in runoff for the study area. The small sized cistern provided the smallest reductions only achieving about a 5 percent reduction in runoff.

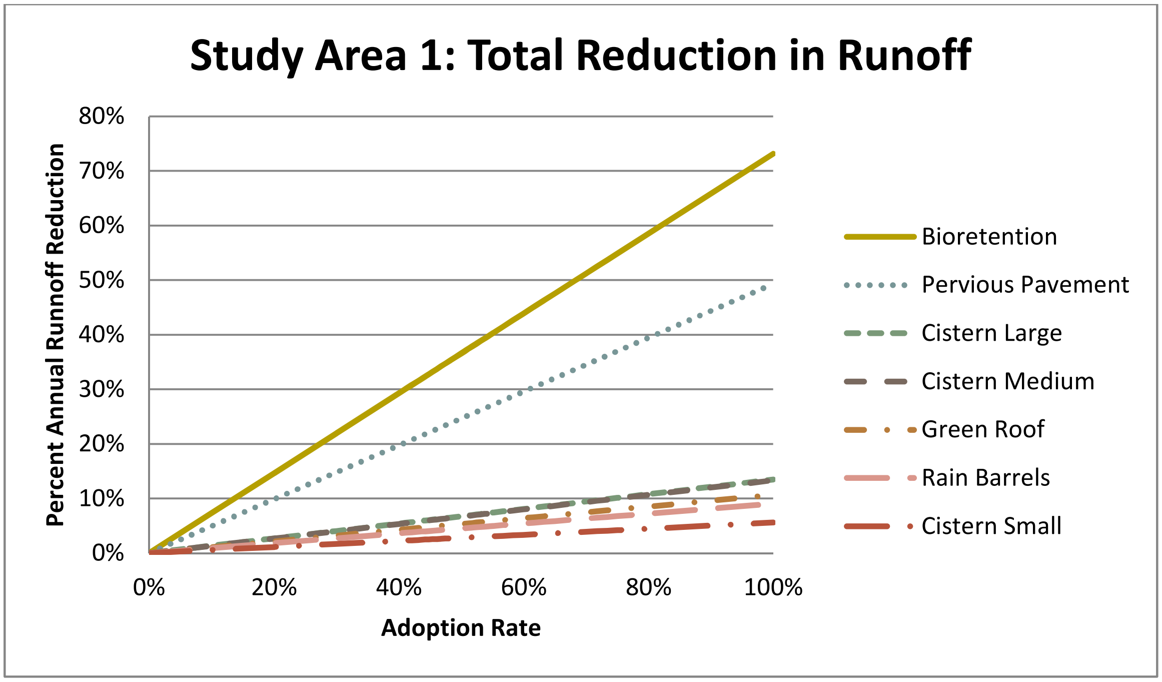


Figure 11: Runoff reduction percentage simulated for each of the LID practices when they were applied at the same rate to all of the land use types within study area 1 based on the adoption rate.

In the downtown urban area, study area 2, similar trends were observed (Figures 12-15). At the lot level, bioretention again provided the highest level of reduction for each use type with over 70 percent reduction in runoff. Pervious pavement demonstrates the second highest level for both residential uses in this area and the industrial land use type, providing approximately 40 to 55 percent reductions. However, for commercial areas, runoff reductions from green roofs exceeded pervious pavement reductions, with green roofs providing almost 50 percent while pervious pavement only provided an approximate 30 percent reduction. Green roofs in the industrial areas showed the capability to reduce runoff by over 20 percent. Rain barrels also provided almost a 20 percent reduction in runoff for the residential uses in this study area.

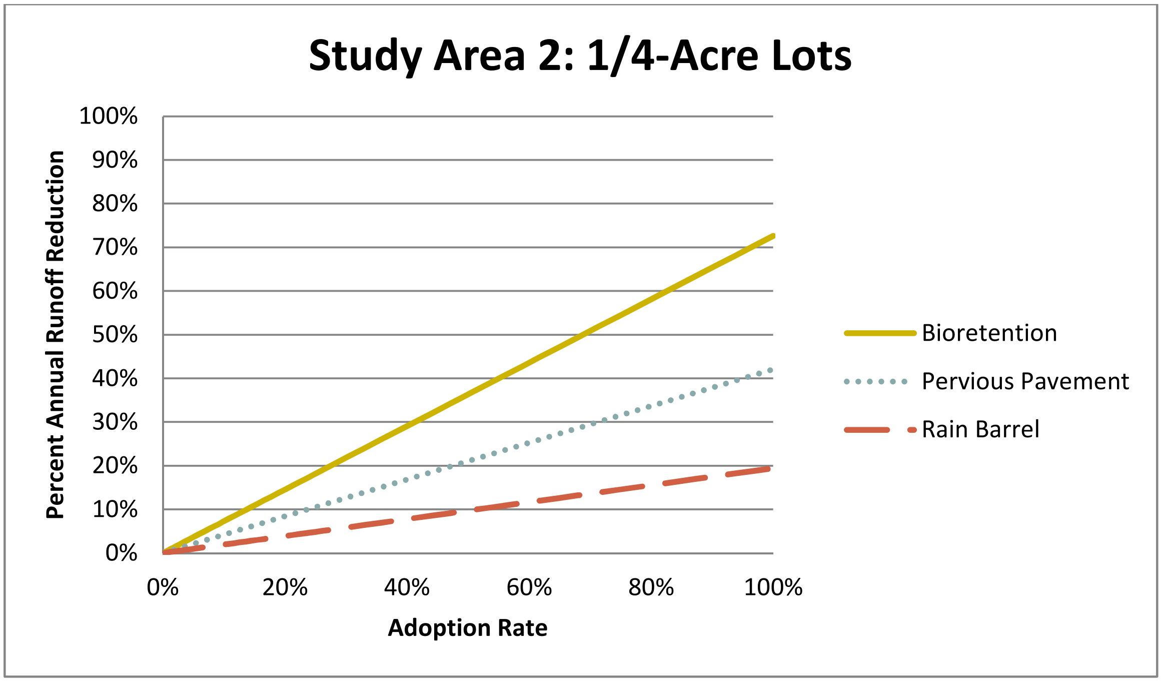


Figure 12: Runoff reduction percentage simulated for each of the LID practices applied to 1/4-acre lots within study area 2 based on adoption rate.

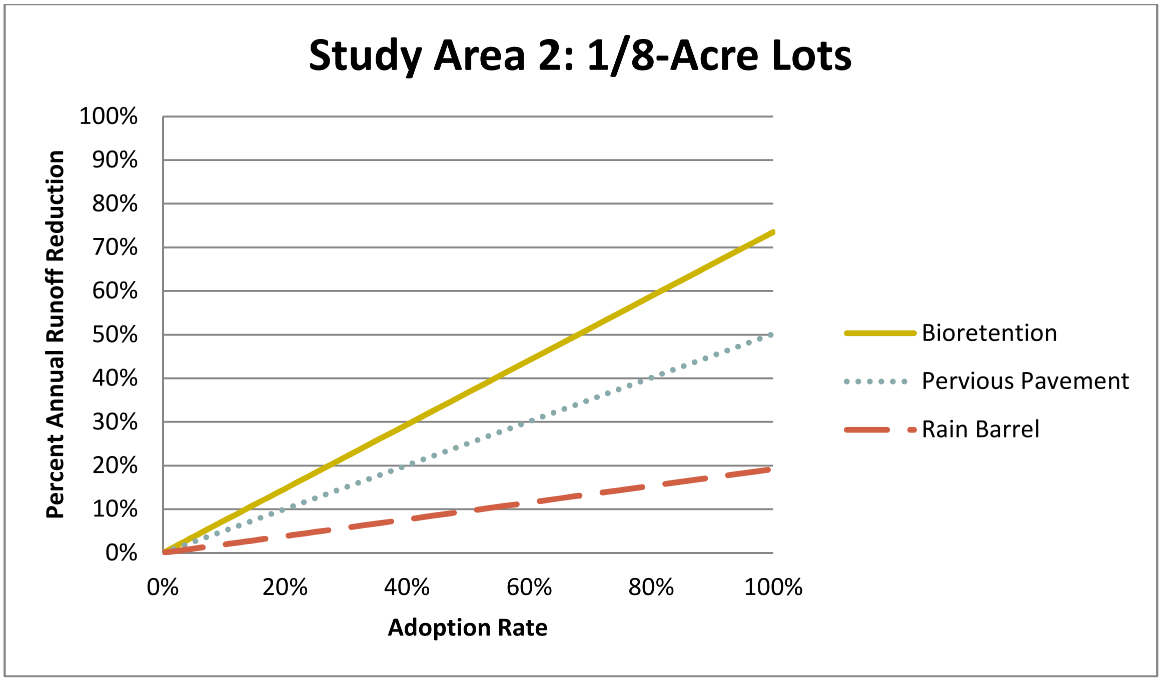


Figure 13: Runoff reduction percentage simulated for each of the LID practices applied to 1/8-acre lots within study area 2 based on adoption rate.

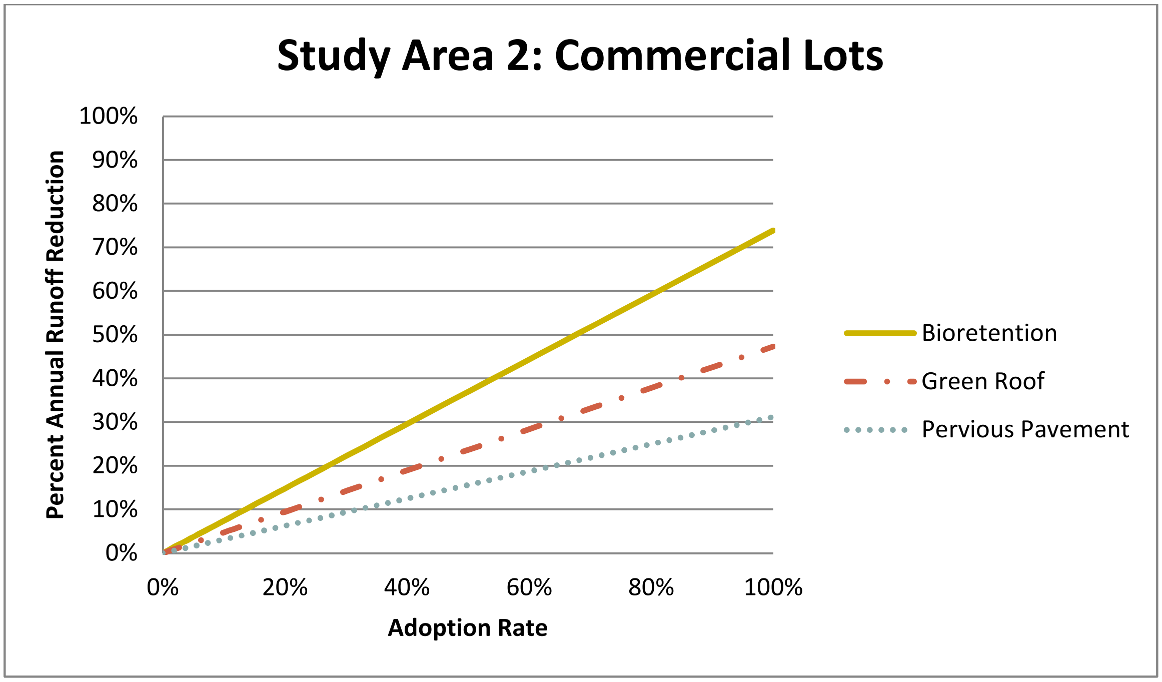


Figure 14: Runoff reduction percentage simulated for each of the LID practices applied to commercial lots within study area 2 based on adoption rate.

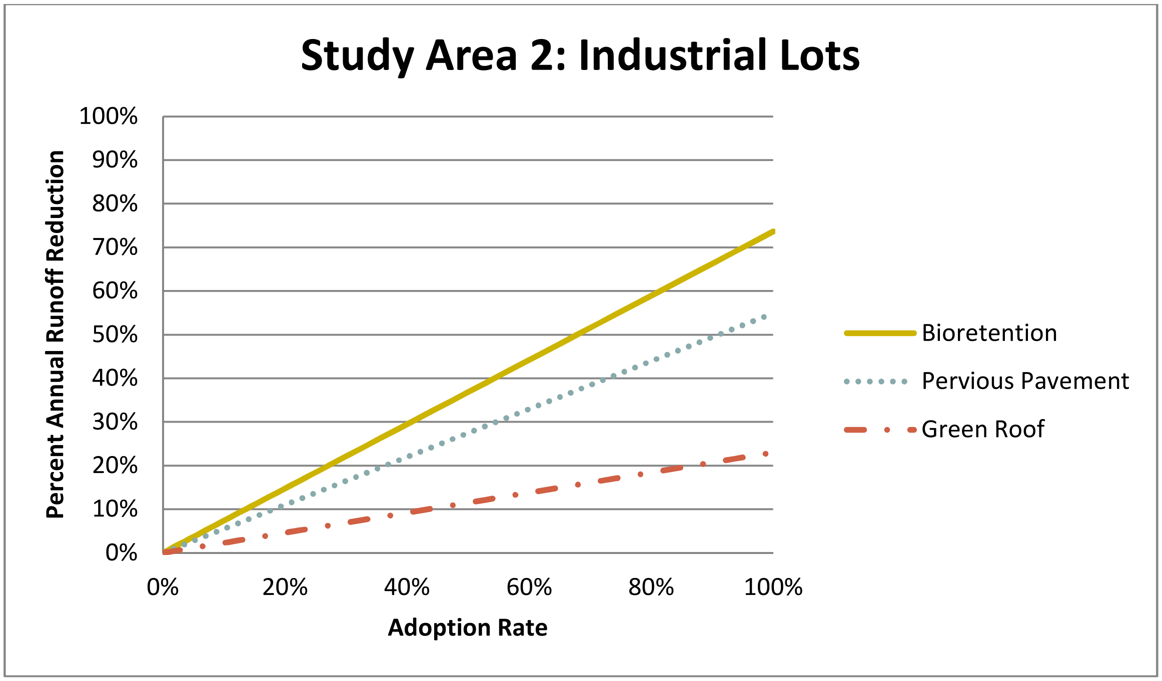


Figure 15: Runoff reduction percentage simulated for each of the LID practices applied to industrial lots within study area 2 based on adoption rate.

With the practices applied at the same rate of adoption to all appropriate land use types in study area 2 (Figure 16), the performance of the selected LID practices can be seen for the entire study area. At this scale, bioretention continued to provide the best reduction in runoff volumes, with a maximum reduction of almost 75 percent. Green roofs and pervious pavement both provided around a 40 percent reduction in runoff, with green roofs slightly out performing pervious pavement. When examined as part of the entire study area, rain barrels only provided an approximately 2 percent reduction in runoff volume at the maximum adoption level.

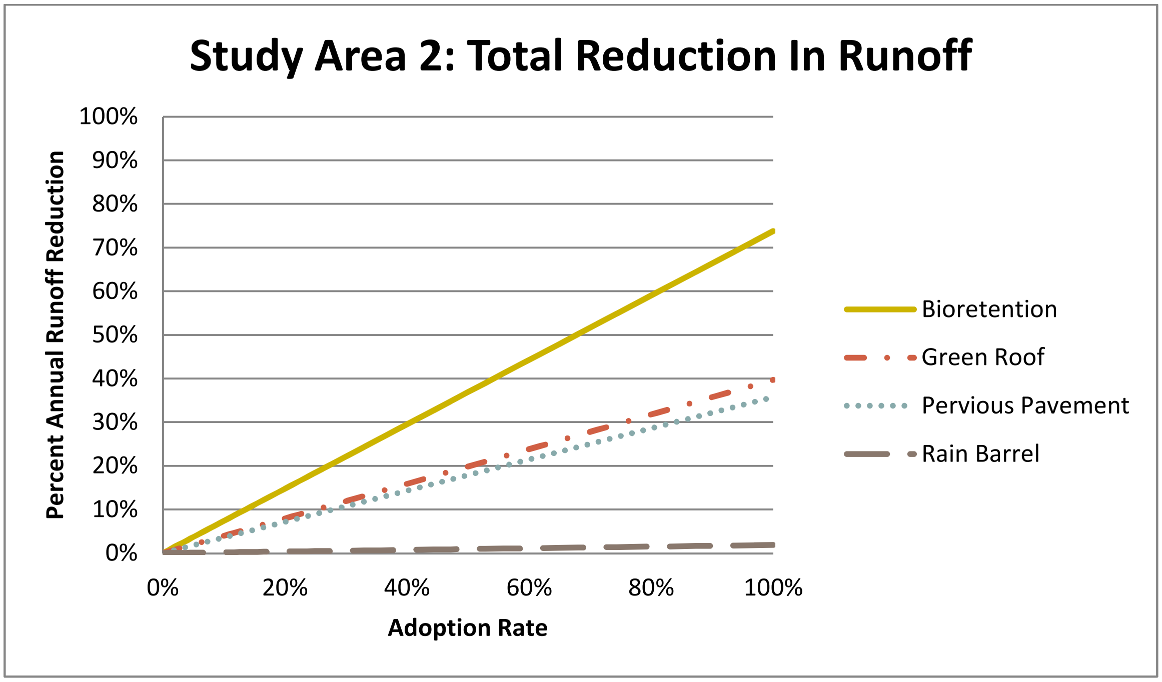


Figure 16: Runoff reduction percentage simulated for each of the LID practices when they were applied at the same rate to all of the land use types within study area 2 based on the adoption rate.

In the area along the commercial corridor, study area 3, the trends (Figures 17-25) that were observed in study areas 1 and 2 continue. For residential land uses, bioretention is again best with an estimated runoff reduction of over 70 percent, followed by pervious pavement with reduction levels estimated between 40 and 50 percent. Rain barrels again offer the smallest level of reduction of between an estimated 10 and 20 percent. Commercial and industrial use types also continue to follow the established trends in this study area with biorentention followed by pervious pavements, large cisterns, medium cisterns, green roofs, and finally small cisterns.

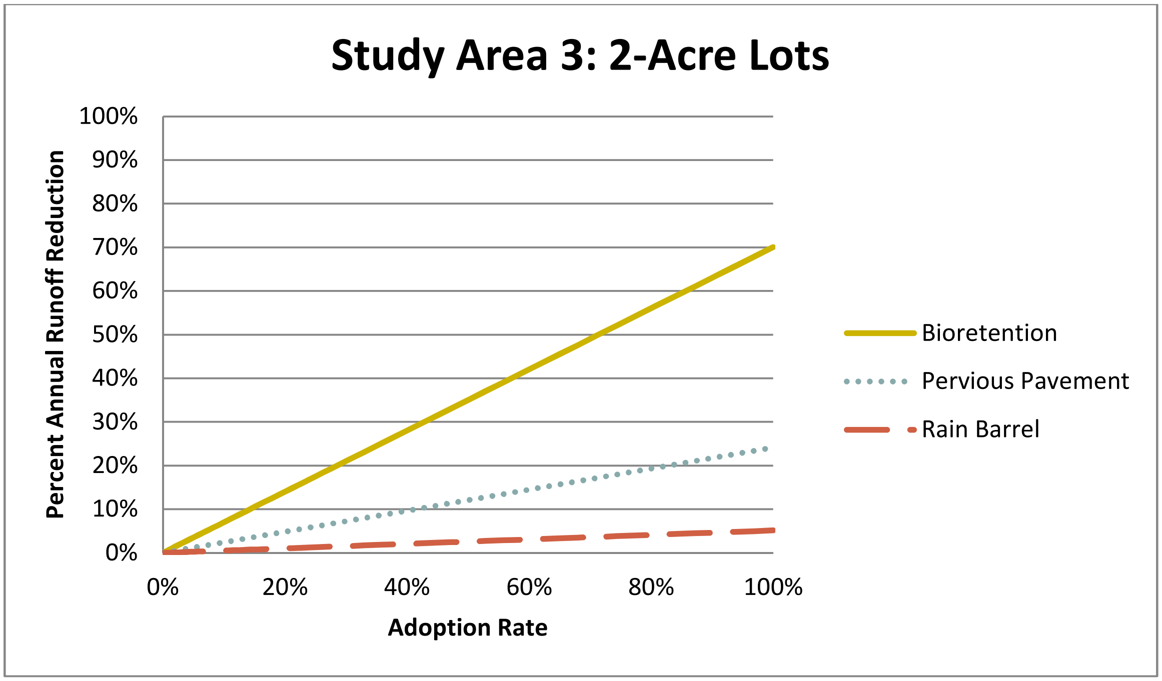


Figure 17: Runoff reduction percentage simulated for each of the LID practices applied to 2-acre lots within study area 3 based on adoption rate.

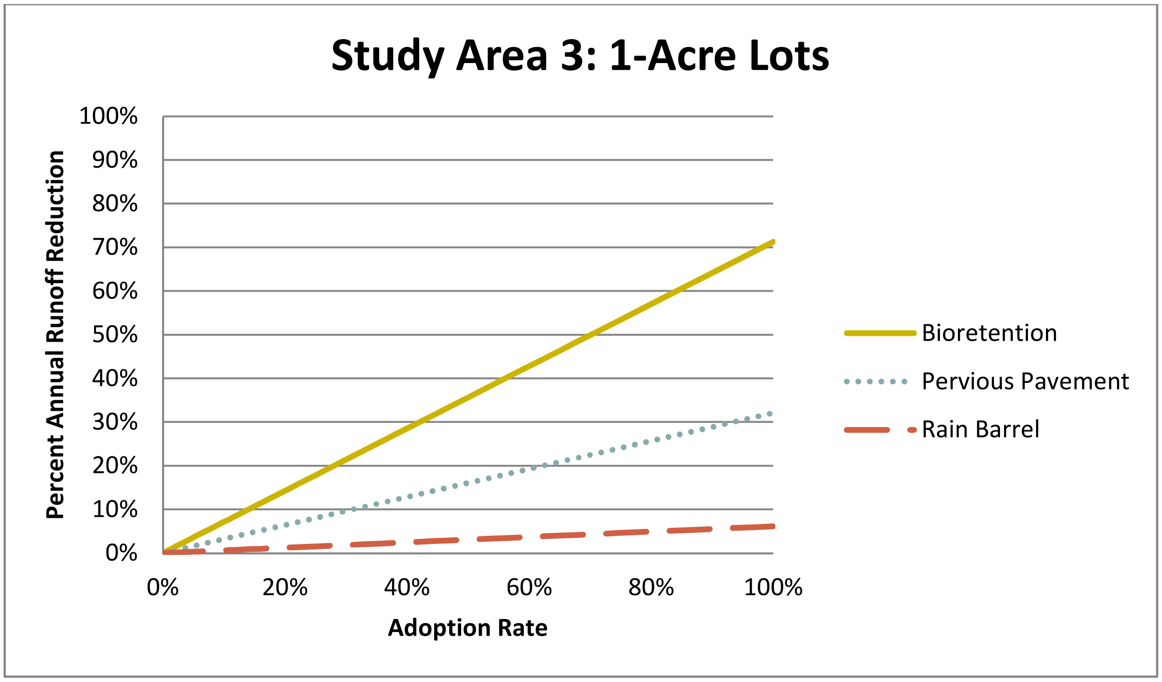


Figure 18: Runoff reduction percentage simulated for each of the LID practices applied to 1-acre lots within study area 3 based on adoption rate.

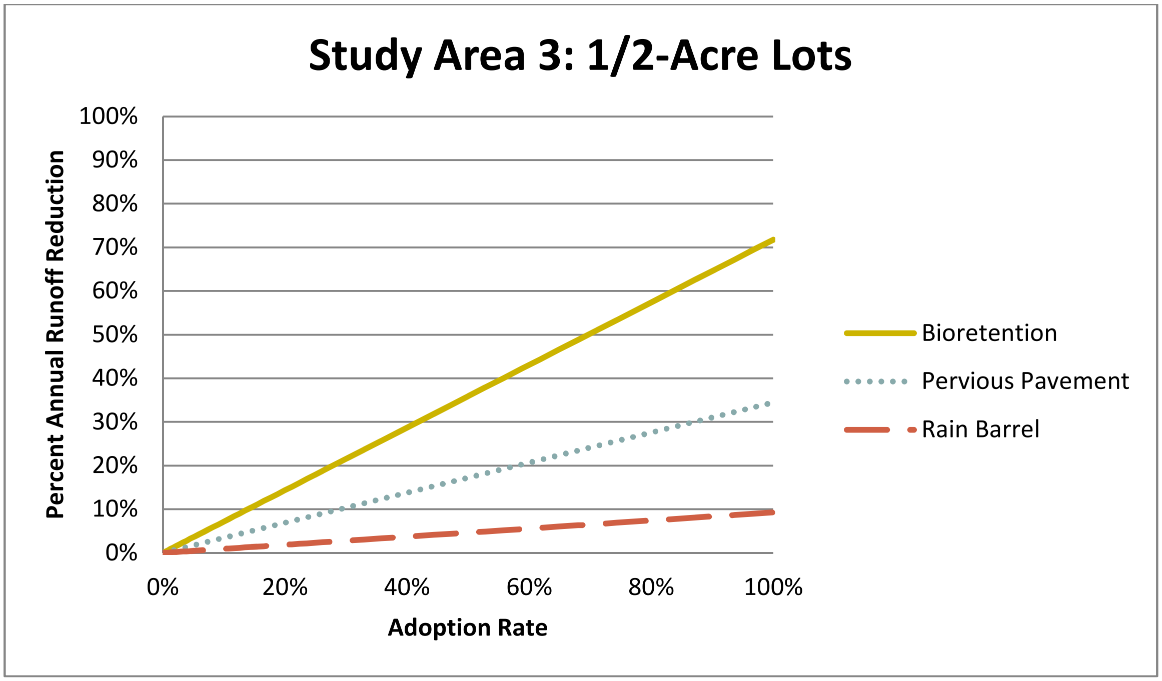


Figure 19: Runoff reduction percentage simulated for each of the LID practices applied to 1/2-acre lots within study area 3 based on adoption rate.

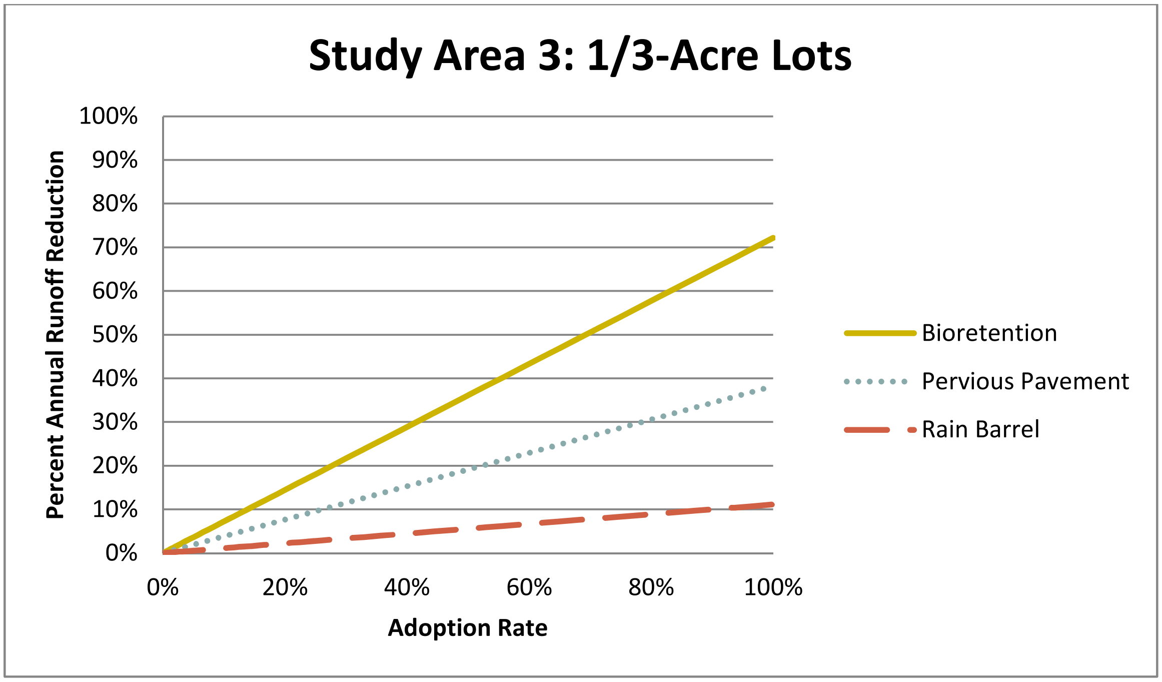


Figure 20: Runoff reduction percentage simulated for each of the LID practices applied to 1/3-acre lots within study area 3 based on adoption rate.

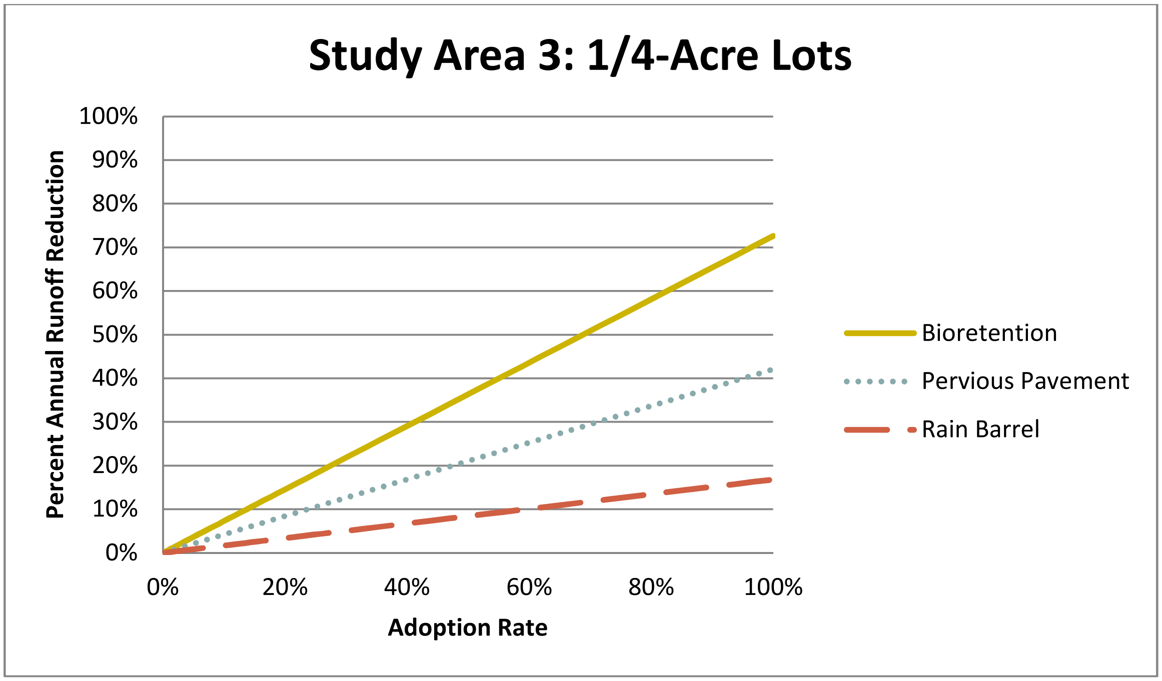


Figure 21: Runoff reduction percentage simulated for each of the LID practices applied to 1/4-acre lots within study area 3 based on adoption rate.

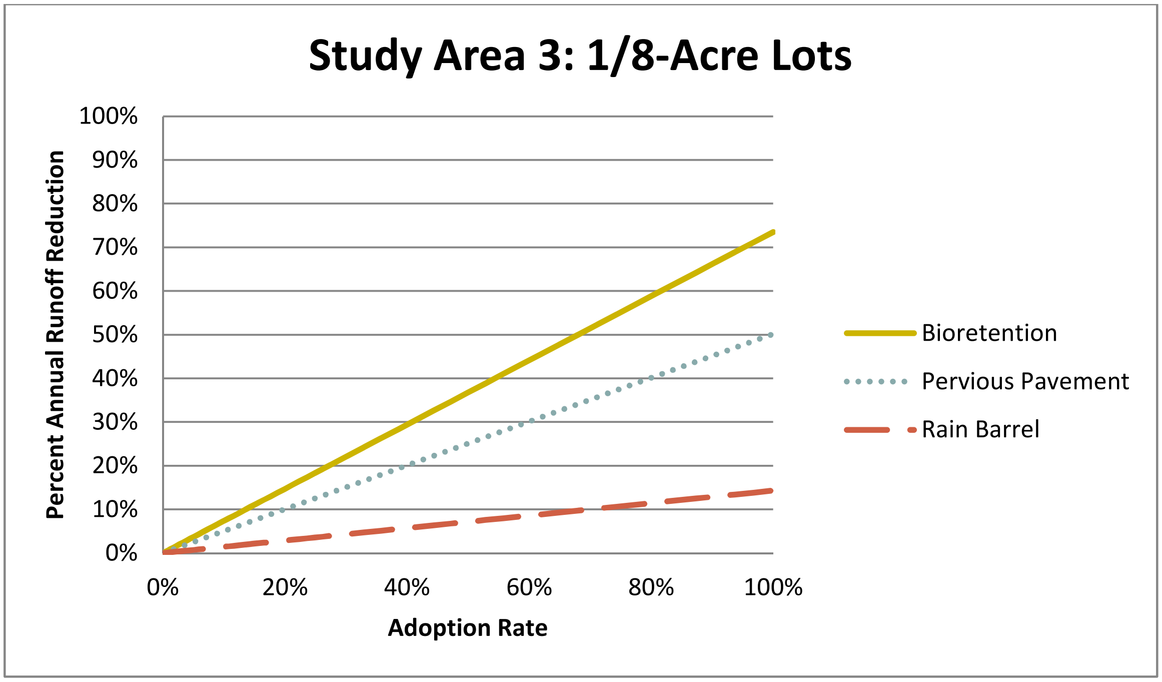


Figure 22: Runoff reduction percentage simulated for each of the LID practices applied to 1/8-acre lots within study area 3 based on adoption rate.

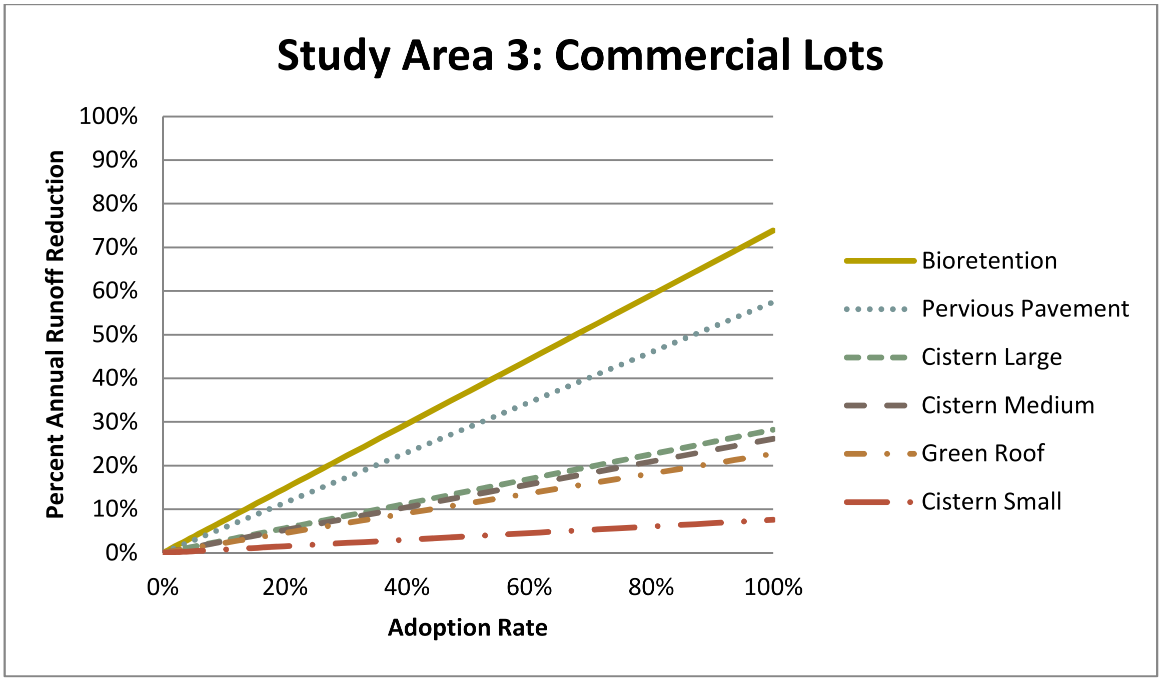


Figure 23: Runoff reduction percentage simulated for each of the LID practices applied to commercial acre lots within study area 3 based on adoption rate.

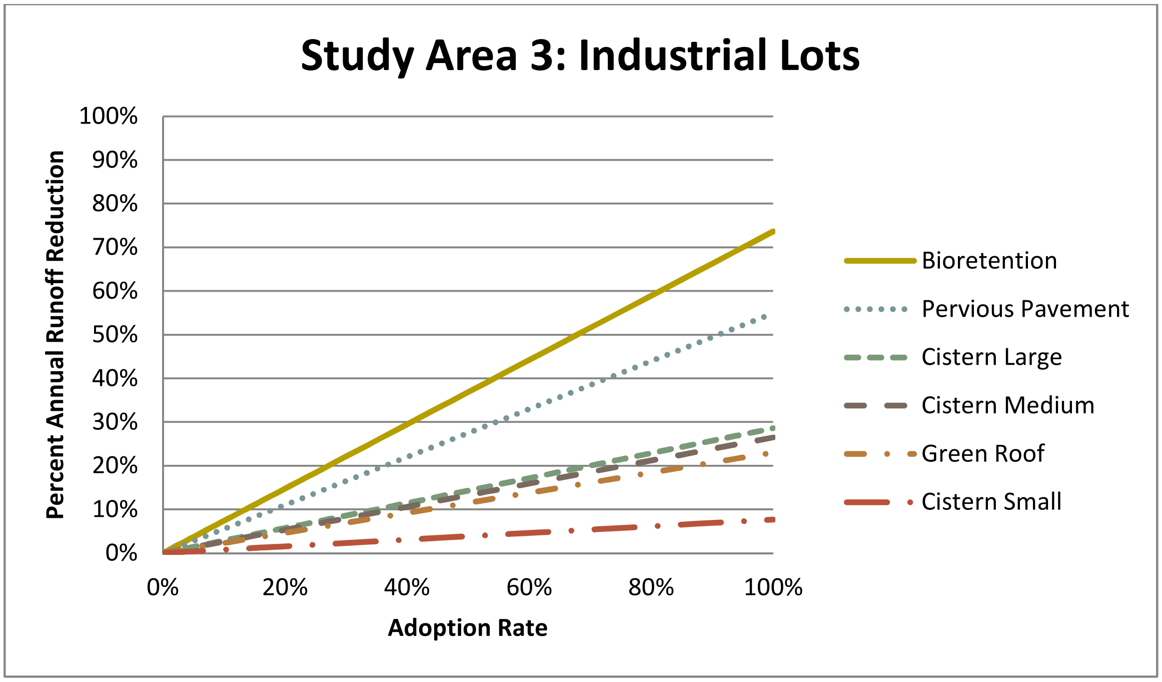


Figure 24: Runoff reduction percentage simulated for each of the LID practices applied to industrial lots within study area 3 based on adoption rate.

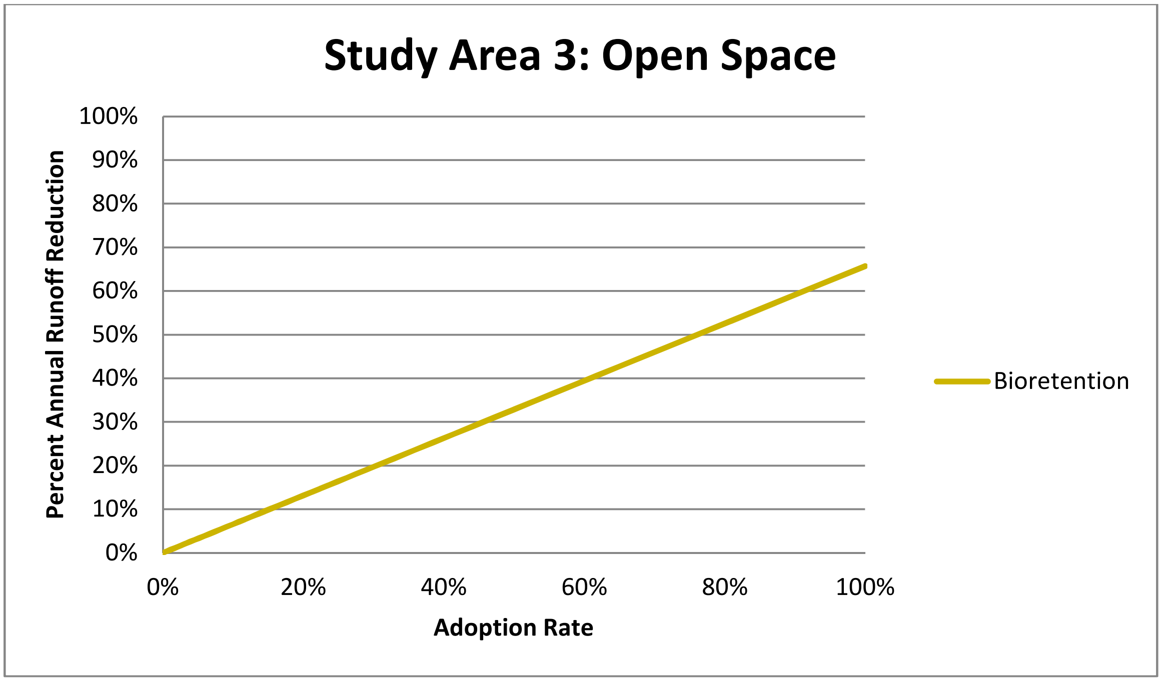


Figure 25: Runoff reduction percentage simulated for bioretention systems in areas of open space. No other LID practices were applied to this use type.

Again looking at the practices being adopted evenly across the study area (Figure 26), a better idea of the effectiveness of each practice within the study area is gained. From this perspective, bioretention and pervious pavements generated the most significant reduction in runoff, over 70 and 50 percent, respectively. The next best performers were green roofs, and the medium and large cisterns, all of which had approximately a 15 percent maximum reduction in runoff. Rain barrels and small cisterns both contributed less than a 10 percent reduction in runoff. Rain barrels proved to be slightly more effective than small cisterns.

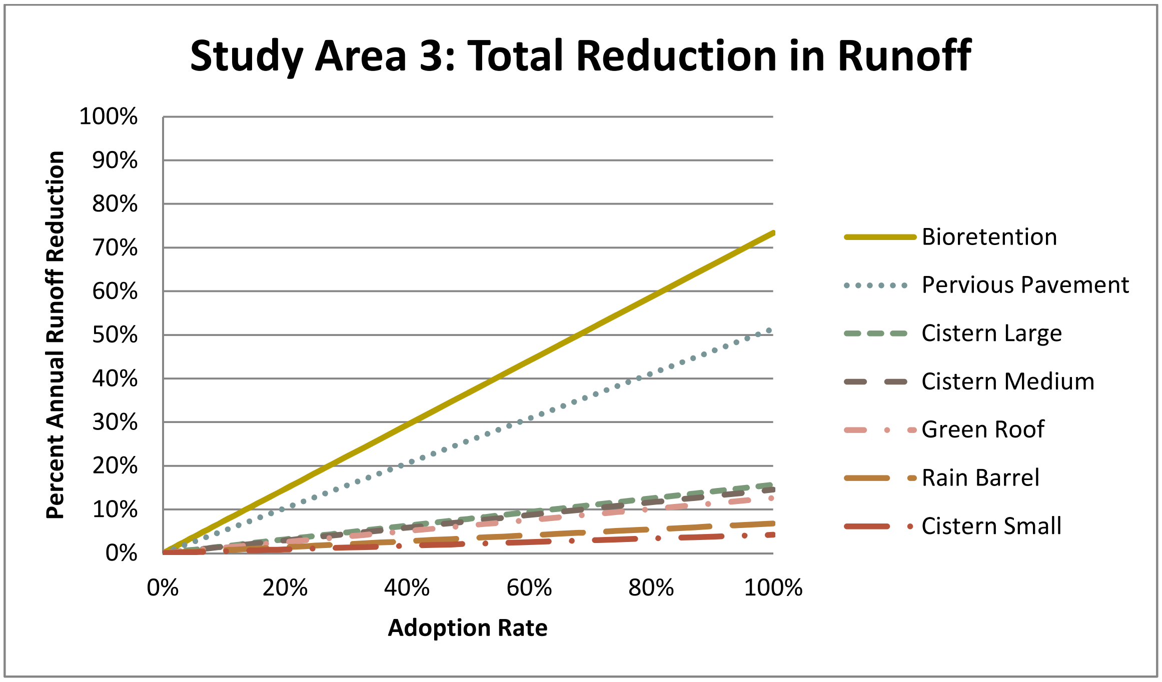


Figure 26: Runoff reduction percentage simulated for each of the LID practices when they were applied at the same rate to all of the land use types within study area 3 based on the adoption rate.

The more modern residential subdivisions, study area 4, showed trends (Figures 27-33) similar to those seen in the residential land uses from study areas 1, 2, and 3. The trends for the total study area (Figure 34) reflect those seen among the individual land use types, with bioretention exceeding 70 percent, pervious pavement around 40 percent, and rain barrels at approximately 15 percent runoff reduction.

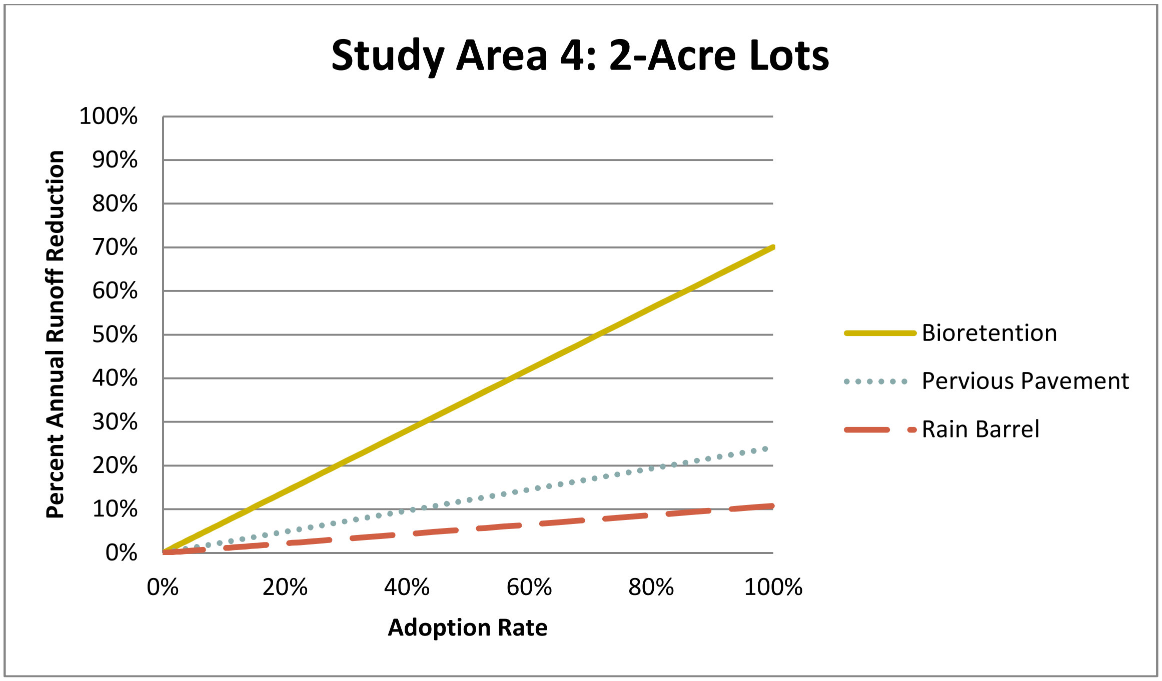


Figure 27: Runoff reduction percentage simulated for each of the LID practices applied to 2-acre lots within study area 4 based on adoption rate.

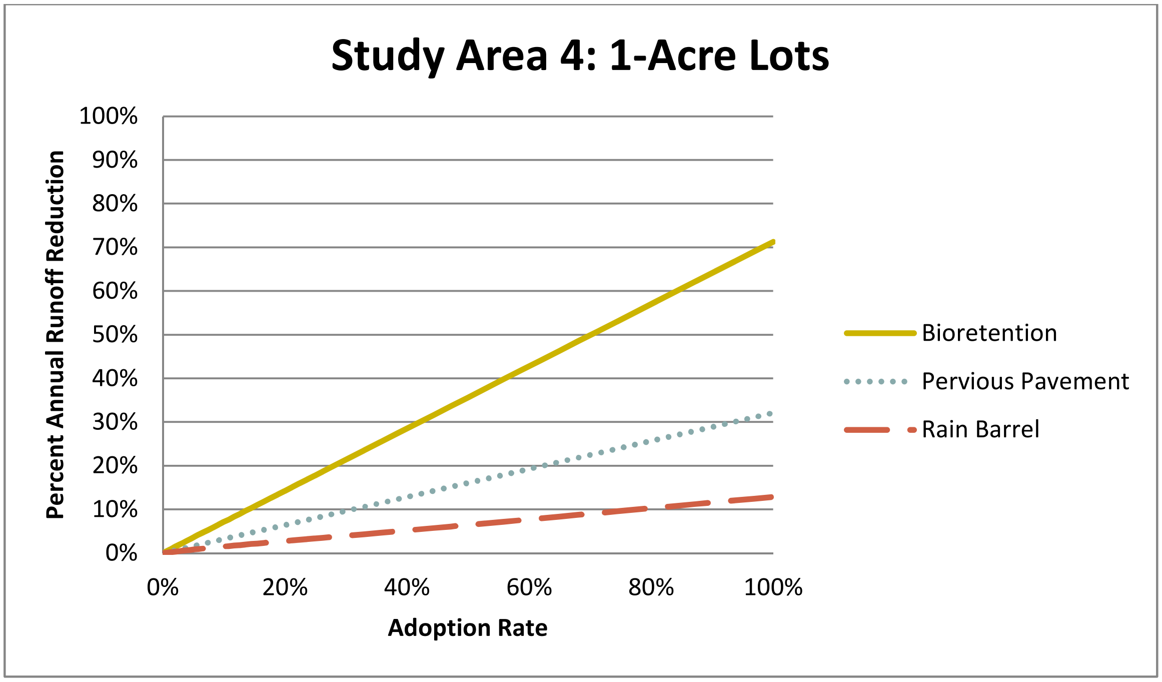


Figure 28: Runoff reduction percentage simulated for each of the LID practices applied to 1-acre lots within study area 4 based on adoption rate.

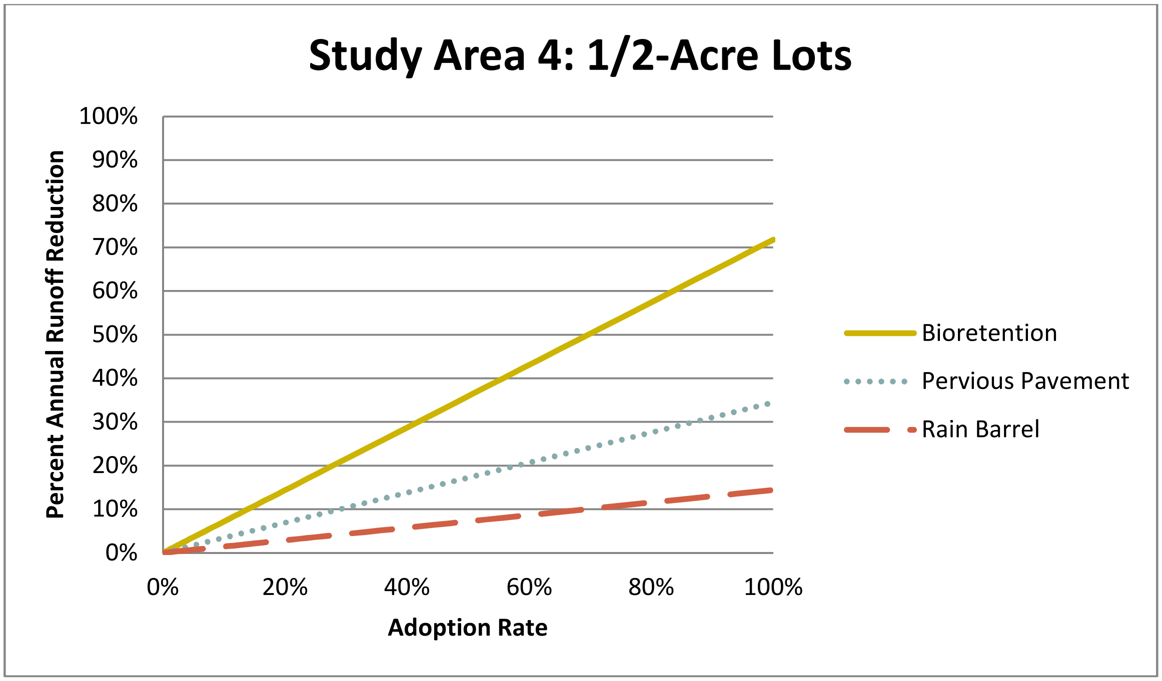


Figure 29: Runoff reduction percentage simulated for each of the LID practices applied to 1/2-acre lots within study area 4 based on adoption rate.

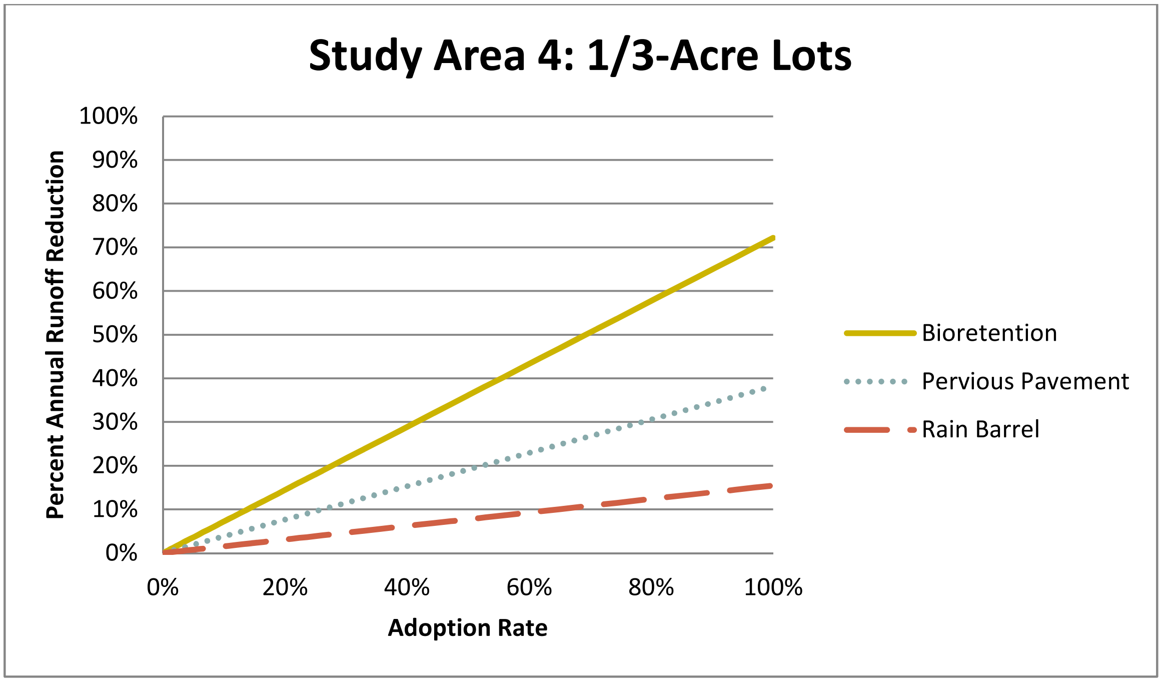


Figure 30: Runoff reduction percentage simulated for each of the LID practices applied to 1/3-acre lots within study area 4 based on adoption rate.

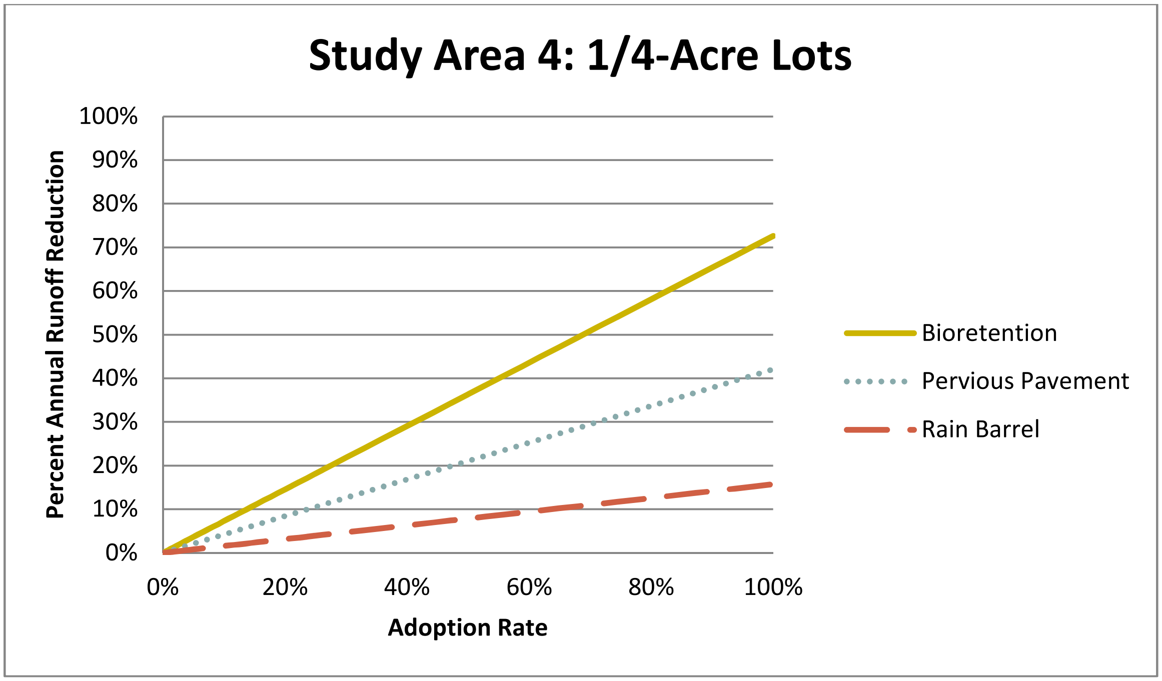


Figure 31: Runoff reduction percentage simulated for each of the LID practices applied to 1/4-acre lots within study area 4 based on adoption rate.

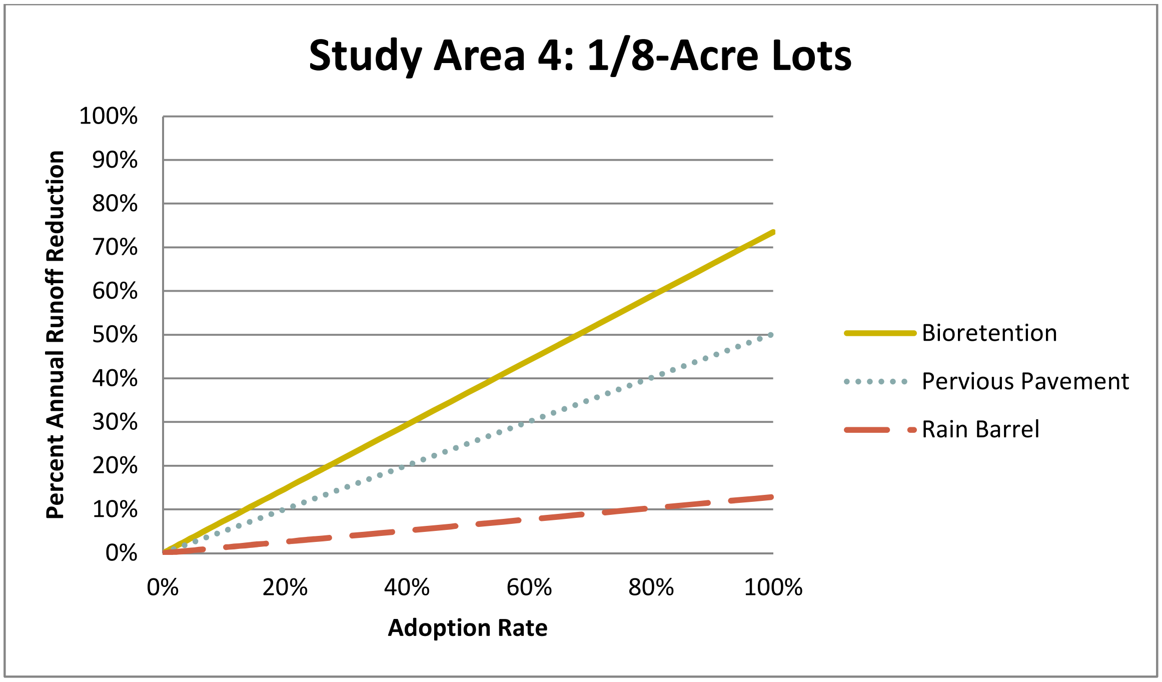


Figure 32: Runoff reduction percentage simulated for each of the LID practices applied to 1/8-acre lots within study area 4 based on adoption rate.

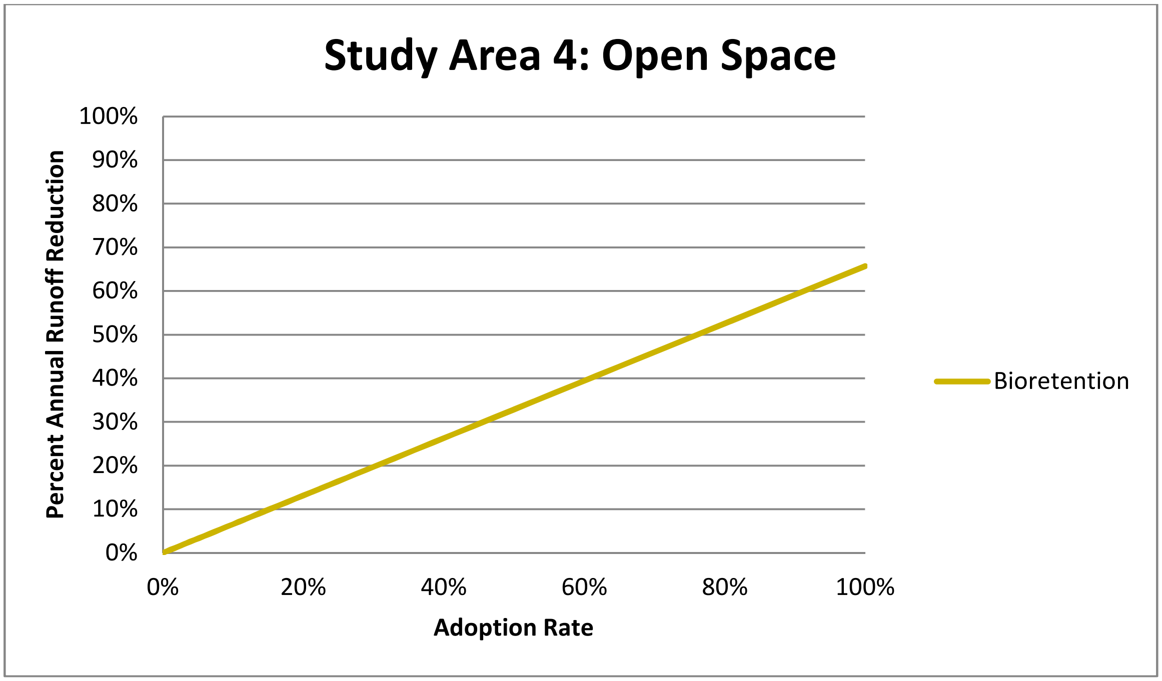


Figure 33: Runoff reduction percentage simulated for bioretention systems in areas of open space. No other LID practices were applied to this use type.

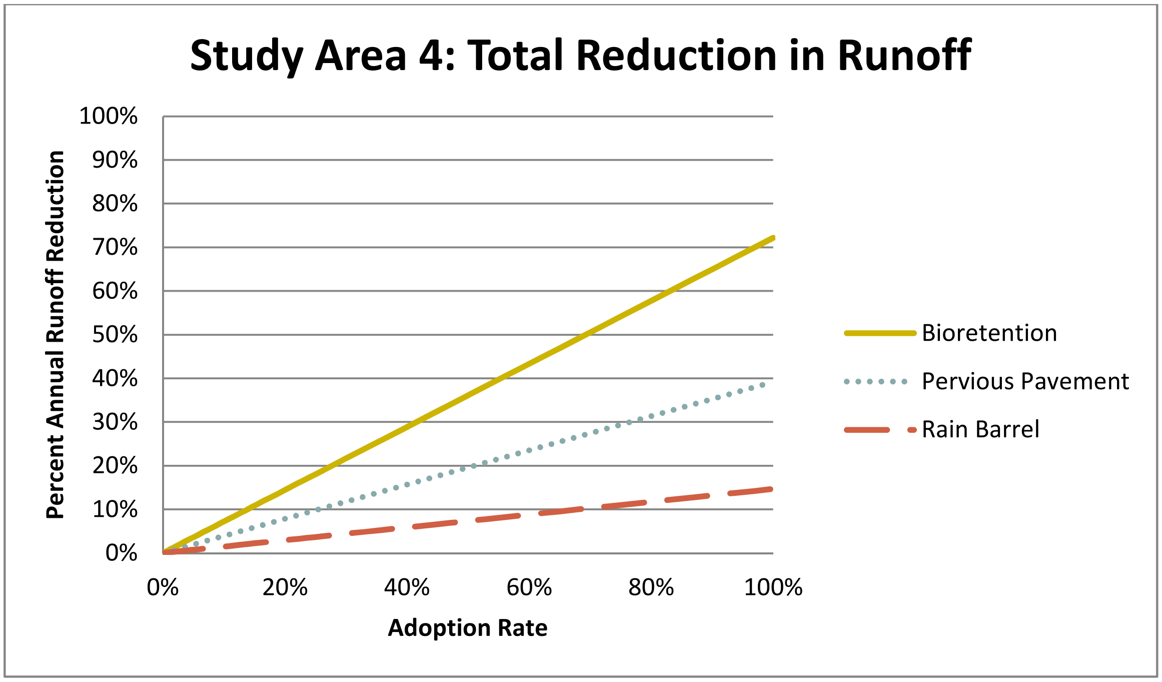


Figure 34: Runoff reduction percentage simulated for each of the LID practices when they were applied at the same rate to all of the land use types within study area 3 based on the adoption rate.

Tables 5-8 provide the slopes of the lines in Figures 2-34. These tables show the slope (m) in the lines described by the formula y=mx, where y is the percent reduction in runoff and x is the percent of the area on which the LID practice will be adopted. Examining the slopes of these lines provides an easy point of comparison for the LID practice effectiveness in the runoff reduction for each of the land use types and study areas. These slopes demonstrate that little variation occurs in the runoff reduction effectiveness of the selected LID practices between the study areas. The most notable variation occurs in the commercial land use type in study area 2 where the higher percentage of roof area made green roofs more effective than pervious pavement. The slopes also demonstrate a consistent trend when compared between land use types.

This trend shows that the LID practices become more effective in reducing runoff as the density of impervious surfaces increases.

Table 5: Relationship (slope) between adoption rate and percentage of runoff reduction in study area 1.

| **Study Area 1: Relationship (Slope) Between Adoption Rate and Percentage of Runoff Reduction** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Landuse Type** | **Rain Barrel** | **Cistern Small** | **Cistern Medium** | **Cistern Large** | **Bioretention** | **Permeable Pavement** | **Green Roof** |
| 2 Ac Lots | 0.10 | - | - | - | 0.70 | 0.24 | - |
| 1 Ac Lots | 0.14 | - | - | - | 0.71 | 0.32 | - |
| 1/2 Ac Lots | 0.14 | - | - | - | 0.72 | 0.34 | - |
| 1/3 Ac Lots | 0.14 | - | - | - | 0.72 | 0.38 | - |
| 1/4 Ac Lots | 0.18 | - | - | - | 0.74 | 0.50 | - |
| 1/8 Ac Lots | 0.19 | - | - | - | 0.74 | 0.50 | - |
| Industrial | - | 0.10 | 0.28 | 0.29 | 0.74 | 0.55 | 0.23 |
| Commercial | - | 0.12 | 0.286 | 0.288 | 0.74 | 0.57 | 0.23 |
| Opens Space | - | - | - | - | 0.66 | - | - |
| Implemented evenly across all uses | 0.09 | 0.06 | 0.133 | 0.135 | 0.73 | 0.49 | 0.11 |

Table 6: Relationship (slope) between adoption rate and percentage of runoff reduction in study area 2.

| **Study Area 2: Relationship (Slope) Between Adoption Rate and Percentage of Runoff Reduction** | | | | |
|---|---|---|---|---|
| **Landuse Type** | **Rain Barrel** | **Bioretention** | **Permeable Pavement** | **Green Roof** |
| 1/4 Ac Lots | 0.19 | 0.73 | 0.47 | - |
| 1/8 Ac Lots | 0.19 | 0.74 | 0.50 | - |
| Industrial | - | 0.74 | 0.55 | 0.23 |
| Commercial | - | 0.74 | 0.31 | 0.47 |
| Implemented evenly across all uses | 0.09 | 0.74 | 0.36 | 0.40 |

Table 7: Relationship (slope) between adoption rate and percentage of runoff reduction in study area 3.

| **Study Area 3: Relationship (Slope) Between Adoption Rate and Percentage of Runoff Reduction** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Landuse Type** | **Rain Barrel** | **Cistern Small** | **Cistern Medium** | **Cistern Large** | **Bioretention** | **Permeable Pavement** | **Green Roof** |
| 2 Ac Lots | 0.05 | - | - | - | 0.70 | 0.24 | - |
| 1 Ac Lots | 0.06 | - | - | - | 0.71 | 0.32 | - |
| 1/2 Ac Lots | 0.09 | - | - | - | 0.72 | 0.34 | - |
| 1/3 Ac Lots | 0.11 | - | - | - | 0.72 | 0.38 | - |
| 1/4 Ac Lots | 0.17 | - | - | - | 0.73 | 0.42 | - |
| 1/8 Ac Lots | 0.14 | - | - | - | 0.74 | 0.50 | - |
| Industrial | - | 0.08 | 0.26 | 0.28 | 0.74 | 0.55 | 0.23 |
| Commercial | - | 0.08 | 0.26 | 0.28 | 0.74 | 0.57 | 0.23 |
| Opens Space | - | - | - | - | 0.66 | - | - |
| Implemented evenly across all uses | 0.07 | 0.04 | 0.14 | 0.16 | 0.73 | 0.51 | 0.13 |

Table 8: Relationship (slope) between adoption rate and percentage of runoff reduction in study area 4.

| **Study Area 4: Relationship (Slope) Between Adoption Rate and Percentage of Runoff Reduction** | | | |
|---|---|---|---|
| **Landuse Type** | **Rain Barrel** | **Bioretention** | **Permeable Pavement** |
| 2 Ac Lots | 0.10 | 0.70 | 0.24 |
| 1 Ac Lots | 0.13 | 0.71 | 0.32 |
| 1/2 Ac Lots | 0.14 | 0.72 | 0.14 |
| 1/3 Ac Lots | 0.15 | 0.72 | 0.38 |
| 1/4 Ac Lots | 0.16 | 0.73 | 0.42 |
| 1/8 Ac Lots | 0.13 | 0.74 | 0.50 |
| Opens Space | - | 0.66 | - |
| Implemented evenly across all uses | 0.15 | 0.72 | 0.39 |

## 4.2 Cost

The cost of installing the LID practices increased proportionately as the treatment area increased. This trend was observed across all of the study areas and land uses categories. The unit costs (see Table 2) were found to be the effective slope for the cost of installation.

For a selected practice, the cost per cubic meter of runoff reduction in an average year would be the same regardless of the adoption rate (Tables 9-12). These values were also observed to be relatively consistent across all study areas. Based on this metric, the small cisterns were found to provide the lowest cost runoff reduction, between $1 and $3.50 per cubic meter of runoff reduction in an average year. Rain barrels were second lowest in cost ranging between $4 and $11 per cubic meter of runoff reduction in an average year. The runoff reduction cost for bioretention decreased in cost as the land use density increased, starting at over $120 per cubic meter of runoff reduction in an average year for open space areas and decreasing to around $15 per cubic meter of runoff reduction in an average year in commercial areas. Pervious pavement was observed to be consistently between $30 and $40 per cubic meter of runoff reduction in an average year regardless of the land use type or the study area that it was applied to. Green roofs were also consistent, returning the same values, around $140 per cubic meter of runoff reduction in an average year at the low price point, for both commercial and industrial use in all study areas.

Table 9: The approximate cost per cubic meter of runoff reduction based on average year within study area 1.

**Study Area 1: Cost per Cubic Meter of Runoff Reduction Based on an Average Year**

| Landuse Type | Cost | Rain Barrel | Cistern Small | Cistern Medium | Cistern Large | Bioretention | Permeable Pavement | Green Roof |
|---|---|---|---|---|---|---|---|---|
| 2 Ac Lots | Low | $ 5.30 | $ - | $ - | $ - | $ 62.83 | $ 38.77 | $ - |
|  | High | $ 20.13 | $ - | $ - | $ - | $ 859.75 | $ 314.35 | $ - |
| 1 Ac Lots | Low | $ 5.96 | $ - | $ - | $ - | $ 47.36 | $ 38.77 | $ - |
|  | High | $ 22.63 | $ - | $ - | $ - | $ 647.99 | $ 314.35 | $ - |
| 1/2 Ac Lots | Low | $ 5.06 | $ - | $ - | $ - | $ 41.04 | $ 38.77 | $ - |
|  | High | $ 19.23 | $ - | $ - | $ - | $ 561.55 | $ 314.35 | $ - |
| 1/3 Ac Lots | Low | $ 5.05 | $ - | $ - | $ - | $ 36.21 | $ 38.77 | $ - |
|  | High | $ 19.20 | $ - | $ - | $ - | $ 495.45 | $ 314.35 | $ - |
| 1/4 Ac Lots | Low | $ 4.11 | $ - | $ - | $ - | $ 30.47 | $ 38.77 | $ - |
|  | High | $ 15.61 | $ - | $ - | $ - | $ 416.93 | $ 314.35 | $ - |
| 1/8 Ac Lots | Low | $ 3.76 | $ - | $ - | $ - | $ 19.85 | $ 38.77 | $ - |
|  | High | $ 14.27 | $ - | $ - | $ - | $ 271.64 | $ 314.35 | $ - |
| Industrial | Low | $ - | $ 3.34 | $ 8.73 | $ 17.43 | $ 18.21 | $ 34.62 | $ 104.40 |
|  | High | $ - | $ 31.45 | $ 82.21 | $ 164.21 | $ 249.14 | $ 280.69 | $ 595.64 |
| Commercial | Low | $ - | $ 2.75 | $ 14.25 | $ 29.34 | $ 15.78 | $ 34.50 | $ 104.40 |
|  | High | $ - | $ 25.88 | $ 134.23 | $ 276.41 | $ 215.91 | $ 279.74 | $ 595.64 |
| Opens Space | Low | $ - | $ - | $ - | $ - | $ 123.24 | $ - | $ - |
|  | High | $ - | $ - | $ - | $ - | $ 1,686.41 | $ - | $ - |
| Implemented evenly across all uses | Low | $ 4.08 | $ 2.86 | $ 13.04 | $ 26.69 | $ 24.26 | $ 36.48 | $ 104.40 |
|  | High | $ 15.50 | $ 26.94 | $ 122.86 | $ 251.46 | $ 331.89 | $ 295.79 | $ 595.64 |

Table 10: The approximate cost per cubic meter of runoff reduction based on an average year within study area 2.

**Study Area 2: Cost per Cubic Meter of Runoff Reduction Based on an Average Year**

| Landuse Type | Cost | Rain Barrel | Bioretention | Permeable Pavement | Green Roof |
|---|---|---|---|---|---|
| 1/4 Ac Lots | Low | $ 7.51 | $ 30.47 | $ 38.77 | $ - |
| | High | $ 28.54 | $ 416.93 | $ 314.35 | $ - |
| 1/8 Ac Lots | Low | $ 7.62 | $ 19.85 | $ 38.77 | $ - |
| | High | $ 28.97 | $ 271.64 | $ 314.35 | $ - |
| Industrial | Low | $ - | $ 18.21 | $ 34.62 | $ 104.40 |
| | High | $ - | $ 249.13 | $ 280.70 | $ 595.64 |
| Commercial | Low | $ - | $ 15.78 | $ 34.98 | $ 104.40 |
| | High | $ - | $ 215.91 | $ 283.68 | $ 595.64 |
| Implemented evenly across all uses | Low | $ 7.59 | $ 16.74 | $ 35.40 | $ 104.40 |
| | High | $ 28.85 | $ 229.05 | $ 287.06 | $ 595.64 |

Table 11: The approximate cost per cubic meter of runoff reduction based on an average year within study area 3.

**Study Area 3: Cost per Cubic Meter of Runoff Reduction Based on an Average Year**

| Landuse Type | Cost | Rain Barrel | Cistern Small | Cistern Medium | Cistern Large | Bioretention | Permeable Pavement | Green Roof |
|---|---|---|---|---|---|---|---|---|
| 2 Ac Lots | Low | $ 5.93 | $ - | $ - | $ - | $ 62.83 | $ 38.77 | $ - |
| | High | $ 22.52 | $ - | $ - | $ - | $ 859.75 | $ 314.35 | $ - |
| 1 Ac Lots | Low | $ 10.48 | $ - | $ - | $ - | $ 47.36 | $ 38.77 | $ - |
| | High | $ 39.83 | $ - | $ - | $ - | $ 647.99 | $ 314.35 | $ - |
| 1/2 Ac Lots | Low | $ 5.75 | $ - | $ - | $ - | $ 41.04 | $ 38.77 | $ - |
| | High | $ 21.87 | $ - | $ - | $ - | $ 561.55 | $ 314.35 | $ - |
| 1/3 Ac Lots | Low | $ 5.01 | $ - | $ - | $ - | $ 36.21 | $ 38.77 | $ - |
| | High | $ 19.05 | $ - | $ - | $ - | $ 495.45 | $ 314.35 | $ - |
| 1/4 Ac Lots | Low | $ 6.11 | $ - | $ - | $ - | $ 30.47 | $ 38.77 | $ - |
| | High | $ 23.23 | $ - | $ - | $ - | $ 416.93 | $ 314.35 | $ - |
| 1/8 Ac Lots | Low | $ 4.94 | $ - | $ - | $ - | $ 19.85 | $ 38.77 | $ - |
| | High | $ 18.79 | $ - | $ - | $ - | $ 271.64 | $ 314.35 | $ - |
| Industrial | Low | $ - | $ 1.07 | $ 5.20 | $ 10.11 | $ 18.21 | $ 34.61 | $ 104.40 |
| | High | $ - | $ 10.07 | $ 48.98 | $ 95.28 | $ 249.14 | $ 280.64 | $ 595.64 |
| Commercial | Low | $ - | $ 1.07 | $ 5.20 | $ 10.11 | $ 15.78 | $ 34.50 | $ 104.40 |
| | High | $ - | $ 10.07 | $ 48.98 | $ 95.28 | $ 215.91 | $ 279.74 | $ 595.64 |
| Opens Space | Low | $ - | $ - | $ - | $ - | $ 123.25 | $ - | $ - |
| | High | $ - | $ - | $ - | $ - | $ 1,686.42 | $ - | $ - |
| Implemented evenly across all uses | Low | $ 5.49 | $ 1.07 | $ 5.20 | $ 10.11 | $ 20.00 | $ 35.70 | $ 104.40 |
| | High | $ 20.84 | $ 10.07 | $ 48.98 | $ 95.28 | $ 273.61 | $ 289.46 | $ 595.64 |

Table 12: The approximate cost per cubic meter of runoff reduction based on an average year within study area 4.

| Study Area 4: Cost per Cubic Meter of Runoff Reduction Based on an Average Year | | | | |
|---|---|---|---|---|
| **Landuse Type** | **Cost** | **Rain Barrel** | **Bioretention** | **Permeable Pavement** |
| 2 Ac Lots | Low | $ 5.52 | $ 62.83 | $ 38.77 |
| | High | $ 20.96 | $ 859.75 | $ 314.35 |
| 1 Ac Lots | Low | $ 5.11 | $ 47.36 | $ 19.85 |
| | High | $ 19.42 | $ 647.99 | $ 160.98 |
| 1/2 Ac Lots | Low | $ 4.10 | $ 41.04 | $ 38.77 |
| | High | $ 15.57 | $ 561.55 | $ 314.35 |
| 1/3 Ac Lots | Low | $ 5.60 | $ 36.21 | $ 38.77 |
| | High | $ 21.26 | $ 495.45 | $ 314.35 |
| 1/4 Ac Lots | Low | $ 5.40 | $ 30.47 | $ 38.77 |
| | High | $ 20.53 | $ 416.93 | $ 314.35 |
| 1/8 Ac Lots | Low | $ 0.65 | $ 19.85 | $ 38.77 |
| | High | $ 2.46 | $ 271.64 | $ 314.35 |
| Opens Space | Low | $ - | $ 123.25 | $ - |
| | High | $ - | $ 1,686.42 | $ - |
| Implemented evenly across all uses | Low | $ 4.98 | $ 32.32 | $ 40.43 |
| | High | $ 18.93 | $ 442.23 | $ 327.83 |

## 4.3 Payback Period of LID Practices

The estimates for LID practice installation costs and savings from the reduction in runoff were used to determine payback periods for each LID practice. The adoption rate did not impact the payback period, although land use types and conditions in the study areas did have some influence. However, rain barrels did generate some variation at the different adoption rates due to rounding the number of barrels required to achieve the reduction up to a whole barrel. It was also discovered that in many cases, the LID practice would not pay for itself through the estimated savings from runoff reduction.

Green roofs, for example, never demonstrated the ability to create a payback in any of the study areas.

In the historic neighborhood, study area 1 (Table 13), rain barrels and cisterns were the most likely to achieve a payback through water savings. Rain barrels tended to achieve payback between about 2.1 and 17.6 years, with the fastest payback being in 1/8-acre lot land use and the longest being the 1-acre lot land use. When applied equally throughout the entire study area, rain barrels required about 2.3 to 10.4 years to achieve payback. Cisterns varied by size, with larger cisterns taking longer to reach the point of payback than smaller ones. For the small cistern, it took between approximately 1.5 and 1.9 years to payback the installation cost with interest at the low price point, but at the high price point, it took between 21.6 to 31 years. The medium cistern reached the payback point between 5.3 and 9.4 years at the low price point and failed to reach the payback point at the high price point. Large cisterns similarly achieved payback at the low price point between 12 and 27 years and failed to payback for the high price point. When applied evenly throughout the study area, small cisterns would payback between 1 and 15 years, medium cisterns payback in about 7 years at the low price point, large cisterns would take almost 18 years at the low price point, and neither large nor medium cisterns would create a payback at the high price point.

Bioretention only demonstrated the ability to create a payback at the low price point for both commercial and industrial uses, ranging between 17 and 22 years. However, when applied throughout the whole study area, it should reach payback in just over 39 years at the low price point. Permeable pavement demonstrated the ability to produce a payback for some residential uses in a time frame between 20 and 33 years, although no payback was achieved at the high price point or when it is applied evenly across the whole study area.

Table 13: Estimated amount of time in years it would take to payback the installation costs using only the savings from runoff reduction for study area 1.

| **Study Area 1: Estimated Payback Period in Years at 4.46% APR Based on Water Savings** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Landuse Type** | **Cistern Size** | **Cost** | **Rain Barrel** | **Cistern** | **Bioretention** | **Permeable Pavement** | **Green Roof** |
| 2 Ac Lots | N/A | Low | 3.06 | n/a | No | No | n/a |
| | | High | 14.92 | n/a | No | No | n/a |
| 1 Ac Lots | N/A | Low | 3.47 | n/a | No | 20.42 | n/a |
| | | High | 17.62 | n/a | No | No | n/a |
| 1/2 Ac Lots | N/A | Low | 2.91 | n/a | No | 22.72 | n/a |
| | | High | 13.86 | n/a | No | No | n/a |
| 1/3 Ac Lots | N/A | Low | 2.91 | n/a | No | 27.11 | n/a |
| | | High | 13.83 | n/a | No | No | n/a |
| 1/4 Ac Lots | N/A | Low | 2.34 | n/a | No | 32.60 | n/a |
| | | High | 10.53 | n/a | No | No | n/a |
| 1/8 Ac Lots | N/A | Low | 2.13 | n/a | No | No | n/a |
| | | High | 9.41 | n/a | No | No | n/a |

Table 13 continued:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Commercial | Small | Low | n/a | 1.54 | 17.46 | No | No |
| | | High | | 21.62 | | | |
| | Med | Low | | 9.39 | | | |
| | | High | n/a | No | No | No | No |
| | Large | Low | | 27.02 | | | |
| | | High | | No | | | |
| Industrial | Small | Low | n/a | 1.88 | 21.89 | No | No |
| | | High | | 31.06 | | | |
| | Med | Low | | 5.28 | | | |
| | | High | n/a | No | No | No | No |
| | Large | Low | | 12.14 | | | |
| | | High | | No | | | |
| Opens Space | N/A | Low | n/a | n/a | No | n/a | n/a |
| | | High | n/a | n/a | No | n/a | n/a |
| Implemented evenly across all uses | Small | Low | 2.32 | 1.23 | 39.24 | No | No |
| | | High | | 15.62 | | | |
| | Med | Low | | 6.98 | | | |
| | | High | 10.44 | No | No | No | No |
| | Large | Low | | 17.72 | | | |
| | | High | | No | | | |

The downtown area, study area 2, demonstrated time frames for payback similar to those seen in the first study area (Table 14). Rain barrels once again demonstrated the fastest payback, at around 4.5 years at the low price point and about 26 years at the higher price point. However, within this study area, the only other LID practice that demonstrated a payback was bioretention and this was only at the lower price point. For the 1/8-Acre residential, industrial, and commercial lots, bioretention achieved payback in about 25.5, 22, and 17.5 years, respectively. When applied evenly throughout the study area, it is estimated that bioretention would take just over 19 years to achieve payback, while rain barrels would still take between about 4.5 to 26 years depending on installation costs.

Table 14: Estimated amount of time in years it would take to payback the installation costs using only the savings from runoff reduction for study area 2.

| **Study Area 2: Estimated Payback Period in Years at 4.46%apr Based on Water Savings** | | | | | |
|---|---|---|---|---|---|
| **Landuse Type** | **Cost** | **Rain Barrel** | **Bioretention** | **Pervious Pavement** | **Green Roof** |
| 1/4-Acre Lot | **Low** | 4.47 | No | No | n/a |
| | **High** | 25.66 | No | No | n/a |
| 1/8-Acre Lot | **Low** | 4.54 | 25.46 | No | n/a |
| | **High** | 26.38 | No | No | n/a |
| Industrial | **Low** | n/a | 21.89 | No | No |
| | **High** | n/a | No | No | No |
| Commercial | **Low** | n/a | 17.46 | No | No |
| | **High** | n/a | No | No | No |
| Implemented evenly across all uses | **Low** | 4.52 | 19.11 | No | No |
| | **High** | 26.18 | No | No | No |

The commercial corridor, study area 3 (Table 15), and the residential subdivision, study area 4 (Table 16), reinforce the trends seen within the first two study areas. Rain barrels and cisterns provide the quickest payback, generally between about 1 to 6 years for the lower installation cost. Bioretention has the potential to achieve payback in the higher intensity uses provided the installation cost is low enough. However, the other LID practices did not demonstrate ability to reliably payback the installation cost based on the savings from reduced runoff.

Table 15: Estimated amount of time in years it would take to payback the installation costs using only the savings from runoff reduction for study area 3.

| **Study Area 3: Estimated Payback Period in Years at 4.46% APR Based on Water Savings** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Landuse Type** | **Cost** | **Rain Barrel** | **Bioretention** | **Pervious Pavement** | **Green Roof** | **Cistern Small** | **Cistern Medium** | **Cistern Large** |
| 2-Acre Lot | **Low** | 3.48 | No | No | n/a | n/a | n/a | n/a |
| | **High** | 19.17 | No | No | n/a | n/a | n/a | n/a |
| 1-Acre Lot | **Low** | 6.53 | No | No | n/a | n/a | n/a | n/a |
| | **High** | 46.35 | No | No | n/a | n/a | n/a | n/a |
| 1/2-Acre Lot | **Low** | 3.36 | No | No | n/a | n/a | n/a | n/a |
| | **High** | 17.67 | No | No | n/a | n/a | n/a | n/a |
| 1/3-Acre Lot | **Low** | 2.89 | No | No | n/a | n/a | n/a | n/a |
| | **High** | 13.72 | No | No | n/a | n/a | n/a | n/a |
| 1/4-Acre Lot | **Low** | 3.57 | No | No | n/a | n/a | n/a | n/a |
| | **High** | 18.21 | No | No | n/a | n/a | n/a | n/a |

Table 15 continued:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1/8-Acre Lot | **Low** | 2.84 | 25.46 | No | n/a | n/a | n/a | n/a |
| | **High** | 13.42 | No | No | n/a | n/a | n/a | n/a |
| Industrial | **Low** | n/a | 21.89 | No | No | 0.59 | 2.999441 | 6.248988 |
| | **High** | n/a | No | No | No | 6.22 | No | No |
| Commercial | **Low** | n/a | 17.46 | No | No | 0.59 | 2.999441 | 6.248988 |
| | **High** | n/a | No | No | No | 6.22 | No | No |
| Open Space | **Low** | n/a | No | n/a | n/a | n/a | n/a | n/a |
| | **High** | n/a | No | n/a | n/a | n/a | n/a | n/a |
| Implemented evenly across all uses | **Low** | 3.18 | 14.63 | 42.35 | No | 0.59 | 2.999441 | 6.248988 |
| | **High** | 15.52 | No | No | No | 6.22 | No | No |

Table 16: Estimated amount of time in years it would take to payback the installation costs using only the savings from runoff reduction for study area 4.

| Study Area 4: Estimated Payback Period in Years at 4.46% APR Based on Water Savings | | | | |
|---|---|---|---|---|
| **Landuse Type** | **Cost** | **Rain Barrel** | **Bioretention** | **Pervious Pavement** |
| 2-Acre Lot | **Low** | 3.20 | No | No |
| | **High** | 15.69 | No | No |
| 1-Acre Lot | **Low** | 2.95 | No | No |
| | **High** | 14.77 | No | No |
| 1/2-Acre Lot | **Low** | 2.37 | No | No |
| | **High** | 11.68 | No | No |
| 1/3-Acre Lot | **Low** | 3.25 | No | No |
| | **High** | 15.98 | No | No |
| 1/4-Acre Lot | **Low** | 3.13 | No | No |
| | **High** | 15.19 | No | No |
| 1/8-Acre Lot | **Low** | 0.36 | 25.46 | No |
| | **High** | 1.41 | No | No |
| Open Space | **Low** | n/a | No | n/a |
| | **High** | n/a | No | n/a |
| Implemented evenly across all uses | **Low** | 2.87 | 32.96 | No |
| | **High** | 13.61 | No | No |

# CHAPTER 5. DISCUSSION

## 5.1 Discussion

This study provides several important insights that should be considered when evaluating LID practices. One of these is that design matters. This is seen most clearly in the runoff reduction provided by the rain barrels and cisterns. Since this study used generalized treatment volumes and did not attempt to appropriately size these systems, it demonstrates that appropriately sized systems are more effective. For rain barrels, this is seen particularly well in the first study area, where the same storage area provides better reduction as the lot size and average roof size decreases. Cisterns also illustrated this point across the three different volumes, with the smallest providing the least runoff reduction, and the medium providing more, but the large size provided only a marginally greater reduction than the medium sized cistern. This demonstrated that there is a point of diminishing returns where increasing the storage volume ceases to impact the amount runoff can be reduced, in part due to the infrequent occurrence of rainfall events that can take advantage of the additional volume. By identifying the appropriate volume of storage needed for a given roof, it would be possible to find a balance between cost and runoff reduction, although if water harvesting is the primary concern, that may require a larger volume.  Ensuring the appropriate sizing should be a key consideration regardless of the LID practice being used.

Another insight is that a LID practice’s effectiveness in reducing runoff is linked to the amount of impervious surface being treated or replaced.  This was demonstrated as being a direct linear relationship between the area being treated and the amount of runoff reduction. This relationship indicates that the more area that can be treated with LID practices, the more runoff can be reduced. This trend also showed up in the results for pervious pavement across the different land use types. Pervious pavement became more effective as the percentage of impervious surfaces in the land uses increased, generally providing a small percentage of runoff reduction in the low density residential lot types and increasing with density to provide a maximum of around 50 percent reduction in commercial uses. Study area 2, the downtown urban area, deviated from this trend in the commercial use type, because the area comprised of rooftops was greater than that of the paved surfaces. Green roofs responded similarly in the study providing a consistent runoff reduction in study areas 1 and 3, and the industrial use in study area 2, but providing increased effectiveness in the commercial use in study area 2 where the rooftop area is a larger proportion of the use. This data suggests that selecting LID practices to target the largest areas of imperviousness may be the most effective way to retrofit LID practices into existing developments.

The one LID practice that went against this trend was bioretention. Using bioretention to capture runoff from all surfaces provided between 70 to 80 percent reduction regardless of the use type, making it the best runoff reducer in the study. Part of this result could be that in this study, the biorentention areas were assumed to receive runoff form the same percentage of the total area for both impervious surfaces and open space. In many cases, it is probably unnecessary for a design to intercept runoff from open space for the small amount of runoff typically generated. It should be noted that excluding open space areas may slightly decrease the effectiveness of bioretention from what is presented in this study. However, it may improve the economics of the practice, because the size of the bioretention area would become smaller, therefore decreasing the cost of implementation.

Each of the selected LID practices was examined individually in order to determine their capabilities within the study areas. This allows the data to also be used to estimate the impact that two or more of the practices should have when installed in parallel, because the effect should be additive. For cases where the LID practices are being used in sequence or in cases where they interact with each other, it would be necessary to calculate a new curve number for the area being affected. This would be required when the total of the rates of adoption for multiple practices exceeds 100 percent of the total area, for example if 75% of the area is being treated with bioretention and 30% is being treated with pervious pavement, a new cure number would need to be calculated for the percentage of the area that is being treated by both practices.

In this study the cost of installing a LID practice was computed as a direct relationship between the LID practice unit cost and the area being treated. This relationship makes it simple to arrive at a cost estimate that can be used in early planning stages. However, this relationship would only hold true under the assumption that there is no economy of scale. It is likely that an economy of scale would exist and that as more LID practices are adopted within an area, the cost of implementing them would decrease. This study also excludes any type of subsidy, cost sharing, or other program that might offset LID practice cost. For example, the Wabash River Enhancement Corporation (WREC) offers a cost sharing program that pays up to 75 percent of the installation costs for some LID practices (http://www.tippeconow.com/participate.php). These factors should be explored as the planning process moves beyond conceptual stages in order to reduce the installation costs as much as possible.

Economically, the performance of many of the LID practices was somewhat underwhelming. For the majority of the practices, the annual interest on the initial investment would be greater than the annual savings generated from the reduction in runoff. In some cases, this is a result of a high cost of the LID practice. Bioretention, permeable pavement, and green roofs all encounter this issue. These practices only generate savings from wastewater treatment, because they do not conserve water, which limits the total amount of savings they are able to achieve. This also means that there is no direct savings seen by the property owner. A case can be made however that indirectly these practices do benefit them by helping to keep user fees lower through decreased demand on infrastructure.

Bioretention and pervious pavement both provided some of the largest reductions in runoff even though they generally did not perform well economically.

While rain barrels and cisterns provided comparatively small reductions in runoff volumes, they were the best performers economically. As previously noted, rain barrels and cisterns generally were able to payback their installation cost in about 1 to 10 years at the low price point, although they did take longer at the high price point. Rain barrels and cisterns also have the distinction of being the only practices examined that provide direct savings to the property owner as well as the municipality. This happens because the water captured in these systems can be used in place of tap water for some uses, such as irrigation.

Runoff reduction is one of the easiest ways to assess the savings that are being achieved by either conserving drinking water or not treating stormwater. There are other economic factors that should be considered beyond runoff reduction. Although, some can be harder to apply a monetary value to than others, they should still be considered. These factors include: aesthetic appeal, improved environmental quality, energy savings, and maintenance.

The aesthetic appeal of a property can be enhanced by landscape oriented LID practices, like bioretention or PICPs. Well-designed landscaping is generally reported to provide a return on investment of between 100 and 200 percent (Taylor 2003). In residential settings, this can translate to approximately a 20 percent increase in property value (Vila 2013). In commercial or industrial settings, improved aesthetics could also increase a business’ appeal to consumers and investors.

Improvements in environmental quality can be difficult to assign a monetary value to as there is not always a clear metric that can be used. The LID practices examined here all demonstrate the ability to improve water quality, but they can also have impacts on other areas like air quality or wildlife habitat. There are multiple criteria that could be used to assess the value of these impacts, some of which could be reduced treatment costs for drinking, safety of recreational uses, and wildlife health and habitat. In a study conducted for the city of Toronto, it was estimated that 5,000 hectares of green roofs, 75 percent of the eligible area, would save approximately $600,000 (750,000 Can) annually from reduced beach closures alone (Banting et al. 2005). To some extent, the valuation of improvement in environmental quality would need to be addressed at a localized scale, dependent on how a community or region interacts with the environment.

Energy savings could also be seen from adopting LID stormwater practices (USEPA 2009a). Some savings could be seen from the reduction in runoff which would reduce energy consumption of treatment plants and pump stations by decreasing the volume of water they handle. Other energy savings could be found through the reduction of the urban heat island effect, since by reducing the ambient temperatures less energy would be used by air conditioners. In the case of green roofs, the energy efficiency of a building can be increased through the additional insulation the green roof provides. The impact of LID practices on energy consumption is another area where local conditions may impact the amount of savings.

However, maintenance is an area where there appears to be some trade-offs. For this study, it was assumed that the maintenance costs would be approximately the same between the LID and the traditional practice, but in reality this may not be the case. The Water Environment Research Foundation (WERF) has assembled a calculation tool that lists maintenance activities, frequencies, and costs for a variety of LID practices (WERF 2009). Based on the WERF tool, it appears that there is little difference between the recommended maintenance activities for the LID practices and what should generally be considered best management practices for traditional systems. Some examples of this would be routine inspections, litter and debris cleanup, and care of vegetation. In most cases, these activities would not be any more frequent than what would be expected with a traditional practice (WERF 2009).

LID practices do have some unique maintenance requirements that could make them more expensive to operate. For example, it is recommended that roofs that drain into rain barrels or cisterns be washed twice a year and that the tanks be sanitized annually, pervious pavements need to be swept at least once a year to maintain function, and green roofs may expand landscape maintenance onto the roof (WERF 2009). LID practices may also offer some maintenance savings in other areas. For example, pervious pavements may require less plowing and salting in winter (Cahill et al. 2003; UNHSC 2009), and green roofs will protect the roof membrane extending its life and making it less likely to need repairs (Rowe 2011; Bianchini and Hewage 2012).
With further research into these factors, it should be possible to establish a more complete picture of the economics of LID practices. It is suspected that the inclusion of these additional factors will improve the economic appeal for some if not all of the practices examined here. It should also be considered whether the environmental benefits of using LID practices to reduce runoff outweigh the economic costs.

# CHAPTER 6. SUMMARY

## 6.1 Summary

This study selected four existing neighborhood areas in greater Lafayette, Indiana as study areas in order to analyze the impacts and economics of retrofitting LID stormwater practices. The four neighborhood areas that were selected for the study were a mixed use neighborhood near downtown, the downtown core, a commercial corridor, and an older subdivision. The land uses and hydrologic soil types in each of these areas were then classified using the NLCD impervious surface layer and the SSURGO soils database. The land uses were categorized according to the approximate percentage of impervious surface area given in TR-55. These data were then used with the L-THIA LID model to simulate the amount of runoff generated from the study areas at various levels of LID adoption, ranging from 0 to 100 percent. The LID practices selected for the study were rain barrels, cisterns, bioretention, pervious pavement, and green roofs. The cost of implementing these practices and the approximate savings generated by the reduction in runoff were also estimated. The cost of implementation was estimated based on published prices for the selected LID practices. The savings generated from reducing the runoff volume were estimated from the user fees for water and waste water in the city of Lafayette. The values were then used to estimate the approximate amount of time it would take for the LID practices to pay for themselves and the cost per cubic meter of runoff reduction based on an average year. The first hypothesis that this study tested was that, the amount of runoff will decrease in proportion to the surface area treated with LID practices and LID practice adoption rate. This hypothesis was accepted because in each of the study areas and land use types, it was found that as the area impacted by a LID practice increased, the volume of runoff decreased by a proportional amount. The relationship between the adoption rate (the percentage of the study area impacted) and the percentage of runoff reduction was shown to have a linear relationship with a slope between about 0.10 and 0.75, with rain barrels and small sized cisterns being at the low end and bioretention at the high end of this range. This would mean that in the case of rain barrels, for every 10 percent of the eligible area that is treated, you could expect roughly a 1 percent decrease in annual runoff volumes.

The second hypothesis tested was that, the reduction in runoff will provide a monetary savings that will offset or surpass the cost of implementing the selected practice. This hypothesis is best examined in two parts with the first being did they provide a monetary savings, and the second being did those savings offset or surpass the cost of implementation. For the first portion of this hypothesis, an approximation of monetary savings was derived using the volume of runoff reduction and the cost of drinking water or treating wastewater in the city of Lafayette, Indiana. These were used assuming that any reduction in runoff would result in decreased volumes of wastewater arriving at treatment facilities, decreased demand for household water, or in some cases both. By this measure, all of the LID practices examined provide some level of savings. However, these savings would not be directly seen by the property owner in most cases, rain barrels and cisterns being the exception. Indirectly, property owners may see savings in the form of fewer rate increases, due to decreased demand on existing systems.

For the second portion of this hypothesis, a time to payback was calculated based on the LID practice cost with interest when using the estimated annual savings as the payment. Through this calculation, the payback period based on the estimated installation cost and an interest rate of 4.46 percent could be calculated. From these timeframes, it was observed that the rain barrels and cisterns would offset their cost of installation in a short time period, with only a few cases where they would not at the higher price point. However, bioretention and pervious pavements only demonstrated the ability to offset the cost of installation at the low price point in a few circumstances. Green roofs in contrast failed to offset their costs in any of the areas they were applied to. This hypothesis can also be accepted, because in all cases the LID practices do demonstrate at least some capability to create a savings, which does offset some of the cost, even though it may not completely cover or surpass it.

# CHAPTER 7. CONCLUSIONS

## 7.1 Conclusions

This study was undertaken with three objectives:

- Estimate the amount of runoff reduction that can be achieved in existing neighborhoods by retrofitting LID practices at varying levels of adoption.
- Estimate the cost of using LID practices to achieve various levels of runoff reduction.
- Demonstrate methods for estimating LID practice cost using assumptions made in the L-THIA LID model and published price information.

The first objective was accomplished by analyzing four existing neighborhoods in greater Lafayette, Indiana. This analysis was conducted by using the NLCD impervious surface layer to classify the land uses within the selected neighborhoods. The land uses were then input into the L-THIA LID model in order to estimate the volume of runoff from the existing conditions. After the base volume of runoff was established, the selected LID practices, pervious pavement, bioretention, green roofs, rain barrels and cisterns, were applied individually to the appropriate land uses. These practices were applied at rates of 10, 50, and 100 percent in order to provide runoff volumes across the full range of possible adoption rates. From these volumes it was possible to determine the percentage of reduction at each of the tested adoption rates. The relationship between the adoption rate of a LID practice and runoff reduction proved to be linear, making it possible to determine the slope of the line and then calculate the estimated percentage of runoff reduction that could be expected at any adoption rate. At the maximum adoption rate, rain barrels provided between 10 and 20 percent reduction, cisterns provided between 10 and 30 percent reduction, bioretention provided between 70 and 75 percent reduction, permeable pavement provided between 24 and 60 percent reduction, and green roofs consistently provided approximately 23 percent reduction, except in areas where the percentage of roof top was higher where they achieved approximately a 54 percent reduction in runoff volume.

The second objective was achieved by researching the range of costs associated with installing the selected LID practices. The costs used were primarily taken from two sources, Low Impact Development Manual for Michigan: A Design Guide for Implementers and Reviewers and National Green Values (tm) Calculator Methodology. From these values, it was possible to create estimates for the costs of implementing these practices at the selected adoption rates. This part was completed using the methodology that was developed as part of the third objective. From those methods and assumptions, it was possible to estimate the areas or volumes of each practice which were then used to estimate the cost of implementation. For better comparison, the cost of installation was divided by the reduction in runoff volume, and this provided the cost per cubic meter of runoff reduction based on an average year. From this calculation, it was found that the cost per cubic meter of using LID practices to reduce runoff ranged for about \$3.00 to over \$100.00 per cubic meter at the low cost estimate and from about \$20.00 to almost \$600.00 at the high cost estimate. It was found that rain barrels were the most cost effective between \$3.00 and about \$20.00 per cubic meter of runoff reduction, followed closely by cisterns, either bioretention or permeable pavement depending on land use, and finally green roofs proved to be the most expensive between \$100.00 and \$600.00 per cubic meter of runoff reduction.

The third objective was to demonstrate how assumptions made in the L-THIA model can be used in conjunction with published price information to generate estimates for the cost of implementing the selected LID practice. Pricing information can be found from a wide variety of sources generally as cost per unit of area or per unit of volume, and assumptions made within the L-THIA LID model can be used to estimate these factors. While the L-THIA LID model examines the broad land use categories as described in TR-55, it also makes assumptions about the percentage and type of impervious surfaces that make up each category. From these assumptions, it was possible to estimate the area of rooftop, streets, sidewalks, and other impervious surfaces to which the LID practices were being applied. These estimated areas can then be used to determine the areas of each type of LID practice at selected adoptions rates. In some cases this area is all that is needed to estimate the cost, however in cases where a volume is needed, it is possible to take the curve number used by the L-THIA LID model and using the methodology outlined in TR-55 calculate the initial abstraction, which is basically units of volume per unit area. The initial abstraction can then be multiplied by the area the LID practice is being applied to in order to estimate the required volume. In either case the estimated area or volume can then be multiplied by the unit cost to generate an estimated cost of installation for the selected LID practice.

# CHAPTER 8. FUTURE RESEARCH

## 8.1 Future Research

There are several areas of this study that could be expanded upon. The first of these areas is the methodology for determining land use classification. The methodology used in this study worked well for areas that were relatively uniform in their development pattern. However, in areas that had a large amount of variation in impervious surfaces, the methodology did not work as well, this would often result in small areas of lower density land uses showing up in areas where it did not seem like they actually should be based on examination of the aerial photography. With further experimentation, it is possible that this problem be minimized. Some possibilities for accomplishing this could be: creating an average of neighboring cells in the NLCD impervious surface layer raster or by not trying to directly classify the land uses and instead calculating the total impervious surface area and then attempting to extract the area of the rooftops.

Another area that could use more research is the economics of the LID practices. In this study the only factor that was considered was the possible savings generated from runoff reduction. However, there are other factors that may influence the economics of these practices. Some of these could be maintenance, the impact on property values, and possible energy savings. Similarly, the impacts of cost sharing programs or other subsidies should be examined. These considerations were beyond the scope of this project but would need to be developed in order to understand the full picture of the economics associated with retrofitting LID practices.

Another area for further research would be the interaction between LID practices. In this study all of the LID practices were looked at independently form one another, although to a point the independent results could be combined to represent the possible gains from using the processes in parallel. This should be expanded to examine how different combinations of these practices would operate in sequence, for example rain barrels that overflow into a bioretention area or a green roof that drains into a cistern. In order to examine this, it is likely that new approaches would need to be developed in order to represent the interaction between the two practices.

# REFERENCES

# REFERENCES

Ahiablame, Laurent M., Bernard A. Engel, and Indrajeet Chaubey. 2012. “Representation and Evaluation of Low Impact Development Practices with L-THIA-LID: An Example for Site Planning.” *Environment and Pollution* 1 (2): 1–13.

———. 2013. “Effectiveness of Low Impact Development Practices in Two Urbanized Watersheds: Retrofitting with Rain Barrel/ Cisterns and Porous Pavements.” *Journal of Environmental Management* 119 (15): 151–61.

Ando, Amy W., and Luiz P. C. Freitas. 2011. “Consumer Demand for Green Stormwater Management Technology in an Urban Setting: The Case of Chicago Rain Barrels.” *Water Resources Research* 47 (W12501): 1–11.

Baird, C., M. Jennings, and D. Ockerman. 1996. “Characterization of Non-point Sources and Loadings to the Corpus Christi Bay National Estuary Program Study Area.” Texas: Texas Natural Resources Conservation Commission.

Banting, Doug, Hitesh Doshi, James Li, Paul Missios, Angela Au, Beth Anne Currie, and Micheal Verrati. 2005. “Report on the Environmental Benefits and Costs of Green Roof Technology for the City of Toronto”. Toronto, Ontario: Ryerson University.

Bean, Eban Zachary, William Frederick Hunt, and David Alan Bidelspach. 2007. “Evaluation of Four Permeable Pavement Sites in Eastern North Carolina for Runoff Reduction and Water Quality Impacts.” *Journal of Irrigation and Drainage Engineering* 133 (6): 583–92.

Berghage, Robert D., David Beattie, Albert R. Jarrett, Christine Thuring, Farzaneh Razaei, and Thomas P. O’ Connor. 2009. “Green Roofs for Stormwater Runoff Control”. EPA/600/R-09/026. Cincinnati, OH: National Risk Management Research Laboratory Office of Research and Development U.S. Environmental Protection Agency.

Bhaduri, B., M. Grove, C. Lowry, and J. Harbor. 1997. “Assessing the Longterm Hydrological Impact of Land-use Change: Cuppy-McClure Watershed. Indiana.” *Journal of the American Water Works Association* 89 (11): 94–106.

Bianchini, Fabricio, and Kasun Hewage. 2012. “How ‘Green’ Are Green Roofs? Lifecycle Analysis of Green Roof Materials.” *Building and Environment* 48: 57–65.

Boulware, E.W. Bob. 2004. “Harvesting the Rain: Considering Rainwater Catchment as a Domestic Source.” *Plumbing Systems & Design* (Nov/Dec): 42–45.

Brattebo, Benjamin O., and Derek B. Booth. 2003. “Long-term Stormwater Quantity and Quality Performance of Permeable Pavement Systems.” *Water Research* 37 (18): 4369–76.

Buranen, Margaret. 2013. “Cleveland’s Stormwater Challange: Strategies for Coping with Aging Infrastructure and CSOs.” *Stormwater* 14 (7): 32–38.

Cahill, Thomas H., Michele Adams, and Courtney Marm. 2003. “Porous Asphalt: The Right Choice for Porous Pavements.” *Hot Mix Asphalt Technology*: 26–40.

Carter, Timothy, and Colleeen Butler. 2008. “Ecological Impaacts of Replacing Traditional Roofs with Green Roofs in Two Urban Areas.” *Cities and the Environment* 1 (2): 1–17.

Carter, Timothy L., and Todd C. Rasmussen. 2006. “Hydrologic Behavior of Vegetated Roofs.” *Journal of the American Water Resources Association* 45 (2): 1261–74.

Choi, Woonsup. 2007. “Estimating Land-use Change Impacts on Direct Runoff and Non-point Source Pollutant Loads in the Richland Creek Basin (Illinois, USA) by Applying the L-THIA Model.” *Journal of Spatial Hydrology* 7 (1): 47–65.

CNT. 2009. “National Green Values (tm) Calculator Methodology”. Chicago, IL: Center for Neighborhood Technology. http://greenvalues.cnt.org/national/downloads/methodology.pdf.

Davis, Allen P. 2005. “Green Engineering Principles Promote Low-impact Development.” *Environmental Science & Technology* 39 (16): 338A–344A.

———. 2007. “Field Performance of Bioretention: Water Quality.” *Environmental Engineering Science* 24 (8): 1048–64.

———. 2008. “Field Performance of Bioretention: Hydrology Impacts.” *Journal of Hydrologic Engineering* 13 (2): 90–95.

Davis, Allen P., Mohammad Shokouhian, Himanshu Sharma, and Christie Minami. 2001. “Laboratory Study of Bioloogical Retention for Urban Stormwater Management.” *Water Environment Research* 73 (1): 5–14.

———. 2006. “Water Quality Improvements through Bioretention Media: Nitrogen and Phosphorus Removal.” *Water Environment Research* 78 (3): 284–93.

Davis, Amelie Y., Bryan C. Pijanowski, Kimberly Robinson, and Bernard Engel. 2010. “The Environmental and Economic Costs of Sprawling Parking Lots in the United States.” *Landuse Policy* 27 (2): 255–61.

Dietz, Michael E. 2007. “Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions.” *Water Air and Soil Pollution* 186 (1-4): 351–63.

Dreelin, Erin A., Laurie Fowler, and C. Ronald Carroll. 2006. “A Test of Porous Pavement Effectiveness on Clay Soils During Natural Storm Events.” *Water Research* 40 (4): 799–805.

Engel, B. 2001. *L-THIA NPS Long-term Hydrologic Impact Assessment Non Point Source Pollutant Model* (version 2.1). West Lafayette, IN: Purdue University.

Engel, B., and L. Ahiablame. 2011. *L-THIA LID Long-term Hydrologic Impact Assessment Low Impact Development Model. Visual Basic Application*. West Lafayette, IN: Purdue University & USEPA.

Engel, B., and J. Hunter. 2009. *L-THIA LID Long-term Hydrologic Impact Assessment Low Impact Development Model. Spreadsheet Version*. West Lafayette, IN: Purdue University.

ESD DER. 2007. “Bioretention Manual”. Prince George’s County, Maryland: Environmental Services Division, Department of Environmental Resources.

Fach, S., and W.F. Geiger. 2005. “Effective Pollutant Retention Capacity of Permeable Pavements for Infiltrated Road Runoffs Determined by Laboratory Tests.” *Water Science and Technology* 51 (2): 37–45.

Fassman, Elizabeth A., and Samuel Blackbourn. 2010. “Urban Runoff Mitigation by a Permeable Pavement System over Impermeable Soils.” *Journal of Hydrologic Engineering* 15 (SPECIAL ISSUE: Low Impact Development, Sustainability Science, and Hydrological Cycle): 475–85.

Glass, Charles, and Saquiequois Bissouma. 2005. “Evaluation of a Parking Lot Bioretention Cell for Removal of Stormwater Pollutants.” *WIT Transactions on Ecology and the Environment* 81: 699.

Grove, Matt, Jon Harbor, Bernie Engel, and Suresh Muthukrishnan. 2001. “Impacts of Urbanization on Surface Hydrology, Little Eagle Creek, Indaina, and Analysis of LTHIA Model Sensitivity to Data Resolution.” *Physical Geography* 22 (2): 135–53.

Gunderson, Jeff, Robert Roseen, Todd Janeski, Jamie Houle, and Michael Simpson. 2011. “Economical CSO Management.” *Stormwater* 12 (3): 10–25.

Gunn, Renee, Akilah Martin, Bernard Engel, and Laurent Ahiablame. 2012. “Development of Two Indices for Determining Hydrologic Implications of Land Use Changes in Urban Areas.” *Urban Water Journal* 9 (4): 239–48.

Harbor, Jonathon M. 1994. “A Practical Method for Estimating the Impact of Land-Use Change on Surface Runoff, Groundwater Recharge, and Wetland Hydrology.” *Journal of the American Planning Association* 60 (1): 95–108.

Hong, Eunyoung, Eric A. Seagren, and Allen P. Davis. 2006. “Sustainable Oil and Grease Removal from Synthetic Stormwater Runoff Using Bench-scale Bioretention Studies.” *Water Environment Research* 78 (2): 141–55.

Hunt, W. F., J. T. Smith, S. J. Jadlocki, J. M. Hathaway, and P. R. Eubanks. 2008. “Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, N.C.” *Journal of Environmental Engineering* 134 (5): 403–8.

IASWCD. 2012. “Indiana Association of Soil & Water Conservation Districts.” Accessed December 12. http://iaswcd.org/district_tools/pwq/rainbarrels.html.

Kok, K H, L M Sidek, M R Z Abidin, H Basri, Z C Muda, and s Beddu. 2013. “Evaluation of Green Roof as Green Technology for Urban Stormwater Quantity and Quality Controls.” *Earth and Environmental Science* 16 (1). IOP Conference Series: 5.

Legret, M., V. Colandini, and C. Le Marc. 1996. “Effects of a Porous Pavement with Resevior Structure on the Quality of Runoff Water and Soil.” *The Science of the Total Environment* 189-190: 335–40.

Legret, Michel, and Valerie Colandini. 1999. “Effects of a Porous Pavement With Reservior Structure on Runoff Water: Water Quality and Fate of Heavy Metals.” *Water Science and Technology* 39 (2): 111–17.

Lim, K. J., B. A. Engel, Z. Tang, S. Muthukrishnan, J. Choi, and K. Kim. 2006. “Effects of Calibration on L-THIA GIS Runoff and Pollutant Estimation.” *Journal of Environmental Management* 78 (1): 35–43.

Lim, Kyoung Jae, Bernard A. Engel, Suresh Muthukrishnan, and Jon Harbor. 2006. “Effects of Initial Abstraction and Urbanization on Estimated Runoff Using CN Technology.” *Journal of the American Water Resources Association* 42 (3): 629–43.

Makepeace, David K., Daniel W. Smith, and Stephen J. Stanley. 1995. “Urban Stormwater Quality: Summary of Contaminant Data.” *Critical Reviews in Environmental Science and Technology* 25 (2): 93–139.

Mentens, J., and M. Hermy. 2003. “Greenroofs as a Part of Urban Water Management.” In *Water Resources Management II*, edited by C.A. Brebbia, 8:35–44. Progress in Water Resources. Southampton, UK: WIT Press.

Mentens, Jeroen, Dirk Raes, and Martin Hermy. 2006. “Green Roofs as a Tool for Solving the Rainwater Runoff Problem in the Urbanized 21st Century?” *Landscape and Urban Planning* 77 (3): 217–26.

NCSU. 2008. “Urban Waterways - Permeable Pavement: Research Update and Design Implications”. AG-588-14W. Raleigh, NC: North Carolina State University and North Carolina A&T State University Cooperative Extension.

———. 2011. “Urban Waterways - Maintaining Permeable Pavements”. AG-588-23W. Raleigh, NC: North Carolina State University and North Carolina A&T State University Cooperative Extension.

Newman, A. P., C. J. Pratt, S. J. Coupe, and N. Cresswell. 2002. “Oil Bio-degradation in Permeable Pavements by Microbial Communities.” *Water Science and Technology* 45 (7): 51–56.

NRCS. 1986. “Urban Hydrology for Small Watershed”. Technical Release 55. Washington, D.C.: USDA Natural Resources Conservation Services.

Pagotto, C., M. Legret, and P. Le Cloirec. 2000. “Comparison of the Hydraulic Behavior and the Quality of Highway Runoff Water According to the Type of Pavement.” *Water Research* 34 (18): 4446–54.

Pezzaniti, D., S. Beecham, and J. Kandasamy. 2009. “Influence of Clogging on the Effective Life of Permeable Pavements.” *Proceedings of the Institute of Civil Engineers - Water Management* 162 (3): 211–20.

Roseen, Robert M., Thomas P. Ballestro, James J. Houle, Joshua F. Briggs, and Kristopher M. Houle. 2012. “Water Quality and Hydrologic Performance of a Porous Asphalt Pavement as a Storm-Water Treatment Stratagy in a Cold Climate.” *Journal of Environmental Engineering* 138 (1): 81–89.

Rowe, D. Bradley. 2011. “Green Roofs as a Means of Pollution Abatement.” *Environmental Pollution* 159 (8-9): 2100–2110.

Sample, David J., James P. Heaney, Leonard T. Wright, and Richard Koustas. 2001. “Geographic Information Systems, Decision Support Systems, and Urban Storm-Water Management.” *Journal of Water Resources Planning and Management* 127 (Special Issue: Mini-Symposium on Urban Drainage): 155–61.

SEMCOG. 2008. “Low Impact Development Manual for Michigan: A Design Guide for Implementers and Reviewers”. Detroit, MI: Southeast Michigan Council of Governments. http://library.semcog.org/InmagicGenie/DocumentFolder/LIDManualWeb.pdf.

Stovin, Virginia. 2010. “The Potential of Green Roofs to Manage Urban Stormwater.” *Water and Environment Journal* 24 (3): 192–99.

Tang, Z., B. A. Engel, B. C. Pijanowski, and K. J. Lim. 2005. “Forecasting Land Use Change and Its Environmental Impact at a Watershed Scale.” *Journal of Environmental Management* 76 (1): 35–45.

Taylor, Chris. 2003. “Fertile Ground.” *SmartMoney Magazine*, March.

Tota-Maharaj, Kiran, and Miklas Scholz. 2010. “Efficiency of Permeable Pavement Systems for the Removal of Urban Runoff Pollutants Under Varying Environmental Conditions.” *Environmental Progress & Sustainable Energy* 29 (3): 358–69.

TunnelTalk. 2009. “Lafayette CSO Breakthrough”. EMagazine. *TunnelTalk*. July. http://www.tunneltalk.com/LafayetteCSO-Jul09-Lafayette-CSO-breakthrough.php.

U.S. Geological Survey. 2011. “NLCD 2006 Percent Developed Imperviousness”. Remote-sensing image. Sioux Falls, SD: U.S. Geological Survey. http://seamless.usgs.gov/.

UNHSC. 2009. “Winter Maintenance Guidelines for Porous Pavements”. Durham, NH: University of New Hampshire Stormwater Center.

USACE. 2012. “U.S. Army Corps of Engineers Train the Trainer Manual”. Detroit, MI: U.S. Army Corps of Engineers.

USDA NRCS. 2011. “Soil Survey Geographic (SSURGO) Database for Tippecanoe County, Indiana”. Fort Worth, TX: Soil Survey Geographic (SSURGO) database for Tippecanoe County, Indiana. http://SoilDataMart.nrcs.usda.gov/.

USEPA. 2000. “Bioretention Applications: Inglewood Demonstration Project, Largo Maryland Florida Aquarium, Tampa, Floridia”. EPA-841-B-00-005A. Washington, D.C.: U.S Environmental Protection Agency.

———. 2003. “Protecting Water Quality from Urban Runoff”. EPA 841-F-03-003. Washington, D.C.: U.S Environmental Protection Agency.

———. 2004. “Report to Congress: Impacts and Control of CSOs and SSOs”. EPA 833-R-04-001. Washington, D.C.: U.S Environmental Protection Agency. http://cfpub.epa.gov/npdes/cso/cpolicy_report2004.cfm.

———. 2005. “Bioretention (Rain Gardens).” *EPA- Stormwater Menu of BMPs*. April. http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm?action=browse.

———. 2007. “Reducing Stormwater Costs through Low Impact Develeopment (LID) Strategies and Practices”. EPA 841-F-07-006. Washington, D.C.: U.S Environmental Protection Agency. www.epa.gov/nps/lid.

———. 2008. “Green Roofs.” *EPA - Stormwater Menu of BMPs*. http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm?action=factsheet_results&view=specific&bmp=114.

———. 2009a. “Incorporating Low Impact Development into Municipal Stormwater Programs”. EPA 901-F-09-005. Washington, D.C.: U.S Environmental Protection Agency.

———. 2009b. “Porous Asphalt Pavement.” *EPA- Stormwater Menu of BMPs*. September. http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm?action=browse&Rbutton=detail&bmp=135.

———. 2009c. “Pervious Concrete Pavement.” *EPA - Stormwater Menu of BMPs*. September. http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm?action=browse&Rbutton=detail&bmp=137.

———. 2009d. “Permeable Interlocking Concrete Pavement.” *EPA - Stormwater Menu of BMPs*. September. http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm?action=browse&Rbutton=detail&bmp=136.

Vaes, G., and J. Berlamont. 2001. “The Effect of Storage Tanks on Design Storms.” *Urban Water* 3 (4): 303–7.

VanWoert, Nicholaus D., D. Bradley Rowe, Jeffery A. Andresen, Clayton L. Rugh, R. Thomas Fernandez, and Lan Xiao. 2005. “Green Roof Stormwater Retention: Effects of Roof Surface, Slope, and Media Depth.” *Journal of Environmental Quality* 34 (3): 1036–44.

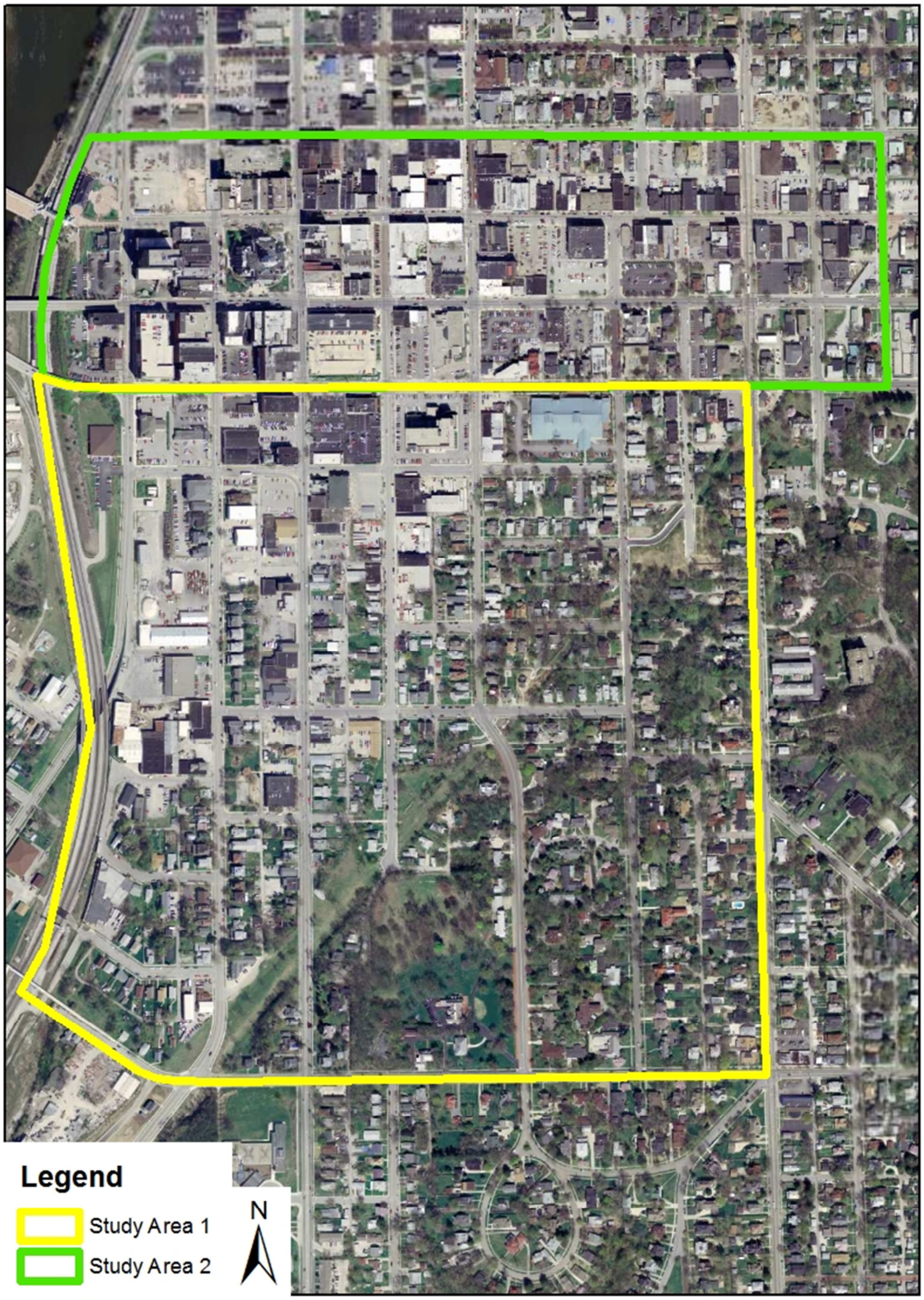
Vijayaraghavan, K., U. M. Joshi, and Balasubramanian. 2012. “A Field Study to Evaluate Runoff Quality from Green Roofs.” *Water Research* 46 (4): 1337–45.

Vila, Bob. 2013. “Landscaping: A Good Investment.” *Bob’s Blogs*. http://www.bobvila.com/articles/347-landscaping-a-good-investment/.

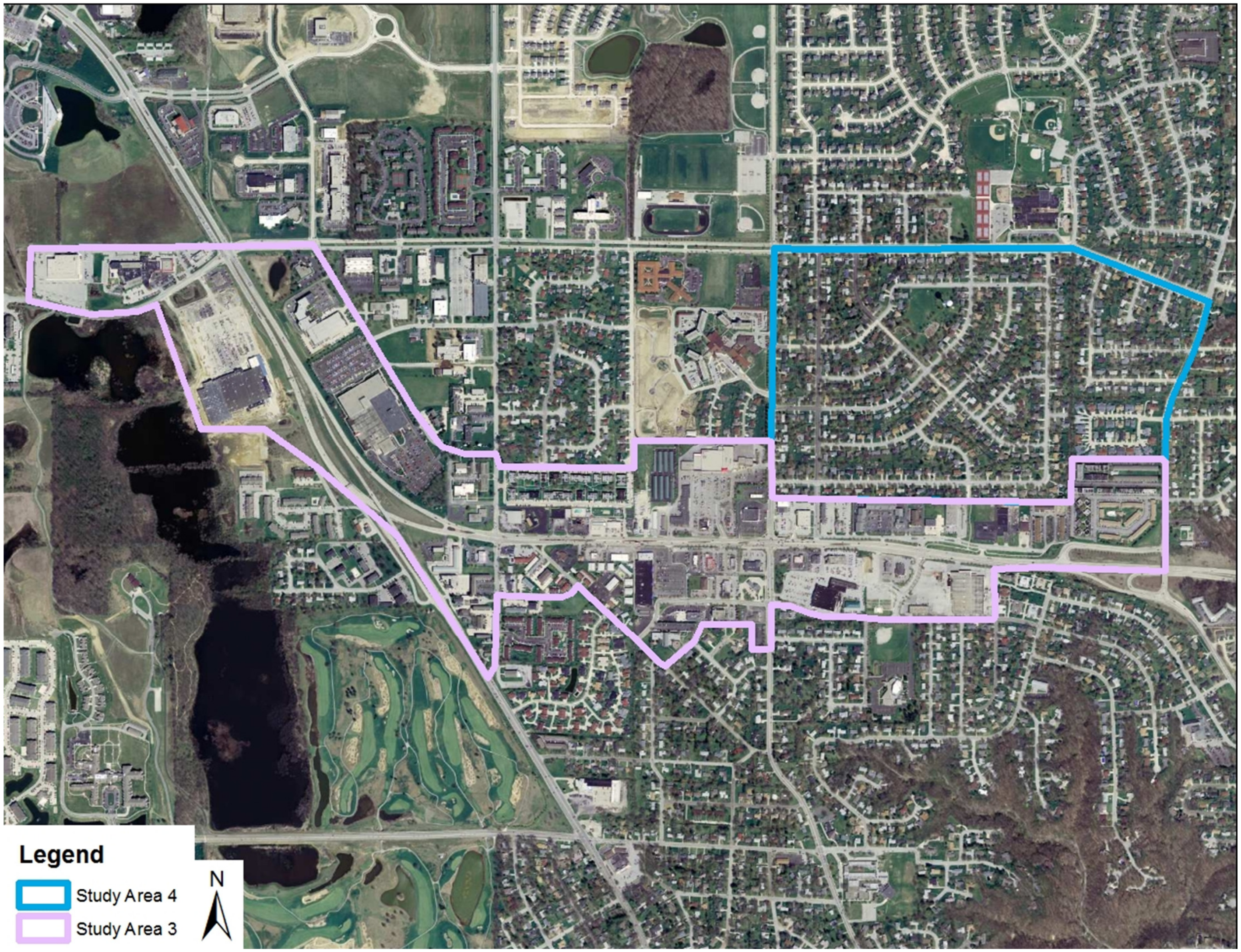
WERF. 2009. “User’s Guide to BMP and LID Whole Life Cost Models Version 2.0”. SW2R08. Alexandria, VA: Water Environment Research Foundation.

# APPENDICES

# Appendix A Enlarged Aerial Photographs of Study Areas



Appendix Figure 1: Enlarged aerial of study areas 1 and 2



Appendix Figure 2: Enlarged aerial of study areas 3 and 4

# Appendix B Average Annual Runoff Volumes

The tables in this appendix summarize the simulated average annual runoff volumes generated by the L-THIA LID model. These average annual values were calculated from the yearly total volumes of runoff generated by the L-THIA LID model. These runoff volumes are based on 30 years of precipitation data starting in 1981 and ending in 2010.

Appendix Table 1: Average annual runoff volumes for study area 1 in cubic meters

| Summary of Average Annual Runoff Volume in Cubic Meters | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **Base** | **Rain Barrel** | | | | | | | |
| **Landuse Type** | **Cistern Size** | **0%** | **10%** | **20%** | **30%** | **40%** | **50%** | **75%** | **100%** |
| 2 Ac Lots | N/A | 4596 | 4551 | 4506 | 4462 | 4417 | 43720 | 4261 | 4150 |
| 1 Ac Lots | N/A | 4046 | 3990 | 3933 | 3876 | 3820 | 3763 | 3621 | 3480 |
| 1/2 Ac Lots | N/A | 4121 | 4062 | 4002 | 3943 | 3883 | 3824 | 3675 | 3526 |
| 1/3 Ac Lots | N/A | 6968 | 6869 | 6770 | 6671 | 6572 | 6473 | 6225 | 5977 |
| 1/4 Ac Lots | N/A | 34965 | 34343 | 33720 | 33099 | 32476 | 31854 | 30299 | 28744 |
| 1/8 Ac Lots | N/A | 53713 | 52682 | 51650 | 50619 | 49587 | 48555 | 45976 | 43396 |
| Commercial | Small | 77244 | 77244 | 77244 | 77244 | 77244 | 77244 | 77244 | 77244 |
| | Med | | | | | | | | |
| | Large | | | | | | | | |
| Industrial | Small | 21874 | 21874 | 21874 | 21874 | 21874 | 21874 | 21874 | 21874 |
| | Med | | | | | | | | |
| | Large | | | | | | | | |
| Opens Space | N/A | 4558 | 4558 | 4558 | 4558 | 4558 | 4558 | 4558 | 4558 |
| Applied evenly throughout the entire study area | Small | 212087 | 210173 | 208260 | 206346 | 204432 | 202519 | 197734 | 192950 |
| | Med | | | | | | | | |
| | Large | | | | | | | | |

Appendix Table 1 continued

| Cistern (Commercial & Industrial Only) | | | | | | |
|---|---|---|---|---|---|---|
| **10%** | **20%** | **30%** | **40%** | **50%** | **75%** | **100%** |
| 4596 | 4596 | 4596 | 4596 | 4596 | 4596 | 4596 |
| 4046 | 4046 | 4046 | 4046 | 4046 | 4046 | 4046 |
| 4121 | 4121 | 4121 | 4121 | 4121 | 4121 | 4121 |
| 6968 | 6968 | 6968 | 6968 | 6968 | 6968 | 6968 |
| 34965 | 34965 | 34965 | 34965 | 34965 | 34965 | 34965 |
| 53714 | 53714 | 53714 | 53714 | 53714 | 53714 | 53714 |
| 76287 | 75330 | 74373 | 73416 | 72459 | 70066 | 67673 |
| 75036 | 72828 | 70621 | 68413 | 66205 | 60685 | 55166 |
| 75022 | 72800 | 70578 | 68356 | 66134 | 60579 | 55024 |
| 21648 | 21422 | 21196 | 20971 | 20745 | 20180 | 19616 |
| 21256 | 20638 | 20020 | 19402 | 18784 | 17240 | 15695 |
| 21239 | 20603 | 19968 | 19333 | 18697 | 17109 | 15521 |
| 4558 | 4558 | 4558 | 4558 | 4558 | 4558 | 4558 |
| 210904 | 209721 | 208538 | 207355 | 206172 | 203215 | 200257 |
| 209262 | 206435 | 203610 | 200784 | 197958 | 190894 | 183829 |
| 209230 | 206372 | 203515 | 200656 | 197800 | 190657 | 183513 |

Appendix Table 1 continued

| Bioretention | | | | | | |
|---|---|---|---|---|---|---|
| **10%** | **20%** | **30%** | **40%** | **50%** | **75%** | **100%** |
| 4274 | 3952 | 3630 | 3308 | 2986 | 2181 | 1376 |
| 3758 | 3469 | 3181 | 2893 | 2604 | 1884 | 1163 |
| 3825 | 3530 | 3234 | 2938 | 2642 | 1903 | 1164 |
| 6466 | 5963 | 5460 | 4957 | 4454 | 3197 | 1940 |
| 32426 | 29887 | 27347 | 24808 | 22268 | 15920 | 9572 |
| 49765 | 45817 | 41868 | 37920 | 33972 | 24100 | 14229 |
| 71539 | 65835 | 60130 | 54425 | 48720 | 34458 | 20196 |
| 20263 | 18652 | 17041 | 15430 | 13819 | 9792 | 5764 |
| 4259 | 3959 | 3660 | 3360 | 3061 | 2312 | 1563 |
| 196575 | 181063 | 165551 | 150039 | 134527 | 95746 | 56966 |

Appendix Table 1 continued

| Pervious Pavement | | | | | | |
|---|---|---|---|---|---|---|
| **10%** | **20%** | **30%** | **40%** | **50%** | **75%** | **100%** |
| 4485 | 4374 | 4263 | 4152 | 4041 | 3764 | 3486 |
| 3916 | 3786 | 3657 | 3527 | 3397 | 3073 | 2748 |
| 3979 | 3837 | 3695 | 3553 | 3411 | 3056 | 2701 |
| 6702 | 6436 | 6170 | 5903 | 5637 | 4971 | 4306 |
| 33494 | 32023 | 30552 | 29081 | 27610 | 23932 | 20254 |
| 51020 | 48326 | 45632 | 42938 | 40243 | 33508 | 26773 |
| 72806 | 68367 | 63930 | 59491 | 55053 | 43957 | 32862 |
| 20673 | 19471 | 18271 | 17070 | 15869 | 12866 | 9863 |
| 4558 | 4558 | 4558 | 4558 | 4558 | 4558 | 4558 |
| 201634 | 191179 | 180727 | 170273 | 159819 | 133685 | 107551 |

Appendix Table 1 continued

| **Green Roof (Commercial & Industrial Only)** | | | | | | |
|---|---|---|---|---|---|---|
| **10%** | **20%** | **30%** | **40%** | **50%** | **75%** | **100%** |
| 4596 | 4596 | 4596 | 4596 | 4596 | 4596 | 4596 |
| 4046 | 4046 | 4046 | 4046 | 4046 | 4046 | 4046 |
| 4121 | 4121 | 4121 | 4121 | 4121 | 4121 | 4121 |
| 6968 | 6968 | 6968 | 6968 | 6968 | 6968 | 6968 |
| 34965 | 34965 | 34965 | 34965 | 34965 | 34965 | 34965 |
| 53714 | 53714 | 53714 | 53714 | 53714 | 53714 | 53714 |
| 75489 | 73734 | 71979 | 70224 | 68469 | 64082 | 59694 |
| 21371 | 20867 | 20364 | 19861 | 19358 | 18100 | 16841 |
| 4558 | 4558 | 4558 | 4558 | 4558 | 4558 | 4558 |
| 209829 | 207570 | 205312 | 203054 | 200795 | 195150 | 189504 |

Appendix Table 2: Average annual runoff volumes for study area 2 in cubic meters

| **Summary of Average Annual Runoff Volume in Cubic Meters** | | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Base** | **Rain Barrel** | | | **Bioretention** | | |
| **Landuse Type** | **0%** | **10%** | **50%** | **100%** | **10%** | **50%** | **100%** |
| 1/4-Acre Lot | 3428 | 3361 | 3095 | 2762 | 3179 | 2183 | 938 |
| 1/8-Acre Lot | 9357 | 9177 | 8458 | 7559 | 8669 | 5918 | 2479 |
| Industrial | 16594 | 16594 | 16594 | 16594 | 15372 | 10483 | 4373 |
| Commercial | 103716 | 103716 | 103716 | 103716 | 96056 | 65416 | 27117 |
| Applied evenly throughout the entire study area | 133094.36 | 132848 | 131863 | 130631 | 123276 | 84000 | 34907 |

Appendix Table 2 continued

| **Pervious Pavement** | | | **Green Roof** | | |
|---|---|---|---|---|---|
| **10%** | **50%** | **100%** | **10%** | **50%** | **100%** |
| 3284 | 2707 | 1986 | 3428 | 3428 | 3428 |
| 8887 | 7010 | 4664 | 9357 | 9357 | 9357 |
| 15683 | 12038 | 7482 | 16212 | 14685 | 12776 |
| 100484 | 87555 | 71394 | 98814 | 79208 | 54700 |
| 128338 | 109310 | 85526 | 127811 | 106678 | 80261 |

Appendix Table 3: Average annual runoff volumes for study area 3 in cubic meters

| **Summary of Average Annual Runoff Volume in Cubic Meters** | | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Base** | **Rain Barrel** | | | **Bioretention** | | |
| **Landuse Type** | **0%** | **10%** | **50%** | **100%** | **10%** | **50%** | **100%** |
| 2-Acre Lot | 2298 | 2286 | 2239 | 2180 | 2137 | 1493 | 688 |
| 1-Acre Lot | 1349 | 1340 | 1307 | 1266 | 1253 | 868 | 388 |
| 1/2-Acre Lot | 1374 | 1361 | 1310 | 1246 | 1275 | 881 | 388 |
| 1/3-Acre Lot | 3291 | 3254 | 3108 | 2925 | 3053 | 2103 | 916 |
| 1/4-Acre Lot | 95983 | 94367 | 87910 | 79838 | 89012 | 61129 | 26276 |
| 1/8-Acre Lot | 81784 | 80614 | 75933 | 70087 | 75772 | 51724 | 21665 |
| Industrial | 75804 | 75804 | 75804 | 75804 | 70222 | 47893 | 19975 |
| Commercial | 156224 | 156224 | 156224 | 156224 | 144687 | 98535 | 40845 |
| Open Space | 1249 | 1249 | 1249 | 1249 | 1167 | 838 | 428 |
| Applied evenly throughout the entire study area | 419356 | 416502 | 405086 | 390820 | 388577 | 265466 | 111569 |

Appendix Table 3 continued

| **Pervious Pavement** | | | **Green Roof** | | | **Cistern Small** | | |
|---|---|---|---|---|---|---|---|---|
| **10%** | **50%** | **100%** | **10%** | **50%** | **100%** | **10%** | **50%** | **100%** |
| 2242.36 | 2020 | 1743 | 2298 | 2298 | 2298 | 2298 | 2298 | 2298 |
| 1305 | 1132 | 916 | 1349 | 1349 | 1349 | 1349 | 1349 | 1349 |
| 1326 | 1137 | 900 | 1374 | 1374 | 1374 | 1374 | 1374 | 1374 |
| 3165 | 2662 | 2033 | 3291 | 3291 | 3291 | 3291 | 3291 | 3291 |
| 91945 | 75791 | 55599 | 95983 | 95983 | 95983 | 95983 | 95983 | 95983 |
| 77682 | 61274 | 40764 | 81784 | 81784 | 81784 | 81784 | 81784 | 81784 |
| 71640 | 54991 | 34180 | 74060 | 67085 | 58364 | 75224 | 72903 | 70001 |
| 147248 | 111343 | 66462 | 152675 | 138476 | 120729 | 155043 | 150319 | 144413 |
| 1249 | 1249 | 1249 | 1249 | 1249 | 1249 | 1249 | 1249 | 1249 |
| 397803 | 311600 | 203846 | 414062 | 392888 | 366420 | 417594 | 410549 | 401741 |

Appendix Table 3 continued

| **Cistern Medium** | | | **Cistern Large** | | |
|---|---|---|---|---|---|
| **10%** | **50%** | **100%** | **10%** | **50%** | **100%** |
| 2298 | 2298 | 2298 | 2298 | 2298 | 2298 |
| 1349 | 1349 | 1349 | 1349 | 1349 | 1349 |
| 1374 | 1374 | 1374 | 1374 | 1374 | 1374 |
| 3291 | 3291 | 3291 | 3291 | 3291 | 3291 |
| 95983 | 95983 | 95983 | 95983 | 95983 | 95983 |
| 81784 | 81784 | 81784 | 81784 | 81784 | 81784 |
| 73797 | 65767 | 55732 | 73638 | 64971 | 54137 |
| 152139 | 135798 | 115370 | 151814 | 134174 | 112124 |
| 1249 | 1249 | 1249 | 1249 | 1249 | 1249 |
| 413263 | 388893 | 358429 | 412779 | 386472 | 353588 |

Appendix Table 4: Average annual runoff volumes for study area 4 in cubic meters

| **Summary of Average Annual Runoff Volume in Cubic Meters** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Base** | **Rain Barrel** | | | **Bioretention** | | | **Pervious Pavement** | | |
| **Landuse Type** | **0%** | **10%** | **50%** | **100%** | **10%** | **50%** | **100%** | **10%** | **50%** | **100%** |
| 2-Acre Lot | 9191 | 9092 | 8696 | 8200 | 8547 | 5972 | 2752 | 8969 | 8082 | 6972 |
| 1-Acre Lot | 7043 | 6938 | 6590 | 6137 | 6541 | 4534 | 2024 | 6817 | 5914 | 4784 |
| 1/2-Acre Lot | 3778 | 3723 | 3505 | 3232 | 3507 | 2422 | 1067 | 3647 | 3127 | 2476 |
| 1/3-Acre Lot | 7742 | 7623 | 7144 | 6545 | 7184 | 4949 | 2156 | 7447 | 6263 | 4784 |
| 1/4-Acre Lot | 121807 | 119892 | 112233 | 102659 | 112961 | 77576 | 33345 | 116682 | 96183 | 70558 |
| 1/8-Acre Lot | 5198 | 5131 | 4864 | 4530 | 4816 | 3288 | 1377 | 4937 | 3894 | 2591 |
| Open Space | 4995 | 4995 | 4995 | 4995 | 4667 | 3354 | 1713 | 4995 | 4995 | 4995 |
| Applied evenly throughout the entire study area | 159756 | 157395 | 148028 | 136300 | 148223 | 102095 | 44434 | 153496 | 128458 | 97161 |