2014

Development of Treatment Train Techniques for the Evaluation of Low Impact Development in Urban Regions

Mike Hardin
University of Central Florida

DEVELOPMENT OF TREATMENT TRAIN TECHNIQUES FOR THE EVALUATION OF LOW IMPACT DEVELOPMENT IN URBAN REGIONS

by

MICHAEL D. HARDIN
B.S. University of Central Florida, 2005
M.S. University of Central Florida, 2006

A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Environmental Engineering
in the Department of Civil and Environmental Engineering
in the College of Engineering and Computer Science
at the University of Central Florida
Orlando, Florida

Fall Term
2014

Major Professor: Manoj B. Chopra

ABSTRACT

Stormwater runoff from urban areas is a major source of pollution to surface water bodies. The discharge of nutrients such as nitrogen and phosphorus is particularly damaging as it results in harmful algal blooms which can limit the beneficial use of a water body. Stormwater best management practices (BMPs) have been developed over the years to help address this issue. While BMPs have been investigated for years, their use has been somewhat limited due to the fact that much of the data collected is for specific applications, in specific regions, and it is unknown how these systems will perform in other regions and for other applications. Additionally, the research was spread across the literature and performance data was not easily accessible or organized in a convenient way. Recently, local governments and the USEPA have begun to collect this data in BMP manuals to help designers implement this technology. That being said, many times a single BMP is insufficient to meet water quality and flood control needs in urban areas. A treatment train approach is required in these regions. In this dissertation, the development of methodologies to evaluate the performance of two BMPs, namely green roofs and pervious pavements is presented. Additionally, based on an extensive review of the literature, a model was developed to assist in the evaluation of site stormwater plans using a treatment train approach for the removal of nutrients due to the use of BMPs. This model is called the Best Management Practices Treatment for Removal on an Annual basis Involving Nutrients in Stormwater (BMPTRAINS) model.

The first part of this research examined a previously developed method for designing green roofs for hydrologic efficiency. The model had not been tested for different designs and assumed that evapotranspiration was readily available for all regions. This work tested this methodology against different designs, both lab scale and full scale. Additionally, the use of the

Blaney-Criddle equation was examined as a simple way to determine the ET for regions where data was not readily available. It was shown that the methods developed for determination of green roof efficiency had good agreement with collected data. Additionally, the use of the Blaney-Criddle equation for estimation of ET had good agreement with collected and measured data.

The next part of this research examined a method to design pervious pavements. The water storage potential is essential to the successful design of these BMPs. This work examined the total and effective porosities under clean, sediment clogged, and rejuvenated conditions. Additionally, a new type of porosity was defined called operating porosity. This new porosity was defined as the average of the clean effective porosity and the sediment clogged effective porosity. This porosity term was created due to the fact that these systems exist in the exposed environment and subject to sediment loading due to site erosion, vehicle tracking, and spills. Due to this, using the clean effective porosity for design purposes would result in system failure for design type storm events towards the end of its service life. While rejuvenation techniques were found to be somewhat effective, it was also observed that often sediment would travel deep into the pavement system past the effective reach of vacuum sweeping. This was highly dependent on the pore structure of the pavement surface layer. Based on this examination, suggested values for operating porosity were presented which could be used to calculate the storage potential of these systems and subsequent curve number for design purposes.

The final part of this work was the development of a site evaluation model using treatment train techniques. The BMPTRAINS model relied on an extensive literature review to gather data on performance of 15 different BMPs, including the two examined as part of this work. This model has 29 different land uses programmed into it and a user defined option, allowing for wide applicability. Additionally, this model allows a watershed to be split into up to four different catchments, each able to have their own distinct pre- and post-development conditions. Based on the pre- and post-development conditions specified by the user, event mean concentrations (EMCs) are assigned. These EMCs can also be overridden by the user. Each catchment can also contain up to three BMPs in series. If BMPs are to be in parallel, they must be in a separate catchment. The catchments can be configured in up to 15 different configurations, including series, parallel, and mixed. Again, this allows for wide applicability of site designs. The evaluation of cost is also available in this model, either in terms of capital cost or net present worth. The model allows for up to 25 different scenarios to be run comparing cost, presenting results in overall capital cost, overall net present worth, or cost per kg of nitrogen and phosphorus. The wide array of BMPs provided and the flexibility provided to the user makes this model a powerful tool for designers and regulators to help protect surface waters.

This dissertation is dedicated to my beautiful wife Erica and daughter Caylie, all I do is for you

ACKNOWLEDGMENTS

First and foremost I would like to thank Dr. Chopra, my major advisor for all his guidance and support throughout this process. I am also very grateful for the financial support he provided me. Special thanks to Dr. Wanielista for his constant support, being on my committee, and the many meetings to discuss my research. I am very grateful of the time he provided to me. I would also like to thank Dr. Chang and Dr. Harper for serving on my committee and for their guidance throughout this process.

I would further like to thank the Florida Department of Transportation and the Florida Department of Environmental Protection for technical and financial support, in particular that of Rick Renna and Eric Livingston. Additionally, the staff and many students of the Stormwater Management Academy who have helped over the years with my research, in particular that of Dr. Gogo-Abite, Erik Stuart, Nicole Runnenbaum, Nikola Najdavski, Ken Horner, Alicia McDougal, Rafiqul Chowdhury, Christopher Kuzlo, and Antony Rios.

Finally, I would like to thank my parents for their never ending support and patience. I wouldn't be who I am today without their countless sacrifices and wonderful example.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

Problem Statement

The protection of surface water bodies is a priority in the United States and around the world. Stormwater discharges are identified by the USEPA as a significant source of pollution to surface water bodies (USEPA, 2009). The control of nutrients in stormwater runoff is a particular concern as it relates to the control of harmful algal blooms and dead zones in water bodies. Methods have been identified in the literature to reduce the volume of stormwater runoff generated in urban areas or reduce the pollutants in stormwater runoff before discharge (Chang, Islam, Marimon, & Wanielista, 2012; M. Hardin, D., 2006; Harper & Baker, 2007; Hood, Chopra, & Wanielista, 2013; O'Reilly, Wanielista, Chang, Xuan, & Harris, 2012; J. Sansalone, Kuang, & Ranieri, 2008; M. P. Wanielista, Yousef, Harper, & Dansereau, 1991). These methods are called low impact development (LID) or best management practices (BMP).

Many of these LIDs and BMPs have been examined to describe their performance however, the use of this information is difficult as the information is scattered in many different sources and the studies have been done for specific regions or conditions. In an effort to address this, many state and local governments have been developing BMP manuals which attempt to gather the information on design and performance in a convenient to use manual (Burack, Walls, & Stewart, 2008; Michigan Department of Environmental Quality, 1999; Urban Drainage and Flood Control District, 2010). However, these manuals are not able to account for changes in expected efficiency due to spatial and temporal differences in site conditions nor do they provide adequate guidance on how to determine overall nutrient reduction achieved. Additionally, in many instances, the use of a single BMP is insufficient to achieve the goals of nutrient reduction and flood control in urban areas. It is for these reasons that a tool to analyze the use of several BMPs in different configurations is needed. This is called a treatment train approach.

The development of a model which can take into account variable site and rainfall conditions as well as provide a database of LIDs and/or BMPs performance could go a long way to encourage the use of these technologies. Several models exist in the literature which attempt to address this such as Evans, Lehning, and Corradini (2008); North Carolina Department of Environment and Natural Resources (2011); Pomeroy and Rowney (2013); and Tetra Tech (2010), to name a few. These models are a significant step in the right direction to promote the widespread use of LID and BMP technologies to improve water quality of surface water bodies. While these models meet their individual goals set forth by the authors they are limited by the selection of BMPs and the methodology used to determine overall effectiveness. Additionally, the ability to evaluate the performance of several BMPs used in different configurations is necessary to meet water quality goals, i.e. a treatment train approach. Presented in this work is the development of a new model to evaluate water quality improvement by BMPs using a treatment train approach. In particular there are two BMPs which need additional description and further development of design techniques, green roofs and pervious pavements.

Green Roofs

The design of green roofs varies depending on the geographic region where a green roof is installed. In the state of Florida, green roofs require the use of irrigation and native plants for long-term success (M. Hardin, D., 2006). Additionally, the capture and reuse of filtrate from a green roof can improve the hydrologic efficiency and reduce the mass of nutrients coming off the green roof. A methodology to develop a model was produced by M. Hardin, D. (2006) which predicted the hydrologic efficiency of green roofs but was developed based off of two different media depths, a single drainage layer, and using the same vegetation. The model also required the input of evapotranspiration (ET) data which may not be available for all areas.

There is a need to verify the model developed by M. Hardin, D. (2006) with different green roof designs and compared with full scale roofs. Additionally, a method to determine ET for different geographic regions where reliable data does not exist needs to be developed. Several methods exist in the literature for ET estimation of soil and plant systems (Martin Wanielista, Kersten, & Eaglin, 1997). It is desired to select a method that predicts the true ET value for green roof systems as well as requiring easily obtainable data. Achieving these goals will result in a model that is applicable for any geographic region where historical rainfall data exists.

Pervious Pavements

Pervious pavements are a viable BMP for the reduction of stormwater volume and removal of pollutants in stormwater runoff (J. Sansalone et al., 2008). The design of these systems varies based on geographic region, soil conditions, and design goals. In areas with poor soils, under drains are typically included as part of the design (L. Haselbach, M., S. Valavala, & F. Montes, 2006). Geographic regions with well-draining sandy soils, such as Florida, do not use under drains as the infiltration rate into parent soils is sufficient to recover the system. Monitoring of these systems is required in the state of Florida using an embedded ring infiltrometer kit (ERIK) device as described by Gogo-Abite, Hardin, Chopra, Wanielista, and Stuart (2014).

The design of pervious pavement systems can vary significantly but typically contains a surface layer over one or more layers of porous stone. These stormwater BMPs can be modeled as retention systems, which is a system that captures and stores stormwater allowing it to infiltrate into the ground. Therefore the efficiency of the system is dependent on the volume of water captured and infiltrated. Determination of the water captured and subsequently infiltrated is dependent on the design and resulting porosity of the pervious pavement system. While there is some information in the literature on the porosity of certain pervious pavement materials and components (Liv Haselbach & Robert Freeman, 2006; J. Sansalone, Kuang, Ying, & Ranieri, 2012), porosity values have not been examined for pavement systems which contain several layers and how interstitial mixing effects the resulting porosity. Additionally, there is little work done to show the effect of sediment loading on the porosity of a pervious pavement system which contains several component layers of rock sub-base.

BMP Models

Models are a powerful tool for engineers and scientists trying to understand and describe natural phenomena. Models are used in many aspects of modern society from weather prediction to material testing. As more is learned about natural and manmade systems it becomes possible to model them to get a better understanding of what factors play an important role in the process of interest. This approach can also be used for stormwater treatment systems and novel approaches to treat stormwater such as BMPs.

The decline of surface water quality in the United States is well documented in the literature (Elliott & Trowsdale, 2007; Lee et al., 2012; Palmstrom & Walker, 1990; USEPA, 2008). Techniques to improve water quality have been introduced in the form of BMPs, however many times in urban areas a single BMP is insufficient to achieve water quality goals. In an effort to reduce pollution and improve the water quality of surface water bodies, models can be a powerful predictive tool. Several models exist in the literature which aim to achieve this, however most are region specific, require very detailed and difficult to obtain data, or do not allow for evaluation of design using a treatment train approach (Evans et al., 2008; Michigan Department of Environmental Quality, 1999; New Hampshire Department of Environmental Services, 2010; North Carolina Department of Environment and Natural Resources, 2011; Pomeroy & Rowney, 2013; Tetra Tech, 2010, 2011; Virginia Department of Conservation and Recreation, 2011). Additionally, due to the temporal and spatial variation in rainfall patterns, a long term simulation using historical rainfall data is required to obtain reasonable results that account for such variability (Harper & Baker, 2007).

Research Objectives

The objectives of this research are to evaluate the performance of several BMPs used in the state of Florida and develop a model to assist designers with their implementation using a treatment train approach. First, data was collected from the literature to describe the performance of several BMPs. Some BMPs had to be further analyzed to fully describe their performance. Specifically, green roofs and pervious pavements were examined within this work as previous work was insufficient to fully describe their performance.

The performance of green roofs were described by M. Hardin, D. (2006), however the model proposed was developed based on only two different growth media depths, a single type of drainage layer, and ET data was based on collected data in the region testing was performed. Further examination of different green roof depths, drainage layer materials, and a method for ET estimation was done. This involved testing the proposed CSTORM model against collected data presented in the literature for different green roof designs including different depths and drainage layers. Additionally, the Blaney-Criddle equation was examined as a way to calculate ET for different geographical regions.

The performance of pervious pavements as related to infiltration capacity has been thoroughly discussed in the literature (Chopra, Wanielista, Spence, Ballock, & Offenberg, 2006; Gogo-Abite et al., 2014; L. Haselbach, M. et al., 2006; J. Sansalone et al., 2008; J. Sansalone et al., 2012). However, important design parameters such as porosity and subsequent storage of different pavements as well as system components have not been adequately described in the literature. The objectives of this research involve testing several common pervious pavement materials including system components for total and effective porosity. This was done for the new condition, sediment loaded condition, and vacuumed condition. Additionally, the effect of drying time on effective porosity was examined. Based on the results of this testing, operating porosity values are suggested for design purposes that are meant to represent a conservative value that describes the available storage of the pervious pavement system over the design life.

The development of a model to evaluate BMPs using a treatment train approach, called the BMPTRAINS model, was based on the above work and a thorough review of the literature. In particular, the work of Harper and Baker (2007) was used to develop the efficiency relationships for retention and detention type BMPs. Retention type BMPs are any BMP that relies on the infiltration of stormwater into the ground for its removal efficiency. Detention type BMPs are any BMP that captures and holds stormwater and relies on the physical, chemical, and biological processes for the removal of pollutants. Harper and Baker (2007) performed many long term simulations for data across the state of Florida to develop these relationships which were instrumental to the development of this model. A detailed analysis of rainfall data with the final result being the separation of the state into five distinct rainfall zones was also performed. Additionally, several different land uses common to the state of Florida were described for nitrogen and phosphorus loading which allowed for determination of mass loading and removal due to said land uses and BMPs, respectively.

The model developed allows for a watershed to be divided into up to four different catchments. The catchments can be arranged in up to 15 different configurations including series, parallel, and mixed. Each catchment can have up to three BMPs, which must be in series with each other. If the BMPs are to be in parallel, they must be in separate catchments. All these combinations make this model applicable for a wide array of designs and give designers and regulators a powerful tool evaluate the reduction in nitrogen and phosphorus being discharged to surface water bodies. Additionally, the calculation methods presented within this work allow for better estimation of true removals using complex systems by incorporation of treatment train calculation techniques.

Evaluation BMP cost is also examined in the BMPTRAINS model. Net present worth and capital cost can both be examined in the model. This allows for designers to not only examine nitrogen and phosphorus removal efficiency of a design but also the associated cost. Different scenarios can be evaluated to see which design gives the most removal for a minimal cost. The results of the cost analysis section of the model present a graph which shows either the net present worth or capital cost of different scenarios and a graph which shows dollars, either in net present worth or capital cost, per pound of nitrogen and phosphorus removed. The inclusion of cost will allow the selection of a design which achieves water quality goals for the least cost.

Significance of the Study

The goals of this study are to further develop methodologies to determine the efficiency for two specific BMPs, namely green roofs and pervious pavements. Additionally, to develop a Microsoft Excel based model that will allow designers to evaluate the nitrogen and phosphorus removal achieved by implementing a treatment train approach to stormwater BMPs on a site design. This contribution is expected to result in green roof and pervious pavement BMPs that are more efficient and less likely to fail during design rainfall events. The development of a model which is capable of evaluating many different pre- and post-development conditions, up to 15 different BMPs including a user defined option, up to 15 different configurations, and associated cost is a powerful tool to assist the design community to design the most efficient design possible. Additionally, the development of treatment train calculation methods to evaluate nitrogen and phosphorus removal is a significant contribution to the field. Currently it is not possible to easily evaluate site designs to determine if TMDL or other regulatory water quality standards are being met; the inclusion of a cost analysis component further increases the usefulness of such a model.

Organization of the Dissertation

This dissertation has five chapters. The first chapter is the introduction chapter and includes the problem statement, research objectives, significance of the study, and organization of the dissertation. This chapter introduces the reader to the work that is presented and explains why it was performed. The second chapter presents the development and testing of a methodology to determine the hydrologic efficiency of green roofs. This chapter has a brief introduction into green roofs and presents the methodology used to determine green roof efficiency. The results and discussion section present data collected and comparisons to the developed methodology. Finally, conclusions and recommendations for future work are presented.

The third chapter presents the development and testing of porosity for different pervious pavement systems. First, a brief introduction is given which describes the types of pervious pavement systems examined and the importance of the porosity and subsequent storage of these systems. Next a methodology is presented to determine the porosity of different pervious pavements, sub-base components, and the effect of drying time on effective porosity. Finally, conclusions and recommendations for future work are presented.

The fourth chapter presents an overview of the BMPTRAINS model which was developed as part of this work. First, a brief introduction and literature review is given which describes other models in the literature and the need for these types of models. Next, the methodologies and modeling components of the BMPTRAINS model are presented. This section discusses how the model was developed and goes over the main features of the model. Finally, a summary and conclusions section is presented.

The fifth and final chapter is a general discussion and conclusion of the presented work. It contains the major findings of the green roof work, pervious pavement work, and BMPTRAINS model work. Contained within the general discussion section is an additional information section which provides relevant information on the BMPTRAINS model that was not covered in Chapter 4. The appendixes are then presented which contain the raw data for the testing performed. The references are presented at the end of the dissertation.

CHAPTER 2: A MASS BALANCE MODEL FOR DESIGNING GREEN ROOF SYSTEMS THAT INCORPORATE A CISTERN FOR RE-USE

Introduction

The ability of green roofs to control stormwater runoff is well documented in the literature. The control of stormwater runoff is a pressing issue facing most urban areas. Stormwater runoff is, by nature, a difficult waste stream to control. Due to the large volumes of water generated, stormwater runoff contributes to poor surface water quality. Urban areas have either separate sewers or a combined sewer system which frequently overflows during storm events causing large amounts of raw sewage to be discharged into surface water bodies (Hoffman, 2006). Stormwater runoff into separate or combined sewers can be polluted in several ways such as contact with corroded and deposited roof materials (Good, 1993), contact with polluted particulate matter on roadways (Vaze & Chiew, 2004), and contact with fertilizers and pesticides from lawns and agricultural land (Chopra, Wanielista, Kakuturu, Hardin, & Stuart, 2010). A sustainable solution for treatment of roof runoff water is the use of a green roof stormwater treatment system.

A green roof with a cistern for reuse offers a sustainable and aesthetically pleasing treatment solution that utilizes unused space to treat and store stormwater runoff. This system is comprised of a green roof with its drainage system connected to a cistern. The cistern in turn supplies irrigation water to the roof via a pump. A supplemental water source is also connected to the cistern to provide water should there not be sufficient water to perform the irrigation event. This supplemental source can be either potable water or, provided that the quality of the water is acceptable for irrigation purposes, grey water or stormwater from a nearby pond. The pump can be either electric or solar depending on the site conditions and project goals. The irrigation is managed via a controller, similar to what is widely used for home lawn irrigation, which only irrigates on the prescribed times unless sufficient rain has fallen within 24 hours of the intended irrigation event. This is controlled via a quark gage which will prevent irrigation when the quark swells with sufficient water, which can be set by the operator. Systems similar to this are fairly common in the state of Florida. With the adaptabilities of a green roof system, it can be applied to almost any roof structure (Kelly, Hardin, & Wanielista, 2007; M. Wanielista & Hardin, 2011). The results in this paper will give developers and builders new sustainable options for stormwater management source control that will allow them to treat polluted stormwater and reduce the volume of discharge and thus eliminate an impervious surface and pollution contributor (Hunt & Moran, 2004).

Recycling the stormwater runoff and irrigating the green roof with stored water enhances hydrologic related factors such as evapotranspiration, the filtering and water holding abilities of the plants and media, as well as greatly reduce the volume of stormwater runoff leaving the site. In order to achieve this, a cistern needs to be used to store the water between irrigation events. The only two ways water will leave the system is through evapotranspiration and as stormwater runoff when the system reaches storage capacity from large storm events. The only two ways water will enter the system is from precipitation and from a supplemental source that is of a quality that is acceptable for irrigation use. The efficiency of the system is determined from the total precipitation and the total overflow from the cistern. Design equations and a model are developed to estimate the size of a cistern given a desired hydrologic efficiency.

A practical approach to the problem of stormwater runoff is to try to treat the water as close to where it is generated as possible. This concept is called source control (Ellis, 2000).

Developing an undeveloped land reduces the evapotranspiration and increases the stormwater runoff for that area, thereby changing the hydrologic cycle for the watershed. The practice of using plant- and soil-based techniques for treating and holding stormwater at the source to decrease stormwater runoff and increase evapotranspiration rates is called low-impact development (LID) (Davis, Shokouhian, Sharma, Minami, & Winogradoff, 2003). A new LID treatment option for some parts of the world, but has been used as standard practice in other parts is introduced within this paper - the use of a green roof and cistern system. Green roofs with cisterns have been shown to remove pollutants from stormwater (M. Hardin, D., 2006; Kelly et al., 2007), making this a way to utilize the unused roof space, which is in many cases a source of stormwater pollution.

Hunt and Moran (2004) completed a water budget on a non-irrigated green roof and found that for small precipitation events, the green roof was able to retain approximately 75% of the precipitation and reduce the peak flow by as much as 90% as well as increase the time of concentration to almost four hours. The time of concentration is the amount of time it takes for stormwater runoff to occur after a precipitation event has begun (Hunt & Moran, 2004; Martin Wanielista et al., 1997).

MacMillan (2004) studied the water quantity of stormwater runoff from an irrigated green roof in Toronto. It was found that green roofs were able to significantly reduce the total stormwater runoff volume and the peak flows coming off a roof for small storm events, around 55% and 85%, respectively, for storm events less than or equal to 10 mm (MacMillan, 2004). Also addressed in MacMillan (2004), is the fact that green roof volume control efficiency changes with time of year noting that the efficiency is higher in the spring and summer months and lower in the winter and fall months.

Moran, Hunt, and Jennings (2004) studied green roofs in North Carolina to examine runoff quantity and quality as well as evaluate plant growth. During the nine month period examined it was found that a green roof was able to retain about 60% of the total rainfall volume while reducing the peak flow by about 80% (Moran et al., 2004).

Green roof stormwater treatment systems are an acceptable way to treat and store stormwater. Modern green roofs have been used for three decades or more in Europe. Despite this longevity, there have been little or no equations developed for the design of cisterns intended to store green roof runoff/filtrate for irrigation. There have been models developed to predict the runoff from a green roof using historical precipitation and evapotranspiration data. Hoffman (2006), Miller (2000, 2006), and Hilten, Lawrence, and Tollner (2008) have developed models for the purpose of green roof stormwater retention, but did not include the addition of a cistern to store and reuse stormwater for green roof irrigation. Hoffman (2006), Miller (2000, 2006), and Hilten et al. (2008) have identified the important factors that determine green roof efficiency without a cistern. These factors are soil moisture, soil water holding capacity, plant water holding capacity, precipitation, evapotranspiration, temperature, and humidity to name a few. While Miller (2000, 2006) and Hilten et al. (2008) discusses the different approaches used to develop a green roof model they use modified groundwater modeling programs for the development of their models. The models proposed by Hoffman (2006) and Miller (2000, 2006) are a representation of the actual findings from several working green roofs. However, the mass balance across the green roof boundary may not be preserved. Further, by using groundwater modeling variables that are not easy to measure or describe with equations could introduce more error into the model rather than the desired result of a fine tuned model. Hilten et al. (2008) did use a mass balance approach but also incorporated groundwater modeling variables which are difficult to estimate over long periods of time limiting the usefulness of this model to individual storm events.

There are a few models in the literature that examine the reuse of stormwater. A model presented by Guo and Baetz (2007) examines the use of a probabilistic model to size rain barrels and cisterns for stormwater reuse. They showed that rain barrels and cisterns can reliably provide water for irrigation and other non-potable uses during interevent dry periods but do not examine the hydrologic efficiency (Guo & Baetz, 2007). The variability in reliability and storage volume with respect to geographic region was noted (Guo & Baetz, 2007). While the development of the model was logical the use of probabilistic variables results in a complicated model. Further the rainfall data used in the development of the model was selected for only four months potentially excluding important rainfall data. Different types of roof cover were not examined, specifically an irrigated green roof which would return water to the cistern during the irrigation event.

Liaw and Tsai (2004) also developed a model to optimize reliability based on cistern storage and roof area. They used historical rainfall data and runoff coefficients that they developed from experimentation. While the use of runoff coefficients is a common method for stormwater volume estimation the values they reported (0.82) are low for impervious roof cover (Liaw & Tsai, 2004). Furthermore, on an event by event basis this number will change, i.e. the runoff coefficient should decrease with decreasing rainfall volume and increase with increasing rainfall volume. The use of a constant value for the runoff coefficient will result in overestimation of runoff volume for small storm events and underestimation for large storm events. Further, Liaw and Tsai (2004) did not examine hydrologic efficiency nor how an irrigated green roof would affect reliability.

Jones and Hunt (2010) also examined the performance of rainwater harvesting systems as related to reliability and hydrologic efficiency. They found that small storage systems such as rain barrels were inadequate to provide water for irrigation and at reducing stormwater runoff while larger systems performed well (Jones & Hunt, 2010). Jones and Hunt (2010) note that the main factors that influence cistern size, hydrologic efficiency and reliability, are conflicting making the sizing of these systems problematic.

Douglas, Jacobs, Sumner, and Ray (2009) examined three models for the estimation of potential ET, namely the Penman-Monteith, the Priestley-Taylor, and the Turc. They found that, while all three give reasonable estimations of the potential ET, the Priestley-Taylor gave the best fit to data from around the state of Florida followed by the Turc and then the Penman-Monteith (Douglas et al., 2009). Douglas et al. (2009) note from their literature review that often simpler, temperature based models provide sufficient estimations for most modeling applications. While Douglas et al. (2009) examined several different types of land cover they did not examine green roofs.

Methodology for Estimating Retention of Water

The intent of this work is to develop a mathematical model based on data presented by M. Hardin, D. (2006) to accurately predict the hydrologic performance of an irrigated green roof system which incorporates the use of a cistern to collect and reuse filtrate water. The data from several full scale and bench scale green roofs were reviewed and used to design a model to size cisterns to achieve a desired hydrological efficiency. It has been shown in previous work that green roofs in Florida need to be irrigated for the survival of the vegetation (M. Hardin, D., 2006; Kelly et al., 2007; M. Wanielista & Hardin, 2011; M. Wanielista, Kelly, & Hardin, 2008). This requires the designer to designate a water supply for this purpose. M. Hardin, D. (2006)

proposed the use of a cistern to capture green roof filtrate and reuse this water for irrigation of the green roof. The work of M. Hardin, D. (2006) was principally used to develop the model presented while other data was used to validate the model and justify model assumptions. M. Hardin, D. (2006) examined several different green roof systems, however for the purposes of developing the model presented in this work two systems are examined, a control roof and an irrigated green roof with a cistern to store and reuse the filtrate. From the work of M. Hardin, D. (2006), a control roof (C1 and C2) is a conventional roof, in this case a thermoplastic membrane roof, i.e. one without vegetation. The green roof system (EVR1 and EVR2) from M. Hardin, D. (2006) consists of a thermoplastic membrane with a geosynthetic protection layer above it, a 50.8 mm (2 inches) gravel drainage layer above that, a non-woven separation fabric above that, a 152.4 mm (6 inches) layer of growth media with vegetation on the top. In addition a cistern with a volume equivalent to 127 mm (5 inches) over the green roof area, which is 0.092 m (16 square feet) is also part of the design (M. Hardin, D., 2006). This design has several benefits, namely reduction in potable water demand and increased hydrologic efficiency of the system just to name a few (M. Hardin, D., 2006).

M. Hardin, D. (2006) measured the change in cistern water volume, irrigation volume, rainfall volume, and filtrate volume. ET volume was estimated based on a mass balance approach. This data was collected over a one year period from October 3rd 2005 to September 29th 2006 in Orlando, Florida. Data was collected twice weekly for the duration of this project (M. Hardin, D., 2006).

Kelly et al. (2007) and M. Wanielista et al. (2008) examined green roofs having different depths namely, 50.8 mm (2 inches), 101.6 mm (4 inches), 152.4 mm (6 inches), and 203.2 mm (8 inches) and reported a full year of hydrologic data. It was shown that depth had no significant effect ($\alpha = 0.05$) on ET rates. It was also shown that there was a significant effect on filtrate factor but it was related to soil water storage capacity (Kelly et al., 2007; M. Wanielista et al., 2008). The filtrate factor is defined as the fraction of applied water, either through irrigation or natural precipitation, which drains off the roof (filtrate). The results from two full scale green roofs examined by Kelly et al. (2007) agreed well with data collected from experimental chambers. These studies show that ET is not dependent on growth media depth but rather local meteorological conditions. The Blaney-Criddle equation is presented and analyzed to determine its acceptability for ET determination and make the model relevant for cistern design in all geographic regions. It should be noted that the media used was largely inorganic expanded clay and will not degrade over time. This is evident from a green roof in central Florida that, despite the hot climate and weather conditions, after seven years has no visual signs of degradation (Hagan, 2012). The media has the trade name of Bold & Gold™. Within the state of Florida, over 5,600 square meters (60,000 square feet) of green roofs have been installed using this media in the last 7 years (Hagan, 2012).

The effect of different drainage materials was also examined by Kelly et al. (2007) and M. Wanielista et al. (2008). Two different types of drainage materials were examined, namely a 15.875 mm (0.625 inch) expanded clay at a depth of 50.8 mm (2 inches), and a geo-synthetic material (Kelly et al., 2007; M. Wanielista et al., 2008). The geo-synthetic material was a plastic sheet with dimples allowing storage of water between precipitation and irrigation events (Kelly et al., 2007; M. Wanielista et al., 2008). No significant difference ($\alpha = 0.05$) in ET or filtrate factor was found for the different drainage materials (Kelly et al., 2007; M. Wanielista et al., 2008). These results show that ET and filtrate factor results should be unaffected by drainage material selection, and thus not an important design factor as it relates to hydrological efficiency.

The species of plants, were held constant for these experiments and include; Helianthus debilis (Dune sunflower), Gaillardia pulchella or aristata (Blanket flower), Lonicera sempervirens (Coral honeysuckle), Myricanthes fragrans (Simpson's stopper), Clytostoma callistegioides (Argentine trumpet vine), Tecomeria capensis (Cape honeysuckle), and Trachelospermum jasminoides (Confederate jasmine). The plants were selected based on hardiness, drought tolerance, the aesthetically pleasing aspects of the plant and whether or not they are native to Florida. The first four plant species are Florida natives while the last three are naturalized. The plant species are an important factor for calculating the ET using the Blaney-Criddle equation. It should be noted that the ET calculated using this equation was for plants similar to the ones listed above, i.e. ground cover plantings.

Results and Discussion

The Filtrate Factor and ET

Average monthly ET rates as well as average monthly filtrate factors for an irrigated green roof in central Florida were estimated from actual measurements for the green roof schematic shown in Figure 1. The variables in Figure 1 are defined as follows: I is the volume of irrigation applied to the roof during the time step, P is the volume of precipitation that fell on the roof during the time step, ET is the volume of evapotranspiration that left the roof during the time step, Ms is the media water holding capacity, and F is the volume of filtrate which drains off the roof during the time step. The monthly ET rates were calculated using a mass balance approach. The irrigation, precipitation, and filtrate were all measured over the course of the one year study period. The only two parameters that were not directly measured were the ET and the media storage. Over a sufficiently long period of time the change in media storage was insignificant compared to the ET, thus allowing for estimation of the ET volume.

The filtrate factor was calculated as the fraction of water collected per water added from both precipitation and irrigation. The ET rates were calculated daily and then averaged for each month. The inputs into the system are the precipitation and irrigation volumes. The outputs to the system are ET and filtrate volumes. The monthly estimated ET and calculated filtrate factors from the experimental data are shown in Table 1 and Table 2 respectively. These tables show data for duplicate control roof chambers (C1 and C2) and duplicate green roof chambers (EVR1 and EVR2).

The control roof chambers show no significant evaporation and high filtrate factor values as expected since storage is minimal and most of the rainfall promptly drains off the surface (Table 1 and Table 2). From Table 1 and Table 2, it can be shown that for the green roof chambers both the evapotranspiration rates and the filtrate factors change with the season. As would be expected, the evapotranspiration rates increased during the summer months and decreased during the winter months. The filtrate factor did the opposite, decreased during the summer months and increased during the winter months.

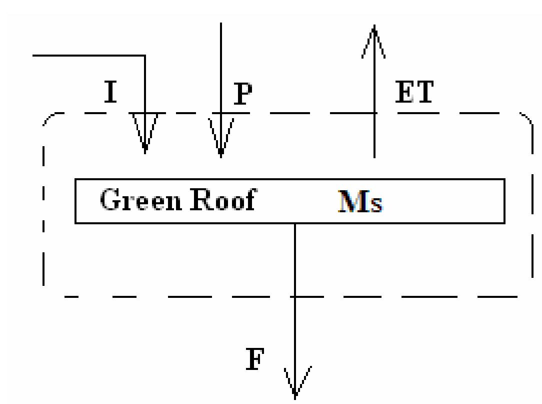


Figure 1: Green Roof System Boundaries. (M. Hardin, D., 2006)

The variables for Figure 1 are as follows:

Ms = Media storage [depth/unit area of green roof]

P' = Precipitation [depth/ unit area of green roof*time]

I' = Irrigation [depth/ unit area of green roof*time]

ET' = Evapotranspiration [depth/ unit area of green roof*time]

F' = Filtrate [depth/ unit area of green roof*time]

Table 1: ET Monthly Average Comparison. (M. Hardin, D., 2006)

ET Monthly Average Comparison of the Chambers [mm/day (in/day)]				
Month	C1	C2	EVR1	EVR2
July – 05	0.51 (0.02)^	0.00*	4.32 (0.17)	4.06 (0.16)
Aug. - 05	0.00*	0.51 (0.02) ^	3.56 (0.14)	3.56 (0.14)
Sept. – 05	0.00*	0.00*	3.56 (0.14)	3.30 (0.13)
Oct. – 05	0.00*	0.25 (0.01) ^	2.54 (0.10)	2.29 (0.09)
Nov. – 05	0.00*	0.00*	2.29 (0.09)	2.29 (0.09)
Dec. – 05	0.00*	0.00*	2.03 (0.08)	2.03 (0.08)
Jan. – 06	0.00*	0.25 (0.01) ^	2.29 (0.09)	2.54 (0.10)
Feb. – 06	0.00*	0.00*	2.54 (0.10)	2.54 (0.10)
Mar. – 06	0.00*+	0.00*+	3.05 (0.12)	3.05 (0.12)
Apr. – 06	0.00*	0.00*	3.81 (0.15)	3.56 (0.14)
May – 06	0.00*	0.51 (0.02) ^	3.30 (0.13)	3.30 (0.13)
June – 06	0.00*	0.76 (0.03) ^	4.32 (0.17)	4.32 (0.17)

* Values are sufficiently close to zero
+ No precipitation occurred during month
^ Depression storage can account for evaporation

Table 2: Filtrate Factor Monthly Average Comparison. (M. Hardin, D., 2006)

Filtrate Factor Monthly Average Comparison of the Chambers				
Month	C1	C2	EVR1	EVR2
July – 05	0.96	0.91	0.52	0.56
Aug. – 05	0.94	0.88	0.39	0.40
Sept. – 05	0.98	1.00	0.52	0.55
Oct. – 05	0.97	0.94	0.55	0.59
Nov. – 05	0.94	0.78	0.40	0.38
Dec. – 05	0.98	0.82	0.58	0.57
Jan. – 06	0.86	0.71	0.45	0.42
Feb. – 06	0.98	0.87	0.45	0.44
Mar. – 06	NA^{+}	NA^{+}	0.19	0.17
Apr. – 06	0.97	0.83	0.14	0.16
May – 06	0.99	0.81	0.27	0.30
June – 06	0.99	0.84	0.44	0.47

$^{+}$ No precipitation occurred during month

The authors acknowledge that ET data may not be readily available for all areas potentially limiting the usefulness of a model developed for design purposes and therefore propose to use the Blaney-Criddle equation to calculate the ET. Values for ET were calculated using the Blaney-Criddle equation and compared to experimentally determined values from M.

Hardin, D. (2006) (Figure 2). An analysis of variance was performed and no significant difference was detected at a significance level of 99%. The Blaney-Criddle equation calculates monthly ET based on a consumptive use coefficient, percent of daytime hours per year in the study month, and mean monthly temperature in ^{o}F. The authors acknowledge that this equation best estimates the potential ET but since irrigation is being regularly performed the soil moisture will remain close to field capacity making this an appropriate estimation. The consumptive use coefficient used was from Table 4.5 in Martin Wanielista et al. (1997) for pasture or grass giving a range of values from 0.6 – 0.75. Based on the best fit to the experimental data presented by M. Hardin, D. (2006) a value of 0.63 was selected for the consumptive use coefficient (Figure 2). The percent of daytime hours per year in the study month was determined from Table 4.6 in Martin Wanielista et al. (1997) for each month examined by M. Hardin, D. (2006). The mean monthly temperature was gathered from historical data for the time period of July 2005 to June 2006 (Underground, 2012). From Figure 2 it can be seen that the Blaney-Criddle equation is an acceptable approximation of ET data for irrigated green roofs.

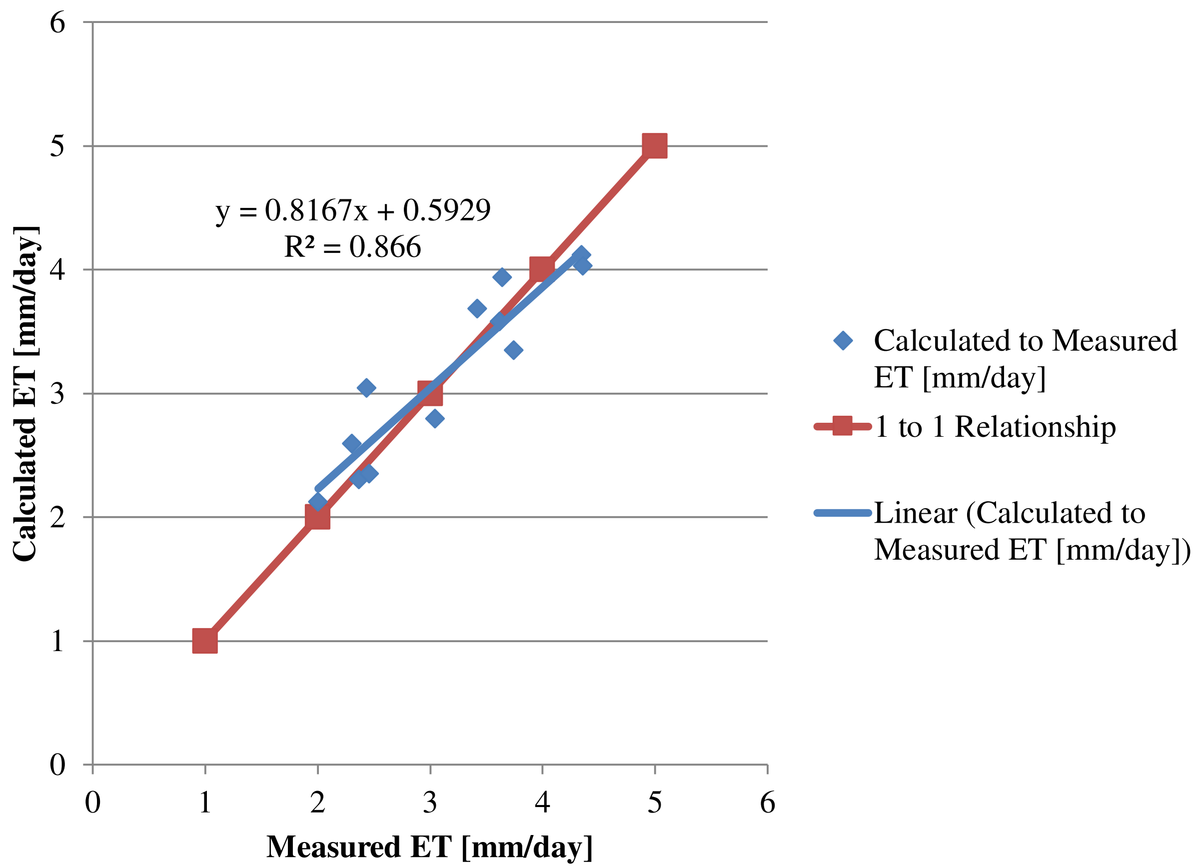


Figure 2: ET Comparison of Blaney-Criddle Calculated vs. Experimentally Determined from M. Hardin, D. (2006)

To further analyze the Blaney-Criddle equation to effectively model actual values it was used with the model and compared with actual data collected from experimental chambers and actual data collected from a full sized operating green roof (Figure 3 and Figure 4, respectively). The cumulative ET verses time for the Blaney-Criddle equation and data collected from experimental chambers as well as data collected from a full sized operating green roof, respectively show a good fit. These figures further support the use of the Blaney-Criddle equation for estimation of ET for the purposes of the model presented.

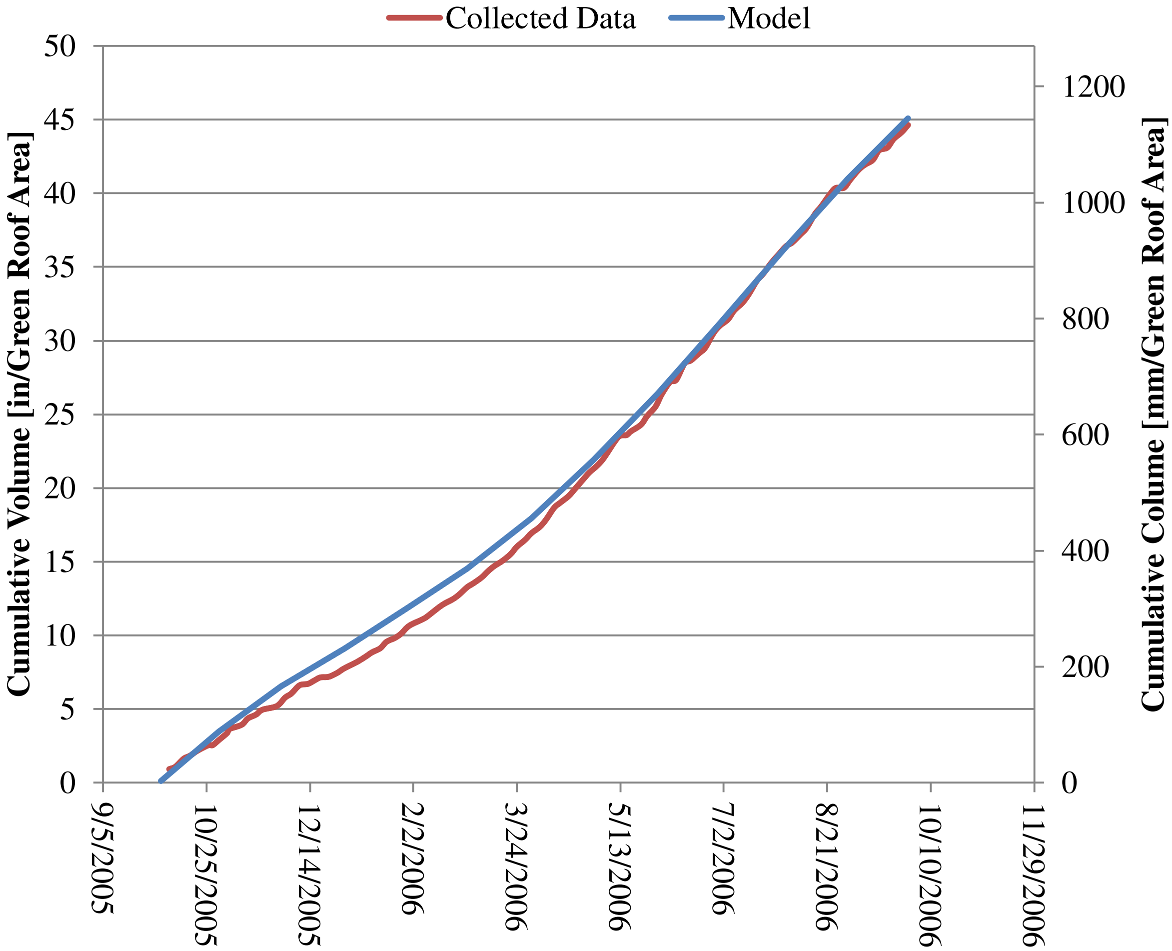


Figure 3: Comparison of cumulative ET volume for the Blaney-Criddle equation and actual data collected from experimental chambers (M. Hardin, D., 2006)

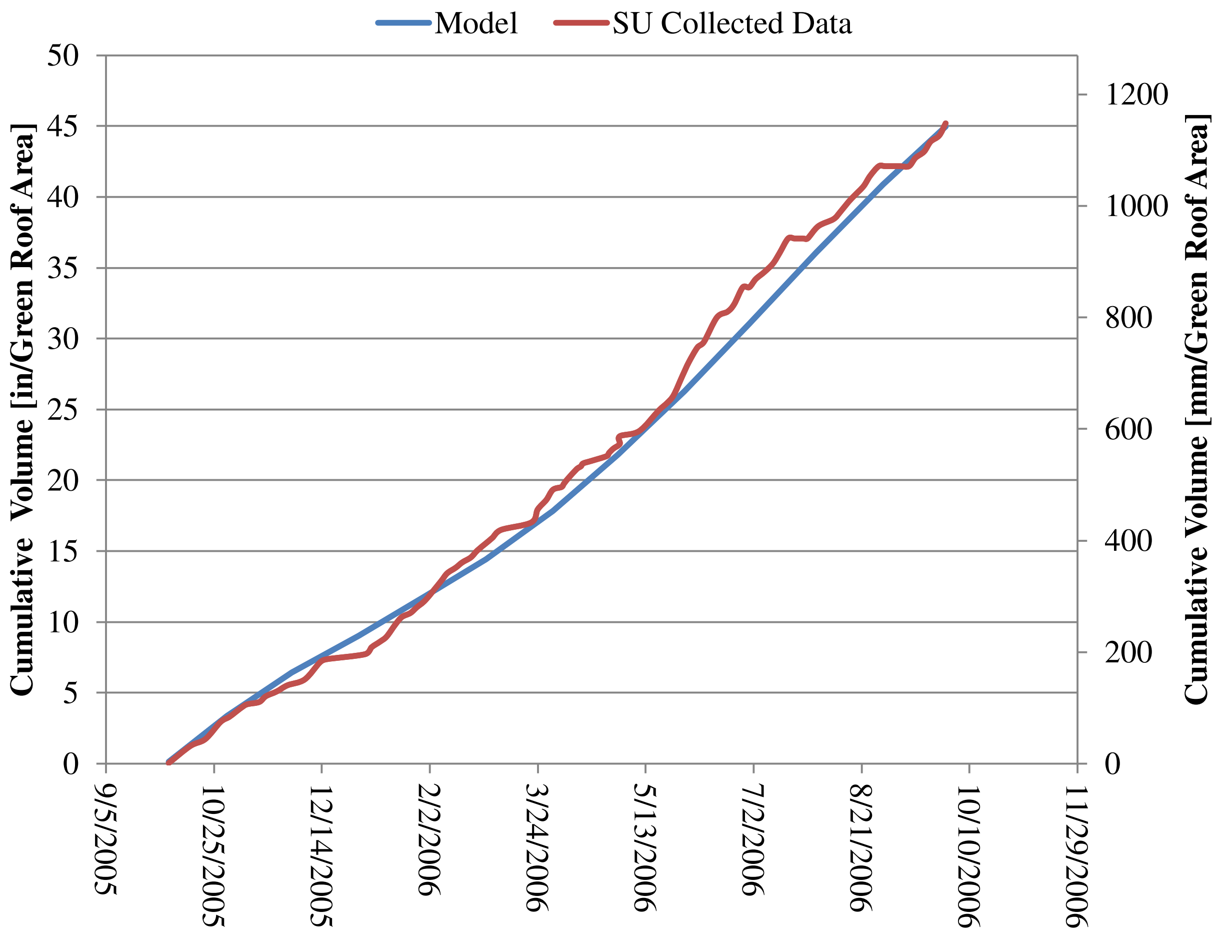


Figure 4: Comparison of cumulative ET determined from the Blaney-Criddle equation and actual data collected from a full sized operating green roof (M. Hardin & Wanielista, 2007)

Continuous Stormwater Treatment Outflow Reduction Model (CSTORM) Development

Mass Balance

Similar to the design of a reuse pond, a mass balance approach can be used for the design of a green roof stormwater treatment system. To design a green roof stormwater treatment system, the inputs and outputs for a mass balance must be preserved (see Figure 5). The main system inputs and outputs are precipitation, evapotranspiration, makeup water, and overflow.

The main factors that influence the cistern water level are the filtrate from the green roof, the irrigation rate, the rate at which makeup water is added, and the overflow rate. The overflow rate will be a function of the maximum cistern storage volume and the rate at which makeup water is added will be a function of available storage water and irrigation rate. Jones and Hunt (2010) evaluated rainwater harvesting systems with a model and showed that these systems can be effective in providing reuse waters and reducing runoff. They point out, however that there is a tradeoff between reducing the cistern volume and runoff reduction (Jones & Hunt, 2010). The irrigation rate is not to exceed 25.4 mm (1 inch) per week in the summer months and half that for the winter months for the purposes of demonstrating the use of the model. It should be noted that irrigation will not occur if, in the twenty four hours previous to the irrigation event, the precipitation volume is greater than or equal to the irrigation volume. From this it can be seen that filtrate from the green roof is the only variable that is not known.

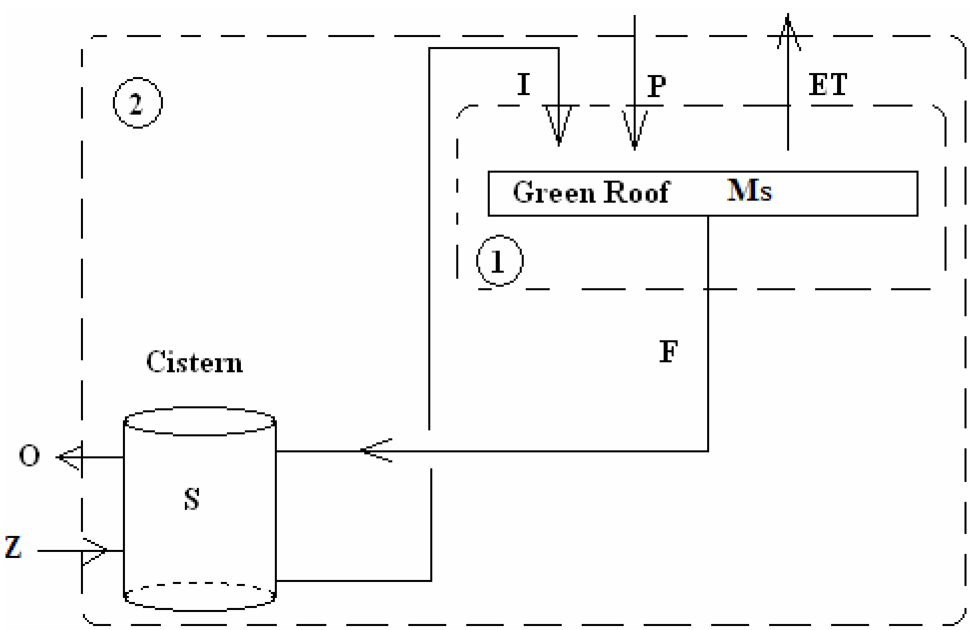


Figure 5: Green Roof Stormwater Treatment System Boundaries (M. Hardin, D., 2006)

The variables of Figure 5 are as follows:

Ms = Media storage [depth/unit area of green roof]

P' = Precipitation [depth/ unit area of green roof*time]

I' = Irrigation [depth/ unit area of green roof*time]

ET' = Evapotranspiration [depth/ unit area of green roof*time]

F' = Filtrate [depth/ unit area of green roof*time]

S = Cistern storage [depth/ unit area of green roof]

Z' = Makeup Water [depth/ unit area of green roof*time]

O' = Overflow [depth/ unit area of green roof*time]

Isolating the green roof stormwater treatment system into mass balances as shown in Figure 5 is necessary in order to determine the filtrate, or the filtrate factor. Using the system boundaries for system one in Figure 5, an expression for the filtrate factor as it varies with soil conditions, precipitation, evapotranspiration, and irrigation amount can be derived.

$$\frac{dMs}{dt} = P + I - ET - F$$

Making the assumption of a finite difference the following simplification can be made:

$$\frac{\Delta Ms}{\Delta t} = P + I - ET - F \qquad (1)$$

This equation is in terms of volume per unit time and needs to be multiplied through by the time step to get volume. This equation then simplifies as follows:

$$\Delta Ms = P' + I' - ET' - F' \tag{2}$$

where the prime nomenclature is indicative of volume. It should be noted that Ms represents the depth of water that the growth media can hold per unit area, and is determined by multiplying the porosity of the chosen growth media by the depth. This gives the media water storage capacity per unit area. Solving for the filtrate gives:

$$F' = P' + I' - ET' - \Delta Ms \tag{3}$$

But:

$$F' = f * (P' + I')$$

Where f = Filtrate factor, the fractional volume of precipitation and irrigation which becomes filtrate

Therefore,

$$f = \frac{P' + I' - ET' - \Delta Ms}{P' + I'} \tag{4}$$

It can be seen from equation 4 that the filtrate will vary depending on the soil conditions and therefore with time. Since green roofs need to be irrigated more frequently when first installed to ensure the health of the plants (FLL, 2002) the assumption that the initial soil storage is equal to the field capacity of the soil is made. The ET′ can either be supplied via experimental data or calculated using the Blaney-Criddle equation. The Blaney-Criddle equation is presented below as equation 5:

$$ET' = \frac{kpt}{100} \tag{5}$$

where ET′ is in inches, k is the consumptive use coefficient, p is the percent of daytime hours per year in the study month, and t is the mean monthly temperature in ^{o}F (Martin Wanielista et al., 1997). The Blaney-Criddle equation was selected for use in this model due to the fact that it is simple and the variables are easily looked up for a given region. Additionally, this equation adequately predicted the actual measured data. All other variables needed to solve this equation are known with the exception of the final soil storage and the filtrate factor.

To solve for the filtrate factor several more assumptions must be made. First, precipitation and irrigation contribute to the soil storage up until the point of field capacity. For this equation, assume that media field capacity is at a volume of 20% of the growing media depth. Also, assume that any precipitation and irrigation past the point of field capacity will contribute to runoff, or the filtrate equals input for any additional water past the field capacity of the soil. Therefore, for field capacity conditions the equation that describes the final soil storage term, M_{S2}, is as follows:

$$M_{S2} = M_{Sfc} - ET' \tag{6}$$

That is, whenever runoff occurs, equation 6 is used to determine the soil storage at the end of the time step. If runoff does not occur, or the soil does not get to the field capacity, then the soil storage at the end of the time step can be found from the following equation:

$$M_{S2} = M_{S1} + P' + I' - ET' \tag{7}$$

Using these assumptions every variable in equation 4 is known except for the filtrate factor. From this information "f" can be solved for any location provided daily precipitation data are available.

Now that the filtrate has been quantified an equation needs to be developed that describes how the cistern behaves. An equation for the change in soil storage between times 1 and 2 needs to be developed using the first system boundaries from Figure 5.

This gives the following equation:

$$M_{S1} - M_{S2} = ET' + f(P' + I') - P' - I' \tag{8}$$

Next, using the second system boundaries in Figure 5, an equation is developed to describe the overall system. The equation for this system is as follows:

$$\frac{d(S + M_S)}{dt} = P + Z - ET - O$$

Assuming a finite time step and converting to volume terms gives:

$$\frac{\Delta(S + M_S)}{\Delta t} = P + Z - ET - O$$

This equation further simplifies to:

$$\Delta(S + M_S) = P' + Z' - ET' - O'$$

Rearranging gives:

$$S_1 + (M_{S1} - M_{S2}) + P' + Z' - ET' - O' = S_2 \tag{9}$$

Finally, a mass balance equation needs to be developed for the cistern. This can be done by combining equations 8 and 9 to give:

$$S_1 + f(P' + I') - I' + Z' - O' = S_2 \tag{10}$$

S_1 and S_2 refer to the cistern storage volume at the initial time and after the time step, respectively. Therefore, this equation describes how the water level in the cistern fluctuates over time.

Using the equations previously developed, equations 4, 5, 6, 7, and 10, a green roof model is formulated. The model developed is called the continuous stormwater treatment outflow reduction model, or CSTORM. The equation developed to solve for the filtrate factor, equation 4, needs to be solved simultaneously with equation 10 using the entire record of daily precipitation data and monthly average evapotranspiration data, either from historical data or using the Blaney-Criddle equation, for a one day time step. The purpose of using the entire precipitation record is to reduce the introduction of error into the model due to the variability of yearly precipitation for any given area. The equations that describe the soil storage potential, equations 6 and 7, are to be used as stipulations that depend on the current conditions of the system.

Operating assumptions for the cistern need to be made, the first is that the initial storage volume of the cistern is equal to the irrigation volume. This is done so as to provide sufficient water to perform the initial irrigation. If the cistern storage is less than the irrigation volume, and irrigation is to occur, then makeup water is added. The amount of makeup water added is equal to the difference of the irrigation volume and the current cistern storage volume. In addition, if the volume of filtrate plus the initial volume of the cistern is greater than the maximum storage capacity of the cistern, then overflow occurs. The volume of overflow is equal to the difference between the beginning period cistern volume plus the filtrate in that period and the maximum cistern storage capacity.

With the CSTORM model, a green roof and cistern system can be designed to achieve desired stormwater retention efficiency. The efficiency, expressed as a percentage, is defined as the volume of stormwater retained within the system and released as ET divided by the volume of precipitation. The fraction of stormwater retained relative to the total precipitation can also be expressed as one minus the fraction of stormwater released as overflow relative to the total precipitation.

$$Efficiency = \left[1 - \left(\frac{O'}{P'}\right)\right] * 100 \qquad (11)$$

Using the above equations the CSTORM model was developed. This model can produce design curves which can be used for quantification of the average year stormwater efficiency. It should be noted that the model will give a cistern storage requirement in terms of depth stored per unit area of green roof. To get the volume or size of cistern required for an individual project, the area of green roof needs to be multiplied by this term along with the appropriate unit conversions.

To examine how the model predicts the filtrate volume from the green roof experimental data from M. Hardin, D. (2006) and M. Hardin and Wanielista (2007) are compared to a short term model run for the precipitation and irrigation that occurred. The cumulative filtrate volume vs time is shown below in Figure 6 and Figure 7 for the model compared to the data from M. Hardin, D. (2006) and for the model compared to the data from M. Hardin and Wanielista (2007). These Figures show good agreement for the modeled data and the experimental data.

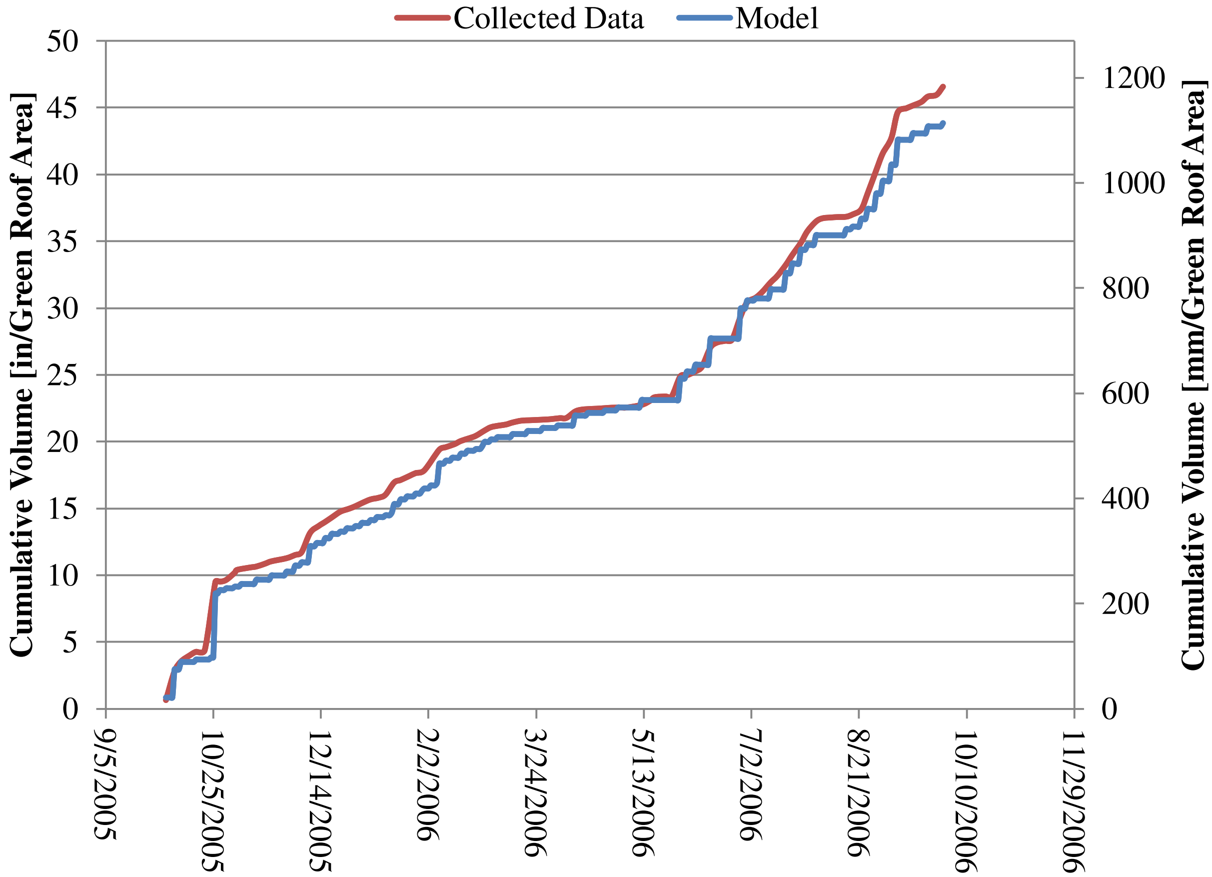


Figure 6: Cumulative filtrate volume vs time for modeled data and experimental chambers data from M. Hardin, D. (2006)

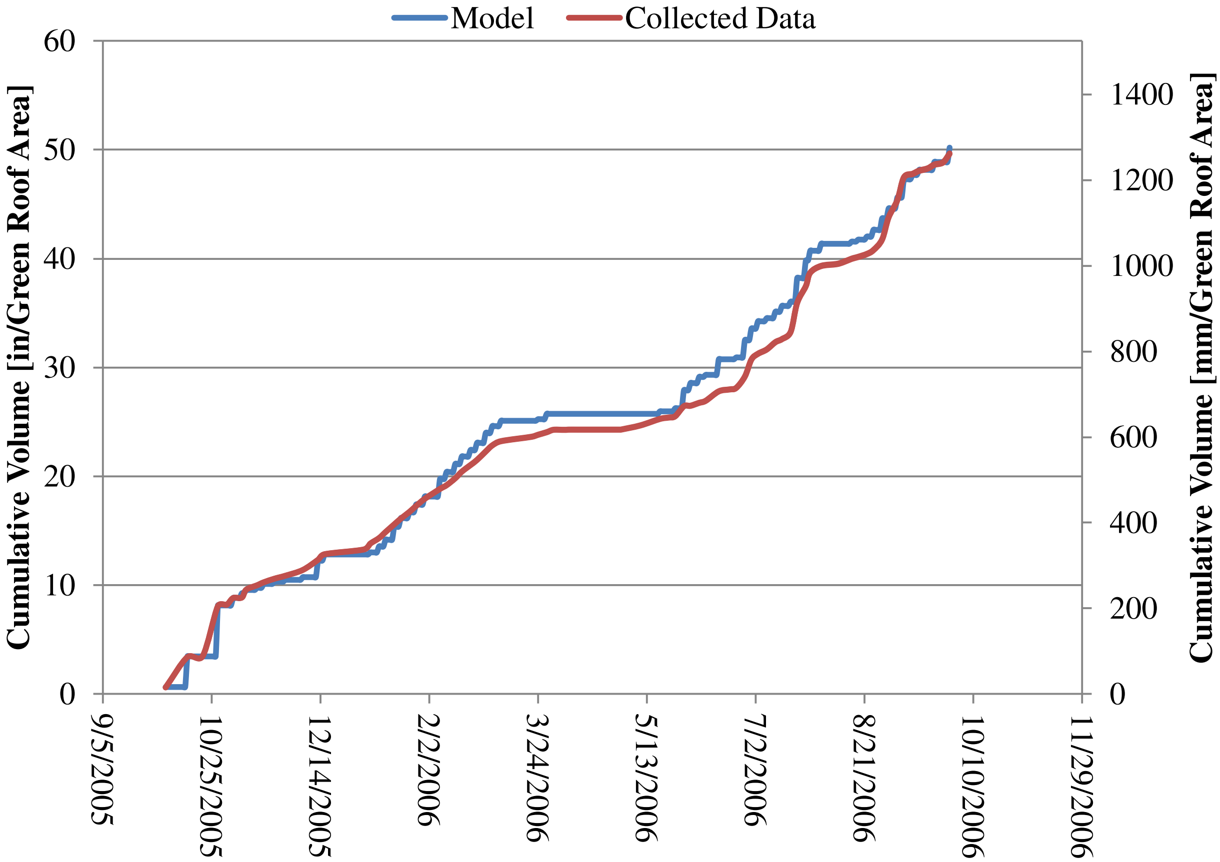


Figure 7: Cumulative filtrate volume vs time for modeled data and a full sized green roof data from M. Hardin and Wanielista (2007)

<u>CSTORM Model Output</u>

The CSTORM model is a valuable design tool for the consulting and design industry. This model has the ability to design a green roof stormwater storage system for a desired efficiency, incorporate additional irrigation areas, and include additional impervious area runoff. The model predicts the expected yearly retention and gives an estimate to the yearly makeup water requirements.

Design curves developed using the above equations can be produced for effective cistern sizing given a desired retention. Presented in Table 3 is a summary of efficiencies for different cistern storage volumes and locations. From Table 3 it can be determined that the main factors that affect the efficiency of the system are precipitation, evapotranspiration, and cistern storage volume. Lower precipitation and higher evapotranspiration produces a higher efficiency green roof stormwater treatment system, while the converse yields a lower efficiency for the system. Also from Table 3, it is noted that for an irrigated green roof the roof runoff without a cistern can be reduced by about 25% - 43% depending on location. If the no cistern option is used, there are more pollutants (nutrients) from the green roof than from the control roof and an additional stormwater management technique will need to be used to help meet TMDL standards (M. Hardin, D., 2006; Kelly et al., 2007; M. Wanielista & Hardin, 2011). Another way to increase the efficiency of the system is to irrigate additional areas, such as ground level landscaping.

The results of the CSTORM model shown below in Table 3 show that an expected efficiency of 87% can be achieved for the Orlando Florida area when storing 127 mm (five inches) over the green roof area. M. Hardin, D. (2006) showed from experimental data that the actual efficiency is about 83%. These results show that the CSTORM model can be used to accurately predict, plus or minus 4%, the green roof system performance for the average year. In addition, rainfall depth and overflow volume from a cistern were collected over a two year period of time on a 1600 SF green roof using a 1400 gallon cistern and the removal effectiveness was 77% (M. Hardin & Wanielista, 2007). The rainfall was about 80% of the average over a two year period of time, and thus it is expected that the removal will be greater than the annual average as predicted by the model (71%).

Table 3: Summary of Yearly Retentions for Different Cistern Storage Volumes and Locations. (M. Hardin, D., 2006)

Location	Cistern Storage Volume [mm (inch) over GR area]					
	0	25.4 (1)	50.8 (2)	76.2 (3)	101.6 (4)	127 (5)
Austin, TX	25%	65%	77%	83%	87%	90%
Miami, FL	42%	63%	69%	73%	76%	78%
Orlando, FL	43%	69%	78%	82%	85%	87%
Tallahassee, FL	35%	58%	66%	70%	72%	74%

Conclusions

Stormwater management to sustain local water supplies continues to be a growing problem in some areas because of limited space and resources. Green roof stormwater treatment systems are a sustainable solution to this problem of water retention without using more land while offering several other benefits (Kosareo & Ries, 2007; Saiz, Kennedy, Bass, & Pressnail, 2006; Sonne, 2006; Teemusk & Mander, 2009). It is shown in this paper that an irrigated green roof with a cistern is an effective way to reduce the volume of stormwater runoff from rooftops. The results from the water budget data presented here and by M. Hardin, D. (2006), Kelly et al. (2007), M. Wanielista and Hardin (2011), M. Wanielista et al. (2008) show that there is a method to estimate the amount of filtrate from a green roof. Also shown is that ET is not dependent on depth or drainage media type (Kelly et al., 2007; M. Wanielista et al., 2008). The filtrate factor, however is dependent on depth but not drainage media type (Kelly et al., 2007; M. Wanielista et al., 2008). This eliminates drainage media as an important design parameter for the purposes of hydrologic efficiency while showing the importance of growth media depth.

From the results of the CSTORM model and the water budget data from M. Hardin, D. (2006); Kelly et al. (2007); M. Wanielista and Hardin (2006, 2011); and M. Wanielista et al. (2008) it can be seen that green roof stormwater treatment systems can effectively reduce the volume of runoff by as much as 87% for the Orlando, Florida region. This efficiency is based on a cistern that stores a volume of 127 mm (five inches) over the green roof area. It should be noted that an irrigated green roof without a cistern will achieve an annual retention of about 43% for the Orlando region. Examination of Table 3 shows that the expected efficiency is dependent on the geographic region. This is due to local climate conditions. To address changes in evapotranspiration, the authors included the Blaney-Criddle equation to estimate the evapotranspiration for a given region, which was shown to be a good approximation based on the experimental data presented within this paper.

CHAPTER 3: DETERMINATION OF POROSITY AND CURVE NUMBERS FOR PERVIOUS PAVEMENT SYSTEMS PLACED OVER WELL-DRAINING SANDY SOILS

Introduction

Most urban areas have limited space available to put traditional stormwater controls, which has led to the emergence of pervious pavements to reduce the volume of stormwater runoff generated from a site. Pervious paving materials are made from concrete, asphalt, and brick pavers, which are modified to allow for the flow of water through the pavement system. Other materials used are recycled tires, crushed glass aggregate, as well as other aggregates bonded by adhesives. Often, these alternative materials are used to create a beneficial use for a waste product. These modified (pervious) pavement systems have the advantage of reducing nonpoint source (NPS) pollution prevalent in urban areas, over conventional impervious pavement systems which discharge into receiving water bodies (Colandini & Legret, 1999; J. J. Sansalone & Buchberger, 1995; Scholz & Grabowiecki, 2007). Nonpoint source pollution is defined as pollution which comes from many diffuse sources (L. M. Haselbach, S. Valavala, & F. Montes, 2006). Urbanization has led to the increase of NPS pollution that has continued to degrade the quality of surface water bodies in the United States (USEPA, 1994).

Pervious pavements are an effective alternative to impervious paved surfaces for low vehicular load applications and areas where soil conditions are favorable. It should be noted that fiber-reinforced pervious concrete may be able to be used to enhance the strength for higher vehicular load applications. These pavements can help reduce the amount of runoff from a developed site, recharge groundwater, support sustainable construction, provide a solution for construction that is being performed in sensitive areas subject to environmental concern, and help owners comply with Environmental Protection Agency (EPA) stormwater regulations (Schlüter & Jefferies, 2002; Tennis, Leming, & Akers, 2004).

The porosity of impervious pavements and other geotechnical and hydrological applications can be found in the literature (Das, 2011; Legret, Colandini, & Le Marc, 1996). On the other hand, the porosity of pervious pavements requires more detailed investigation and explicit specification. L. Haselbach, M. et al. (2006) examined the permeability of sand clogged pervious concrete however the porosity and storage were not measured directly. J. Sansalone et al. (2008) and J. Sansalone et al. (2012) examined pervious concrete as a filter which included identification of total and effective porosity, hydraulic conductivity, and tortuosity, other pervious pavements and additional components were not examined. They observed that the total porosity of pervious concrete was from 10 to 30% and the effective porosity varied from 4 to 27%. Of additional interest are the performance of pervious pavement systems under sediment loading conditions and the response to rejuvenation attempts from vacuum sweeping. J. Sansalone et al. (2008) and J. Sansalone et al. (2012) examined cored pervious concrete samples in a laboratory setting to examine the change in hydraulic conductivity due to sediment loading and response due to vacuuming and sonication. They noted that pervious concrete systems removed particles via straining and depth filtration due to the fact that the hydraulic conductivity follows an exponential decrease with loading. Recovery of hydraulic conductivity due to rejuvenation varied between 96 to 99% (J. Sansalone et al., 2012). This information gives insight to the long-term performance of these pervious pavement systems but does not examine the effects of sediment loading on sub-base components.

Porosity, for the purposes of this paper, is defined as the ratio of the volume of voids to the total volume of the specimen. However, not all of the pore space in a porous material is effective in either holding liquids or is available for the liquids to flow through it (L. Haselbach, M. et al., 2006). This is due to lack of connectivity among pore spaces, which render some pores inactive (dead ends). Therefore, the effective pore spaces available for flow through are the total pore space less the inactive (dead ends) pore spaces. The effective porosity is described as excluding isolated pores, dead-ended pores, and capillary pores (L. M. Haselbach et al., 2006; Meiarashi, Nakashiba, Niimi, Hasebe, & Nakatsuji, 1995). On the other hand, total porosity is the total void space that includes the isolated void spaces and the space occupied by clay-bound water. Both total and effective porosity are relevant to the storage volume in a pervious pavement system however, due to the fact that over time sediment will fill parts of the void spaces neither is appropriate to use for design purposes.

The porosity of pervious pavement and sub-base materials are an important parameter used to determine the potential storage of these systems and are essential in effective design calculations. The water management districts in the state of Florida allow for water quality credit for the volume provided by pervious and permeable pavement systems provided they are able to maintain, at a minimum, an infiltration rate of 50 mm/hr (2 in/hr) into the parent soils (Gogo-Abite et al., 2014). In situ field measurement and verification of this is required by use of the embedded ring infiltrometer kit (ERIK), a device described by Gogo-Abite et al. (2014). The St. Johns Water Management District in Florida allots full credit for void space for water quality requirement as long as the system can recover the treatment volume within 72 hours (Cammie Dewey, personal communication, February 8, 2013). Attenuation credit is given either as the curve number (CN) or as a runoff coefficient (C) for the system above the parent soil or by treating the system as impervious, i.e. a CN value of 98, (C=1) and giving credit for the storage provided by the void space within the system. The State of New Hampshire allows for stormwater quality credits for pervious pavement design without an underdrain provided the parent soils infiltrate greater than 12.7 mm/h (0.5 inches/hour). In addition, the reservoir or sub-base layer has to be greater than 305 mm (12 inches) for any of the pervious pavements and the system must be sufficient to store the larger of either the water quality volume or the recharge volume (Burack et al., 2008). These regulations are consistent with the statement from Chopra et al. (2006) that the entire system including the sub-base materials and parent soils need to be considered when predicting the capacity of pervious concrete pavements.

Vertical porosity distributions, particularly within pervious concrete pavements, tend to be fairly linear with the lowest porosities in the top quarter and the highest porosities near the bottom (L. Haselbach & R. Freeman, 2006). Additionally, it is recognized that as these systems age, sediment will reduce the storage capacity of these systems (Scholz & Grabowiecki, 2007). Due to this, appropriate values for the storage of these materials must be determined for use in designs. This study intends to build upon earlier findings (L. Haselbach & R. Freeman, 2006; L. M. Haselbach et al., 2006; Meiarashi et al., 1995; J. Sansalone et al., 2008; J. Sansalone et al., 2012) by testing different pervious pavement systems. The examination presented is intended for the specific application of pervious pavements over well-draining sandy soils such as those found in the state of Florida. The results are expected to applicable to other geographic areas where similar soil conditions exist.

Experimental Procedure and Materials

The systems tested are both poured in place pervious pavement systems and permeable paver systems that are commonly used in Florida, including the different sub-base materials.

The pavement systems and materials considered are:

1. pervious concrete (PC)
2. recycled tire pavement (FP)
3. two varieties of permeable pavers (large gap (PP) and small gap (HP))
4. #89 pea-rock (crushed limestone)
5. #89G pea-rock (granite)
6. #57 stone (crushed concrete)
7. #4 stone (crushed limestone)
8. #4G stone (granite)
9. a new biosorption media called Bold & Gold (B&G™)

Additionally, an examination of effective porosity with drying time was performed. Three drying times were investigated, namely 1 hour, 6 hour, and 24 hour. The materials examined are as follows:

1. #89 stone (granite)
2. #89 stone (limerock)
3. #57 stone (granite)
4. #57 stone (limerock)

The pervious concrete mix design had an aggregate to cement ratio (A/C) of 6 and a water to cement ratio (W/C) of 0.38 based on weight and volume, respectively. The mix design for recycled tire pavement was a 1:1 ratio of shredded rubber to crushed granite, and 4.7 liters (five quarts) of single component urethane. The rubber was 9.53 mm (0.375 inch) nominal rubber granule and the granite was 12.7 mm (0.5 inch) nominal crushed granite. The designs for the permeable pavers opening per unit were 10.9% for PP and 6% for HP. The aggregate effective size ranges are 6.4 – 9.5 mm (0.25 to 0.38 inch) for the #89 stone, 12.7 – 38.1 mm (0.5 to 1.5 inch) for #57 stone, and 19.1 – 50.8 mm (0.75 to 2 inch) for #4 stone.

The testing protocols presented in this paper are used to measure the combined porosity of a composite pavement system and the separate components of the system. Two types of tests were performed for the purposes of this experiment: pilot scale component porosity using a modified plastic jar and bench scale system porosity using a barrel shown in Figures 1 and 2, respectively. It should be noted that once the material was placed and compacted into the test vessel, the whole system was quite rigid and minimal, if any, flexing occurred. The objective of the system porosity testing method is to approximate porosity values of pervious pavement systems that have been fully installed into a simulated field environment. Installation and field conditions are carefully simulated in controlled laboratory conditions to improve the accuracy of the porosity analysis. Details for the construction of the system porosity testing are presented below. The component porosity method uses small containers to examine the differences in porosity determined from taking a depth-weighted average of the individual components versus the system as a whole. Additionally, the effect of drying time was examined as it relates to the effective porosity. The materials examined in this paper are all first loaded with sediment and then the surface layer materials are rejuvenated by vacuuming, to observe the effects on effective porosity.

Materials and Sample Preparation for Component Porosity Testing

The materials used for this phase of the project includes: the aforementioned specified testing media, a 1.9 L (½-gallon (US)) plastic jar (including the cap) with the bottom cut off (Figure 8), a 18.9 L (5 gallon (US)) bucket, nonwoven geotextile (Mirafi 160N), rubber bands, a scale with an accuracy of 0.01g (the OHAUS Explorer Pro), a 22.7 L (6 gallon) Ridgid wet/dry vacuum, an evaporation pan, 0.03 m^3 (1 ft^3) of sand, a paint brush, box cutters, 12.7 mm (½ inch) diameter polyurethane tubing, a 739 mL (25 fl. Oz.) plastic container, a proctor hammer, an oven, and a data sheet for the purpose of documentation.

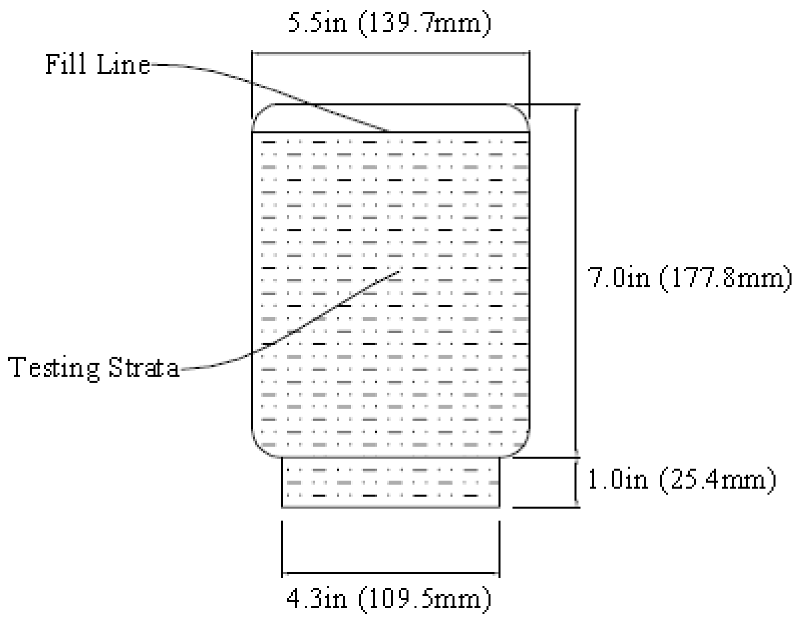


Figure 8: Typical component porosity setup

The description for the component porosity set up and construction procedure is presented as follows. The bottom of a 1.9 L (½-gallon) plastic jar was cut off in accordance with the illustration in Figure 8 using box cutters. The cap was removed and the cap side opening was wrapped in non-woven geotextile and fastened with rubber bands to hold the geotextile in place. The geotextile allowed for drainage without loss of sediment. Next, the cap was replaced over the newly installed geotextile. A specific testing media was then placed in the modified 1.9 L (½-gallon) plastic jar and compacted with a 2.5 kg (5.5 lb.) tamping in accordance with rodding procedure (ASTM C29/C29M, 2009) from a height of 305 mm (12 inches) , which is a slight modification of the jigging procedure because of the weight of tamping rod. The media was subjected to 10 blows from the falling weight hammer using approximately 101.6 mm (4 inch) lifts. The plastic jar was filled as precisely as possible to the specified “Fill Line”. Subsequently, 0.03 m^3 (1 ft^3) of sand was oven dried at 105ºC for 24 hours and then poured into an evaporation pan. This was used to aid in draining and drying the media samples in the plastic jar. This setup was also used for the examination of effective porosity with time.

Component Porosity

The storage capabilities of the individual components of the substrates were examined for a more thorough understanding of the overall system design. On the basis of this conclusion, a variety of substrates were tested including: B&G™ (mix of 45% washed mason sand, 45% tire crumb, and 10% Cedar sawdust by volume), pea rock (#89 stone), crushed concrete (#57 stone), crushed limestone (#4 stone) and granite (#4 stone). Two poured in place pervious paving materials were also tested for their individual porosities, namely, pervious concrete (PC) and a recycled tire pavement (FP). Additional testing was performed to examine the effect of drying time on effective porosity for #89 stone limestone and granite and #57 stone limestone and granite.

The calculation method for component porosity differs from the system porosity. While the system porosity was determined using volumetric calculations, component porosity required weight-based (gravitational) calculations to obtain total and effective porosity values. The total porosity is determined from oven-dried samples while the effective porosity is determined from air-dried samples. Additionally, all these materials with the exception of the B&G™ and the samples analyzed for variable dry time were loaded with quartz sand to examine the effects of sediment loading on porosity. The sand was poorly graded fine sand (AASHTO A-3) with particle sizes of 0.12 mm (D_{10}), 0.16 mm (D_{30}), and 0.21 mm (D_{60}). These particle sizes are in the range of those tested by J. Sansalone et al. (2008) and J. Sansalone et al. (2012). All the surface layer materials were subsequently vacuumed to examine the effects of rejuvenation on porosity.

The experimental process consisted of the following steps. A 739 mL (25 fl. Oz.) plastic container, used to prevent direct spillage, was placed on the scale and the weight was recorded. The sample, which was installed in a modified jar (Figure 8), was placed onto the plastic container. The dry weight of the sample was recorded. Next, the sample was placed into an 18.9 L (5 gallon (US)) bucket. The bucket was then filled with water. This allowed water to seep up through the bottom of the modified plastic jar (Figure 8) until it reached the fill line. The sample was slowly saturated for approximately 30 minutes, occasionally tapping the exterior of the jar to eliminate air voids (Montes, Valaval, & Haselbach, 2005). The bottom cap was carefully added to the submerged modified jar so as to prevent spillage and the saturated sample was then quickly removed from the bucket, placed onto the plastic container, and the saturated weight of the sample was recorded. The bottom cap was then removed from the plastic container, and the sample was placed on top of the sand previously spread over the surface of the evaporation pan. The samples for the primary analysis was allowed to drain and air-dried for 24 hours while the samples that examined dry time were allowed to air-dry for 1 hour, 6 hours, and 24 hours. The cap was then replaced over the non-woven geotextile. The sample was reweighed and recorded as the weight of drained water and media.

The porosity equation is presented below as equation 12.

$$n(\%) = \frac{V_{voids}}{V_{total}} \tag{12}$$

where V_{total} is the total specimen volume and the V_{voids} is the volume of voids. V_{total} was determined by filling the testing apparatus (see Figure 8) with water to the designated fill line:

$$V_{total} = \frac{W_w}{\gamma_w} \tag{13}$$

where W_w is the weight of water to the fill line and γ_w is the unit weight of water. For all cases of component porosities, the total volume was shown to equal 1.7 L (101.6 in^3). After adding the desired media into the testing apparatus, the volume of voids (V_{voids}) was determined using the following equation:

$$V_{voids} = \frac{W_{wm} - W_{dm}}{\gamma_w} \tag{14}$$

where W_{wm} is the weight of the water and media and W_{dm} is the weight of the dry media. This volume of voids is used in equation 12 to calculate the total porosity. After the required draining period based on the previous specifications, the sample was reweighed to determine the amount of residual water. Hence, a new volume of voids (V'_{voids}) value was determined yielding an effective void space measurement:

$$V'_{voids} = \frac{W_{wm} - W_{dwm}}{\gamma_w} \tag{15}$$

where V'_{voids} is the volume of voids remaining after the required draining period and W_{dwm} is the weight of drained water and media. The new volume of voids is used in Equation 12 to calculate the effective porosity, or the porosity of the sample excluding dead end pores and other pores that will not drain readily.

Materials and Sample Preparation for System Porosity Testing

The system porosity set up was as follows: a 208 L (55 gallon) barrel was utilized for this portion of the project. A well pipe was prepared by cutting a 38.1 mm (1-½ inch) diameter PVC pipe too approximately 1,016 mm (40 inches) in length. Slits were then cut in the well pipe and lined up in two rows, which were on opposite sides of the cylinder (slits were evenly spaced at 38.1mm (0.25 inch) intervals up to a height of 406.4 mm (16 inches)). This 406.4 mm (16-inch) section of the well pipe was then wrapped in a nonwoven Geotextile (Mirafi 160N) and fastened with rubber bands to hold the geotextile in place. The wrapped well pipe was approximately centered in the plastic barrel and epoxy glue was applied to the bottom surface of the geotextile wrapping to hold the well pipe upright and in place. A 1.1 meter (3.6 feet) measuring tape was fastened upright against the inside wall of the drum using epoxy glue. At this point, the oven dried testing media was installed in a manner consistent with Figure 9. The testing media was installed in 101.6 mm (4 inch) lifts and compacted with approximately 15 blows of tamping. This was repeated for each lift until the testing media reached the surface layer. The surface layer was installed in accordance with manufacturer recommendations. The barrels used were quite rigid and did not experience noticeable flex during installation or testing.

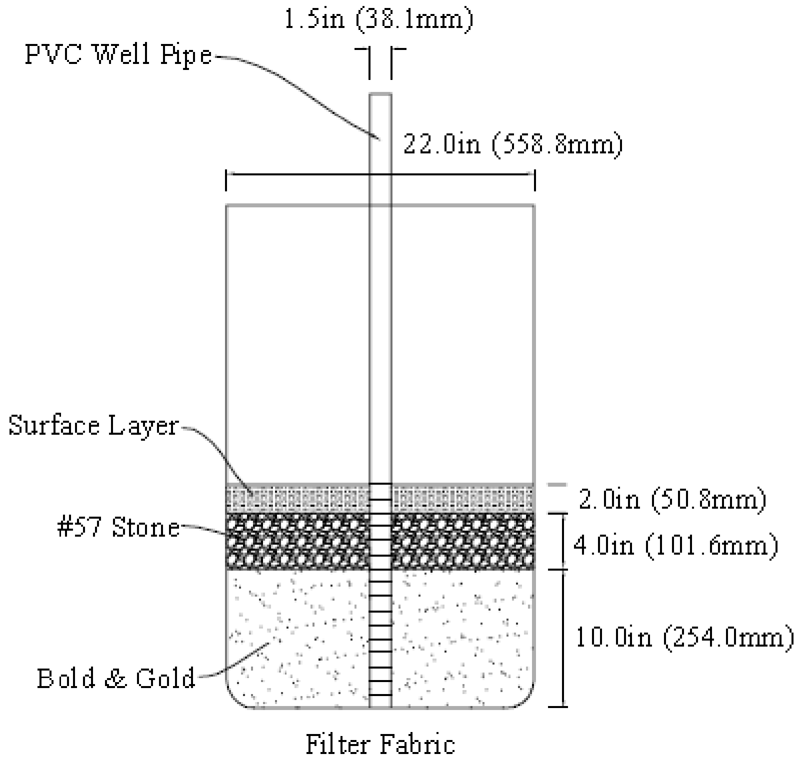


Figure 9: Typical system porosity setup (example for FP system)

System Porosity

System porosity testing was done to examine the total and effective porosities of the pervious pavement system as a whole. The decrease in porosity of the system as a whole due to interstitial mixing between different media layers was examined. Additionally, these systems were loaded with quartz sand (same particle sizes as in the component porosity testing) and subsequently vacuumed to examine the effects of sediment loading and rejuvenation on the system porosity. The pervious pavement systems tested are shown in Table 4.

Table 4: Description of the pervious pavement systems

Pavement System	Surface Layer		Base Layer		Sub-base Layer 1		Sub-base Layer 2		Sub-base Layer 3	
	Material	Depth mm (in.)	Material	Depth mm (in.)	Material	Depth mm (in.)	Material	Depth mm (in.)	Material	Depth mm (in.)
Pervious Concrete (PC)	Pervious Concrete	152.4 (6)	B&G™	254 (10)	N/A	N/A	N/A	N/A	N/A	N/A
Recycled rubber pavement (FP)	Recycled rubber pavement	50.8 (2)	#57	101.6 (4)	B&G™	254 (10)	N/A	N/A	N/A	N/A
Small gap permeable pavers (HP)	Small gap permeable pavers	79.4 (3.1)	#89	50.8 (2)	#57	101.6 (4)	#4	127 (5)	B&G™	50.8 (2)
Large gap permeable pavers (PPG)	Large gap permeable pavers	79.4 (3.1)	#89G	50.8 (2)	#57	101.6 (4)	#4G	127 (5)	B&G™	50.8 (2)
Large gap permeable pavers (PPL)	Large gap permeable pavers	79.4 (3.1)	#89	50.8 (2)	#57	101.6 (4)	#4	127 (5)	B&G™	50.8 (2)

#4G - Number 4 stone granite
#4 - Number 4 stone crushed limestone
#57 - Number 57 stone crushed concrete
#89G - Number 89 stone granite
#89 - Number 89 stone crushed limestone

The experimental process was as follows: all sub-base materials were oven dried for 24 hours at 105ºC to remove any moisture prior to being installed in the testing apparatus. The PC and FP pavement sections were then installed above the sub-base materials according to manufacturer specification and allowed to cure for 7 and 2 days, respectively. The PP and HP pavement sections were also installed above the sub-base materials according to manufacturer specifications but did not require a cure time. 2000 milliliters (0.5 US gallons) of water was portioned using a graduated cylinder. The measured volume of water was then poured into the top of the 38.1 mm (1-½ inch) diameter well pipe (PVC), through a large funnel that was placed in the top opening of the well pipe to minimize water loss due to transfer spillage, and until water saturated the system entirely. Total saturation was achieved when the top layer of the pavement system was entirely submerged. The system was then allowed to rest for 20 to 30 minutes while the side walls of the barrel were tapped to reduce air voids and allowing the water to distribute to all the pore spaces at which time more water was added if needed. The cumulative volume of water added to achieve saturation, in addition to the final depth of water was recorded. Equations 16 and 17 were then used to determine the system porosity. The first test signified the total porosity while subsequent tests measured effective porosity.

The total volume of the specimen was calculated based on the height within a 208 L (55-gallon) barrel. The barrel was calibrated previously by adding known volumes of water and recording the height. The porosity was then calculated by recording the volume of water added to effectively saturate the specimen and by utilizing the following method. It should be noted that the preceding method was used to determine both the total and effective porosities. The total porosity signifies the system water storage when the materials were oven dried. The effective porosity was determined by first vacuuming out the water from the total porosity test through the well pipe and then allowing to air dry for more than 24 hours. This vacuuming was done several times until no water was being removed from the system.

The volume of voids can be calculated as shown below in Equation 16

$$V_{voids} = V_{added} - \left[H_{wateradded} \left(\frac{\pi d_{inner}^{2}}{4} \right) \right] \quad (16)$$

where V_{voids} is the volume of voids; V_{added} is the volume of water added to the system; $H_{wateradded}$ is the final height of the water measured in the system and d_{inner} is the inner diameter of the PVC pipe shown in Figure 9.

Equation 17 presents the total specimen volume in SI units.

$$V_{total} = 0.2601 H_{wateradded} - \left[H_{wateradded} \left(\frac{\pi d_{outer}^{2}}{4} \right) \right] \ (\text{SI units}) \quad (17)$$

where 0.2601 is a constant that relates the water depth in mm to volume in liters based on prior calibration for SI units.

Experimental Results and Discussion

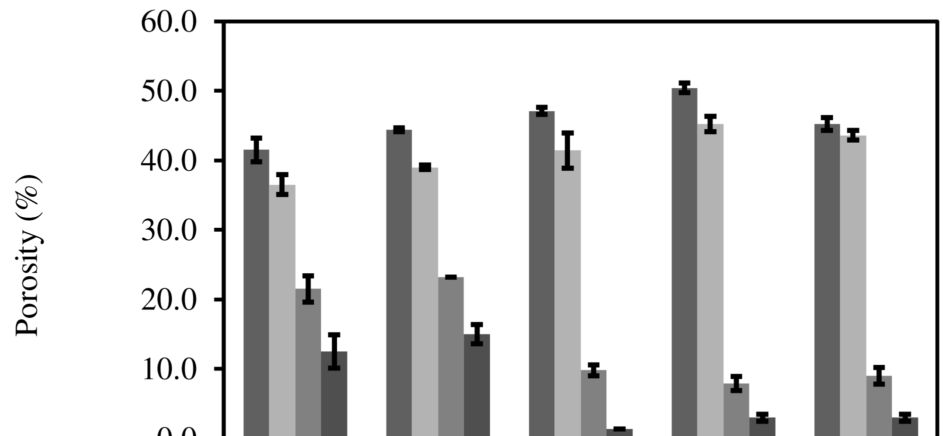
Two simple methods have been presented in this paper to measure the total and effective porosity based on volumetric and weight centric calculations for the component and system porosity respectively. The results of the testing for each of the component and systems are discussed below.

Component Porosity

The component porosity test was performed on 14 samples utilizing the equipment at the Stormwater Management Academy Research and Testing Laboratory facilities located at the University of Central Florida (UCF), Orlando. Tests were performed on the following samples: the B&G™ mixture, pervious concrete, the recycled tire pavement, #89 limestone, #89 granite, large gap and small gap pavers from different companies, #57 limestone, #57 granite, #57 crushed concrete, #4 crushed limestone and #4 stone granite.

The testing performed varied slightly depending on the testing media. As it pertains to B&G™, effective and total porosity was the subject of analysis. The substrates, i.e. the sub-base materials, were loaded with sediment to examine the effect on porosity and separate samples were allowed to dry for different periods of time to examine the effect on effective porosity. The pervious/porous paving surface layer materials were also loaded with sediment and subsequently vacuumed. This was done to observe the effects of loading and rejuvenation on effective porosity. The vacuum used was a 22.7 L (6-gallon) Ridgid wet/dry vac, which produces 1.3 m (53 in) of water column. It was repeatedly applied to the paving surface until no more sediment was removed. As a point of comparison, the force applied by vacuums in the field can range from 0.38 m (15 in) to 1.73 m (68 in) of water column depending on what equipment is used. J. Sansalone et al. (2012) applied a vacuum force of 100 kPa (approximately 400 inches of water column) to samples they analyzed, however the authors were unable to find any field equipment that is able to achieve this force.

Vacuum rejuvenation was not performed on the system sub-base components, as they would not be in contact with the vacuum in a typical field application. Vacuuming these components directly would not be representative of what would happen in the field and would remove the component testing media from the testing apparatus. It should be noted however, that the larger size aggregate allowed more soil into the open pores and deeper into the sample having a significant effect on the resulting total and effective porosity values. Figure 10 illustrates the overall change in total and effective porosity before and after sediment loading. The authors note that the degree of sediment transport and subsequent clogging of the sub-base materials is highly dependent on the physical characteristics, such as pore size and tortuosity of the surface pavement layer as well as the size of the clogging sediment. Additionally, while it has been shown that pervious concrete will reduce sediment transport into sub-base layers (J. Sansalone et al., 2008; J. Sansalone et al., 2012), fine sediments will still migrate to these layers eventually filling the void space provided.



	Limerock (#89)	Granite (#89)	Crushed Concrete (#57)	Limerock (#4)	Granite (#4)
Initial (Total)	41.5	44.4	47.1	50.4	45.2
Initial (Effective)	36.5	39.0	41.4	45.2	43.6
Loaded (Total)	21.5	23.2	9.8	7.9	9.0
Loaded (Effective)	12.5	15.0	1.4	3.0	3.0

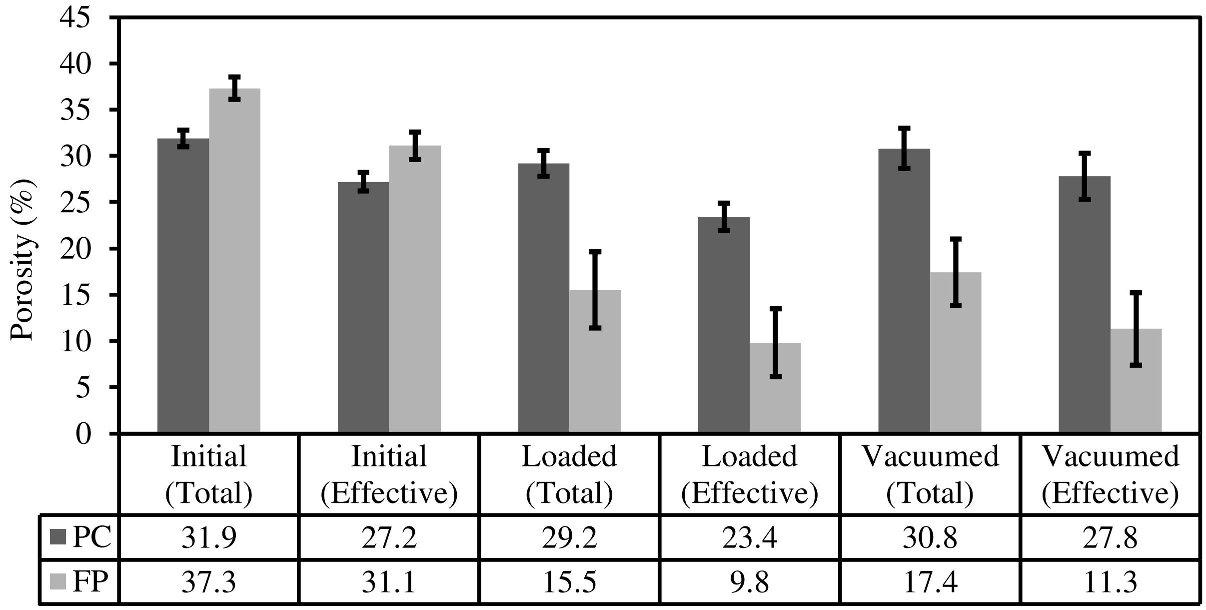
Figure 10: Comparison of sub-base component porosity values

Figure 10 shows that all the sub-base materials examined initially have a high total and effective porosity. Once the materials were loaded with sediment however, a significant drop in both total and effective porosity was noted. The extreme changes, particularly within the crushed concrete (#57), crushed limestone (#4) and granite (#4) can be attributed to two phenomena: the relatively porous structure of the material and a pore structure which is prone to infiltration from soils and other clogging agents. It is noted that this kind of loading would be representative of a pervious pavement sub-base after many years of use, an extreme event such as a spill, or a system after a few years with poor site conditions and/or maintenance practices. While ASTM C29/C29M standard materials were not used for this phase of testing, coefficient of variation ranged from 1.9% to 13.7% for the different samples showing good repeatability.

The B&G™ porosity results show an average total porosity value of 38.9% and an average effective porosity value of 15.2% with a standard error of 0.9 and 2.4, respectively. Analysis of the B&G™ media porosity results demonstrates a sizeable difference between the total and effective porosity. Some of this can be attributed to the elastic nature of tire crumb which has random void space depending on confining conditions and the hydrophilic nature of sawdust. Sawdust's propensity to absorb water, coupled with its subsequent volumetric expansion upon absorption, skews the porosity values by reducing pore space due to swelling and altering the previously constant V_{total} value.

Presented in Figure 11 are the total and effective porosities of the surface component for the pervious pavements examined for new, sediment-loaded, and vacuumed (rejuvenated) conditions. The sediment loading was done to represent the "worst case scenario" for a location in Florida with sandy soils. All of the pervious pavements respond as expected to the conditions of the test. The effective porosities are always less than the total porosities. Loading the pavements with sediment reduced the effective porosities. The FP pavement showed a larger decrease in both total and effective porosity than the PC pavement after sediment loading. Vacuuming the pavements showed improvement from the sediment loaded state. The PC pavement was returned close to initial conditions which is consistent with what was found by J. Sansalone et al. (2008) and J. Sansalone et al. (2012) while the FP pavement did not.

Initially, it was thought that the FP pavements inability to rejuvenate was attributed to the binding agent utilized in the installation of the pavement system causing any sediment to adhere and clog void spaces. However, this binding agent sets fully within two weeks of installation. A potential explanation for the inability of the pavement to rejuvenate is due to the migration of soil particles below the effective depth of the vacuum force and/or the large open pore structure of the pavement. It should be noted that due to the fact that the FP pavement took significantly more sand for it to be considered clogged compared to the PC pavement indicates that the FP system will have a longer service life before being rendered ineffective. Clogging was taken as the point when soil would no longer pass through the pores and began to accumulate above the paving surface material.



	Initial (Total)	Initial (Effective)	Loaded (Total)	Loaded (Effective)	Vacuumed (Total)	Vacuumed (Effective)
PC	31.9	27.2	29.2	23.4	30.8	27.8
FP	37.3	31.1	15.5	9.8	17.4	11.3

Figure 11: Comparison of the poured in place surface layer porosity values

Presented in Figure 12 are the total and effective porosities of the permeable pavers for new conditions, sediment loaded conditions, and post vacuumed conditions. For all the pavers examined the effective porosity was less than the total porosity. Loading with sediment showed little reduction in effective porosity and vacuuming had little effect. This was due to the fact that the permeable pavers took very little sediment before considered clogged. One reason for the minor reduction in porosity is the filler stones between the paver blocks held the sediment close to the surface acting as a filter straining out the sediment particles. Thus, there is very little difference between the average effective porosity, the sediment loaded effective porosity, and the vacuumed effective porosity. This indicates that as long as these systems are properly maintained they will be effective in allowing rainfall to drain through the pavement to the sub-base and subgrade materials.

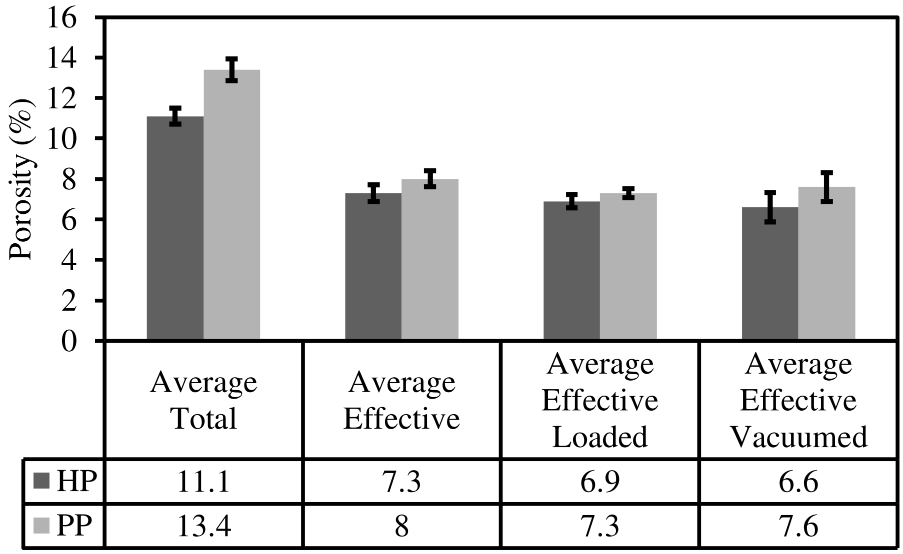
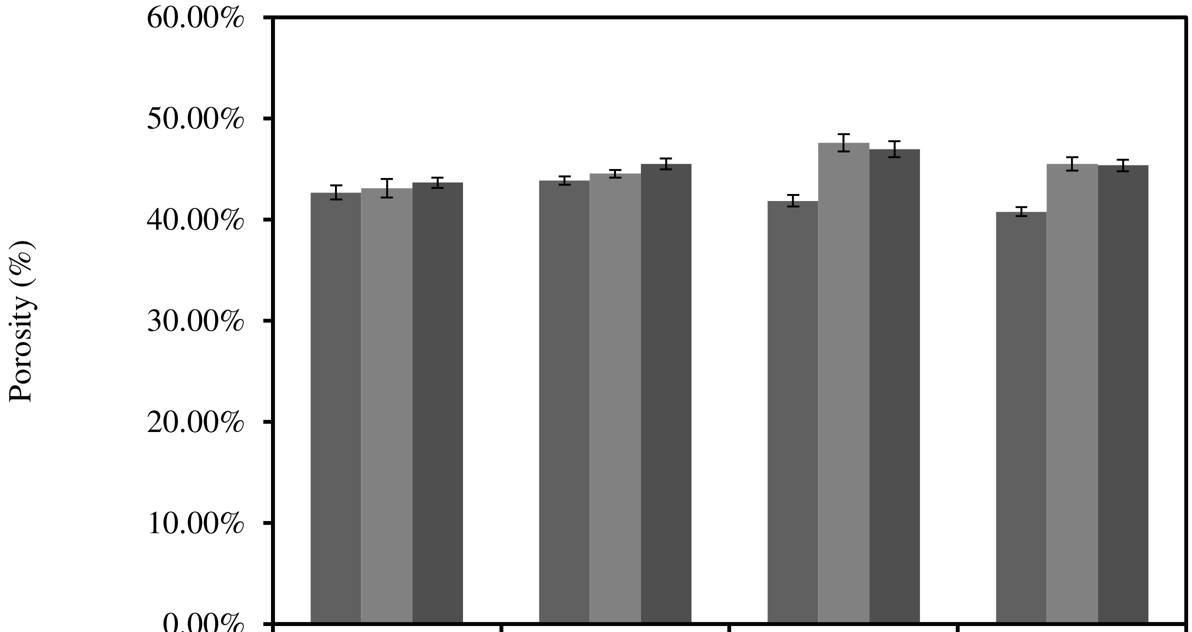


Figure 12: Comparison of paver surface layer porosity values

Figure 13 shows the effect of drying time on selected sub-base materials. Drying times of 1 hour, 6 hours, and 24 hours were examined in an effort to reduce the drying time in determining effective porosity. It can be seen from Figure 13 that the drying time had more effect on the larger aggregate, the #57 stone compared to the smaller #89 stone. A Mann-Whitney U test was performed on the data to examine if there was any significant difference for effective porosity with different drying times using a significance level of $\alpha=0.05$. This testing showed that there was not sufficient evidence to conclude that there was a significant difference between the 6 hour and 24 hour dry times for all four media examined. There was a significant difference in effective porosity for a 1 hour dry time compared with a 6 hour dry time. These results indicate that for #89 limestone, #89 granite, #57 limestone, and #57 granite a 6 hour dry time is sufficient for testing purposes.



	Limerock (#89)	Granite (#89)	Limerock (#57)	Granite (#57)
1-HR Dry Time	42.66%	44%	42%	41%
6-HR Dry Time	43.09%	45%	48%	45%
24-HR Dry Time	43.63%	45%	47%	45%

Figure 13: Comparison of sub-base components effective porosity with respect to drying time

System Porosity

Each pervious pavement system tested was composed of different layers of materials at varying depths. While there are an enormous amount of different combinations and depths of sub-base components and surface layers, this work used the same system depth of 406.4 mm (16 in) for every system examined. There were many system configurations tested with the pervious pavement itself as the top layer for each system. It is desired to verify that the component values for porosity provide a good estimate of the system storage by taking a depth-weighted average. There may however, be changes in storage due to interstitial mixing that could result in a decrease in the system storage. Thus, a total of five different paving systems were tested using a system porosity test apparatus (Figure 9) at the laboratory facilities located at the University of Central Florida (UCF) Stormwater Management Academy.

The results of these tests were compiled using Microsoft Excel™ and plotted to illustrate comparisons. Error bars were also provided to indicate the significance level. To clarify, the systems tested are presented in Table 4.

Sediment was loaded into the system until the point of clogging. The sediment was poured onto the surface of the pavement and washed into the pavement with water. This was done to represent the pervious pavement system after several years of service in the state of Florida in an area with sandy soil or after an extreme sediment loading event such as a dump truck spill. This was achieved by adding quartz sand, one liter at a time, and washing it into the pavement system. It is recognized that other factors could affect the performance of pervious pavement systems; however other factors such as mechanical and chemical impacts were outside the scope for this project. The poured in place materials were found to have a much higher sediment loading capacity when compared to the permeable brick paving systems which had an extremely low sediment loading capacity (Figure 14). The diminished sediment loading capacity of the permeable brick paving systems was due to the fact that the small gaps between the pavers and filler stone (#89 limestone and #89 granite for the PP and HP systems, respectively) did not allow the sediment into the sub-base system. This demonstrates the need for a more frequent maintenance regimen to maintain functionality; however, the potential storage of the sub-base layers will be protected ensuring a long service life. Again, while this is true for loading of sandy soils, which are common in Florida, the authors acknowledge that in areas with fine grained soils this will likely not be the case. These systems were also vacuumed with the previously mentioned Ridgid wet/dry vacuum in the same way described above. This was done to simulate vacuum sweeping maintenance.

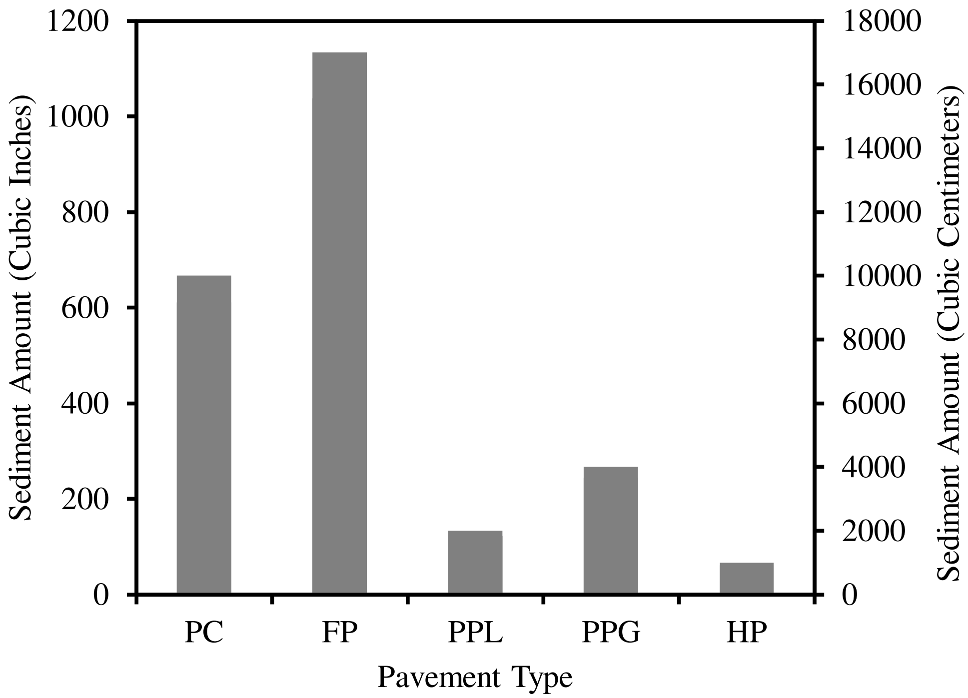
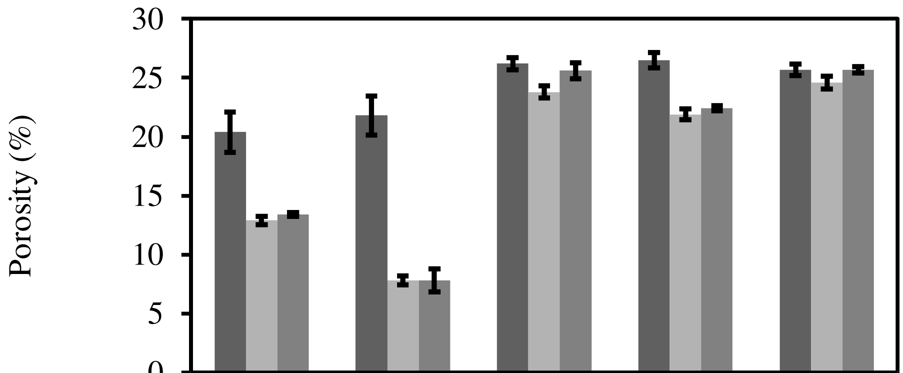


Figure 14: Comparison of sediment volume loaded to each pavement system

The porosity of all the newly installed pervious pavement systems, the sediment loaded pervious pavement systems, and the vacuumed pervious pavement systems are shown in Figure 15. Standard error bars are presented to show the variability in the measurements taken. Interpretation of the test results illustrate that while these paving systems have relatively high initial porosity values, the poured in place systems are not able to maintain their high void ratio when loaded with sediment. The pore structure of the poured in place systems allows for a migration of soil particles deeper into the pavement system, below the effective vacuum force depth. This greatly hinders the performance of the system as well as reduces the effectiveness of vacuum rejuvenation. This was especially true for the FP system due to the large pore size of the material. The poured in place pavement systems will require replacement if not regularly maintained. It should be noted that both the PC system and FP system behave in a similar manner, except the FP system is able to take significantly more sediment than the PC system (Figure 14). Neither system shows a significant difference in porosity after a vacuum sweeping (Figure 15).



	PC	FP	PPL	PPG	HP
Initial	20.4	21.8	26.2	26.5	25.7
Loaded	12.9	7.8	23.8	21.9	24.6
Vacuumed	13.4	7.8	25.6	22.4	25.7

Figure 15: Comparison of the pavement system porosity values

The permeable paver systems did not behave in a similar manner to the poured in place pervious pavement systems. As discussed above, the small gaps and #89 (limestone for the PPL and granite for the PPG and HP) between the bricks in the permeable paver systems hold the sediment close to the surface. This feature significantly reduced the sediment loading capacity of the system due to more surface straining (Figure 14) but also allows for more efficient vacuuming while also protecting the sub-base from filling with sediment (Figure 15). Both the PP and HP systems performed similarly for this testing regardless of the sub-base materials used. This is illustrated in Figure 15.

Storage Calculations

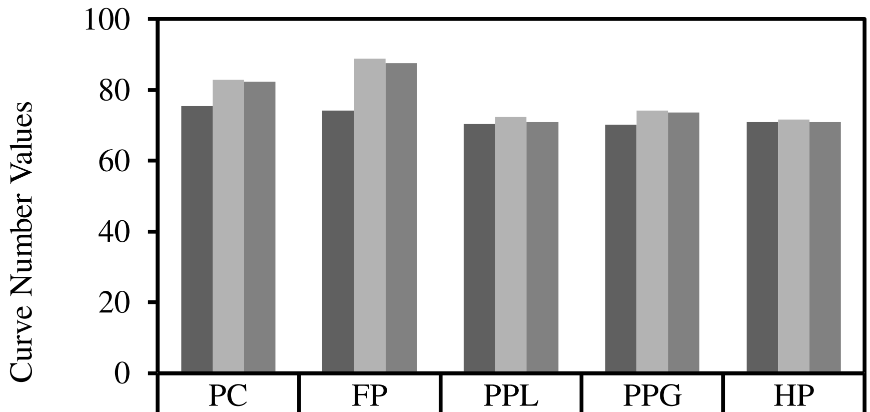
The porosity values presented in this work are subsequently used to calculate the storage capacity of the entire system in SI units and Imperial units (millimeters and inches). It should be noted that the sediment loaded condition was at the point of clogging (defined above) and represents a pavement system at the end of its service life, after an extreme loading event, or after a few years with poor site conditions and little or no maintenance performed. Therefore, the effective porosity was used to calculate system storage and not the sediment loaded or rejuvenated porosity. For the purposes of design in the state of Florida, curve numbers are calculated from the measured storage of the systems provided that the underlying soils are able to maintain the minimum infiltration rate specified above. Curve numbers were calculated using equation 18 below:

$$S' = \left(\frac{1000}{CN}\right) - 10 \tag{18}$$

where S' is the maximum storage capacity of a given medium or system in inches (M.P. Wanielista, 1990).

Curve numbers are an empirical description for infiltration and rainfall excess. These values are valuable design aids, as they are indicators of the true infiltration, and subsequent storage and effectiveness of a pervious/permeable paving system. Again, if the underlying soils are not able to infiltrate under the design conditions, this approach is not appropriate to use for design. A value of 98 is generally accepted as the curve number of an impervious surface.

The results of the system CN computations are shown in Figure 16. The PC and FP systems (the poured in place systems) perform similarly. Both started with an initial CN of about 75. The FP system showed the biggest increase in CN (from 74.1 to 88.9) after sediment loading but the PC system also had an increase (about 7). It should be noted that the FP system was able to accept much more sediment than the PC system (Figure 14), indicating a longer effective pervious pavement service life assuming similar site conditions and no or minimal maintenance is performed. Both systems showed a minor decrease from the sediment loaded condition after a vacuum sweeping. It was observed at the time of testing that vacuuming was effective at removing surface sediment but sediment that traveled deeper into the system was not affected by the vacuum force.



	PC	FP	PPL	PPG	HP
Initial	75.4	74.1	70.4	70.2	70.9
Loaded	82.9	88.9	72.4	74.1	71.7
Vacuumed	82.3	87.5	71	73.6	70.9

Figure 16: Comparison of curve numbers for the pavement systems at a total thickness of 406.4 mm (16 in)

The CN's for the permeable brick paver systems are also shown in Figure 16. The PPL, PPG, and HP systems (the permeable brick paver systems) have a lower CN than the poured in place systems. This was due to differences in the depths and materials used for the sub-base components; the permeable pavers have deeper rock sub-base layers and different size rocks. The permeable paver systems also did not experience as much of a decrease in storage due to sediment loading and were able to maintain their storage better than the poured in place paving systems. This was due to the structure of the paver gaps, which prevents sediment from traveling deep into the system as well as the type of sediment, used for loading. Since this study is examining the design of systems in sandy soils found in Florida, sandy soils were used for loading. All the permeable pavers showed a minor increase in CN due to sediment loading and minor decrease in subsequent vacuuming. Similar to the poured in place systems, vacuuming was observed as very effective at removing surface sediments and not effective at removing deeper sediments.

The porosity values measured in this study were subsequently used to examine whether or not a depth-weighted average of the component porosities was a good estimation of the entire system porosity for the materials and systems examined in this study. This comparison was also performed for CN values. These comparisons are presented in Table 5 – Table 9. These trials were limited specifically to effective porosity due to the fact that it more closely simulates field conditions.

Table 5: Comparison of pervious concrete (PC) porosity and CN as determined from system measurement and weighted average of the individual components

Parameter	PC System	PC	B&G media	Component weighted average
Thickness, mm (inches)	406.4 (16)	152.4 (6)	254 (10)	
Effective Porosity (%)	20.40	27.20	15.20	19.70
Standard Error (%)	1.72	1.0	2.4	
Storage, mm (inches)	82.8 (3.26)	76.0 (1.63)	38.6 (1.52)	80.1 (3.15)
Curve Number	75.4			76.0

Table 6: Comparison of recycled tire pavement (FP) porosity and CN as determined from system measurement and weighted average of the individual components

Parameter	FP System	FP	#57 Crushed concrete	B&G media	Component weighted average
Thickness, mm (inches)	406.4 (16)	50.8 (2)	101.6 (4)	254 (10)	
Effective Porosity (%)	21.80	31.10	41.40	15.20	23.74
Standard Error (%)	1.64	1.5	2.5	2.4	
Storage, mm (inches)	88.6 (3.49)	15.8 (0.62)	42.1 (1.66)	38.6 (1.52)	96.5 (3.80)
Curve Number	74.1				72.5

The effective porosity, standard error, system storage, and curve number for the two poured in place systems examined are shown in Table 5 and Table 6 for the PC and FP systems, respectively. These values were determined by direct measurement through system porosity and calculated based on taking a depth-weighted average of the individual components porosity. The comparison for the PC and FP systems reveals that the component depth-weighted average was a good estimate of the systems true effective porosities, storage capacities, and curve numbers.

Table 7: Comparison of large gap permeable paver with limestone sub-base materials (PPL) porosity and CN as determined from system measurement and weighted average of the individual components

Parameter	PPL System	Pavers	#89 Crushed limestone	#57 Crushed concrete	#4 Crushed limestone	B&G media	Component weighted average
Thickness, mm (inches)	406.4 (16)	76.2 (3)	50.8 (2)	101.6 (4)	127 (5)	50.8 (2)	
Effective Porosity (%)	26.20	8.00	36.50	41.40	45.20	15.20	32.44
Standard Error (%)	0.5	0.4	1.4	2.5	1.1	2.4	
Storage, mm (inches)	106.4 (4.19)	6.1 (0.24)	18.5 (0.73)	42.1 (1.66)	57.4 (2.26)	7.7 (0.30)	131.8 (5.19)
Curve Number	70.5						65.8

Table 8: Comparison of large gap permeable pavers with granite sub-base materials (PPG) porosity and CN as determined from system measurement and weighted average of the individual components

Parameter	PPG System	Pavers	#89 Granite	#57 Crushed concrete	#4 Granite	B&G media	Component weighted average
Thickness, mm (inches)	406.4 (16)	76.2 (3)	50.8 (2)	101.6 (4)	127 (5)	50.8 (2)	
Effective Porosity (%)	26.50	8.00	39.00	41.40	43.60	15.20	32.25
Standard Error (%)	0.64	0.4	0.3	2.5	0.7	2.4	
Storage, mm (inches)	107.7 (4.24)	6.1 (0.24)	19.8 (0.78)	42.1 (1.66)	55.4 (2.18)	7.7 (0.30)	131.1 (5.16)
Curve Number	70.2						66.0

Table 9: Comparison of small gap permeable paver (HP) porosity and CN as determined from system measurement and weighted average of the individual components

Parameter	HP System	Pavers	#89 Crushed limestone	#57 Crushed concrete	#4 Crushed limestone	B&G media	Component weighted average
Thickness, mm (inches)	406.4 (16)	76.2 (3)	50.8 (2)	101.6 (4)	127 (5)	50.8 (2)	
Effective Porosity (%)	25.70	7.30	36.50	41.40	45.20	15.20	32.31
Standard Error (%)	0.49	0.41	1.4	2.5	1.1	2.4	
Storage, mm (In)	104.4 (4.11)	5.6 (0.22)	18.5 (0.73)	42.1 (1.66)	57.4 (2.26)	7.7 (0.30)	131.3 (5.17)
Curve Number	70.9						65.9

Table 7 through Table 9 show the effective porosity, standard error, system storage, and curve number for the three permeable paver systems examined in this study. These values were determined by direct measurement through system porosity and calculated based on calculating a depth-weighted average of the porosity of the individual components. All of the permeable paver systems showed a sizeable difference between the porosity values determined from taking a depth-weighted average of the individual components and the system porosity. However, if it is assumed that the standard error for the individual components is compounded when combined, then the differences are not significant. This large standard error value indicates that there may be some interstitial mixing taking place, reducing the porosity at the interface between any two layers. Since these systems have so many layers this reduced porosity zone had a significant effect on the entire system.

Conclusions

This paper presents total and effective porosities as well as curve numbers for various pervious pavement components and systems. These parameters are considered useful in stormwater management plans using pervious pavements. The data presented in this report are for pervious pavement systems that are to be placed on well-draining, sandy soils in Florida that are able to maintain a minimum infiltration rate of 50 mm/hr (2 in/hr).

The first significant conclusion from this study is that the storage capacity of the pervious pavement systems, even when loaded with sediments, resulted in a CN that is less than those used for conventional impervious paving materials assuming infiltration can occur (impervious paving materials CN are typically 98). This lends credence to the claim that pervious pavements are an effective alternative to reduce rainfall excess or runoff compared to impervious paved surfaces, provided the site conditions are appropriate, i.e. well-draining sandy soils. Additionally, it was shown that in calculating effective porosity, there was no significant difference (α=0.05) between the value obtained using a 6 hour dry time and 24 hour dry time for common media used in pervious pavement systems sub-base layers. Pervious pavements can help to reduce the amount of runoff from a developed site, support sustainable construction, and help comply with stormwater management regulations.

It is recognized that there are a number of different systems that could be constructed in practice and it is not reasonable to conduct tests on every possible depth and material combination, therefore using the weighted average of the porosity of the individual components that make up a given system is the most logical way to determine the storage of the overall system. The results of this work showed that component porosity results can be used to estimate the effective porosity for different pervious pavement systems. The results of the measurements show that, for systems with several layers, interstitial mixing may reduce the experimentally calculated porosity from the individual components.

The poured in place systems have a higher sediment loading capacity than the permeable paving systems when the loading sediment is a sandy soil as described previously. However, rejuvenation capabilities by vacuum are hindered because of their pore structure, which allows a migration of soil particles deep into the system layers, below the effective depth of the vacuum force. The migration of soil particles will vary depending on the sizes of the pores of the pervious surface layer and the clogging sediments.

Recommended porosity values for pervious pavement components during typical operating conditions are based on the average of both the effective porosity and the sediment loaded effective porosity. This is defined as the operating porosity. Operating porosity values are recommended based on the fact that these systems are exposed to the elements and will therefore be subject to sediment loading from different sources. Additionally, while the authors recognize the importance of maintenance, it is also recognized that it seldom happens in practice on a timely manner. To base a design on the porosity of the new system or to base it on an “end of service life” condition would be unreasonable. It is for this reason that the recommended porosity values used for design are the proposed operating porosity as these values give good approximations of the system porosity results while adding an understanding that extreme loading conditions may exist. The recommended operating porosity values for the materials tested in this study are as follows:

a) Pervious concrete – 25%

b) Recycled tire pavement – 21%

c) Pea rock limestone (#89) – 25%

d) Granite (#89) – 27%

e) Crushed concrete (#57) – 21%

f) Crushed limestone (#4) – 24%

g) Granite (#4) – 23%

The pervious concrete value agrees well with those reported by (L. M. Haselbach et al., 2006; J. Sansalone et al., 2008; J. Sansalone et al., 2012; Tennis et al., 2004).

Design of pervious pavement systems in the state of Florida requires that parent soils are able to infiltrate at a minimum of 50 mm/hr (2 in/hr) when compacted to 95% modified proctor (Gogo-Abite et al., 2014). When this 50 mm/hr (2 in/hr) rate occurs, the operating porosity of the different system components can be used to calculate a curve number that can be used for design purposes. Where required by regulation, curve numbers for pervious pavement systems analyzed during typical operating conditions are recommended based on the average of the initial and vacuumed CN's presented in Figure 16. For the pervious pavements evaluated here, the CN for pervious concrete, recycled tire pavement, large gap pavers with a crushed limestone sub-base, large gap pavers with a granite sub-base, and small gap pavers are as follows; 79, 81, 71, 72, and 71 respectively for the specific reservoir depth examined.

CHAPTER 4: A MODEL AND METHODOLOGY TO EVALUATE STORMWATER BMP EFFECTIVENESS AND ASSOCIATED COSTS

Introduction

Stormwater discharges from developing and urban areas have been identified as a significant source of pollution for surface water bodies in the United States (Shaver, Horner, Skupien, May, & Ridley, 2007; USEPA, 2008). Additionally, the USEPA has identified thousands of surface water bodies that are impaired (USEPA, 2008). As a result of this, and in accordance with section 303(d) of the Clean Water Act, states must identify and rank impaired water bodies and establish total maximum daily loads (TMDLs) that limit the amount of pollutants these water bodies can receive (USEPA, 2008). Regulation is also the responsibility of States. As an example, the state of Florida regulates it stormwater discharges to surface water bodies via the Florida Department of Environmental Protection and five water management districts (WMDs). Harper and Baker (2007) provided an in depth review of Florida stormwater regulations. Additionally, the District of Columbia has recently developed updated standards in relation to the use of BMPs (District of Columbia Department of Transportation, 2014).

To meet the Federal, State and even local regulations, methods to manage and treat stormwater must be examined for their potential to help achieve the specific removal effectiveness of these regulations. The historical use of best management practices (BMPs) to achieve regulatory nutrient removal effectiveness have been largely presumptive; and the basis of the BMPs design considers only specific storm events for sizing, which does not account for long term rainfall data (Shaver et al., 2007). This approach to stormwater BMP design does not take into consideration rainfall volumes and inter-event dry periods, which vary spatially and temporally and may have an impact on removal effectiveness of the BMP (Harper & Baker, 2007). In addition, different land uses will result in different pollutant loadings and thus, requires different level of treatment to meet a specific removal effectiveness target.

Several computer models are available to assist with assessing the performance of different BMPs; however, the bases for the designs of the models are restricted to specific applications. These computer models can be found in the literature and a select few that were the most relevant to the development of the model presented in this paper are briefly discussed. The Best Management Practices Treatment for Removal on an Annual basis Involving Nutrients in Stormwater (BMPTRAINS) model was developed to assist stormwater professionals in evaluating the nutrient reduction achieved by the use of BMPs in a watershed and cost analysis. It was desired that an easy to use model that has a high degree of flexibility and is able to analyze complex watersheds be created to assist with analyzing the nutrient reduction achieved by the use of BMPs. This model is easy to use and capable of analyzing complex watersheds. The current form of the model is specific to Florida; however, the methodology is applicable to any location where historical rainfall data exists.

Literature Review of Existing Nutrient Analysis Models

The use of BMPs to treat stormwater discharges is a common practice; however, the performance of BMPs related to nutrient removal has been largely presumptive (Shaver et al., 2007). There often is no methodology for determining the field performance under different rainfall conditions; however, the performance of BMPs in specific applications can be found in the literature. Elliott and Trowsdale (2007) and Tsihrintzis and Hamid (1997) provide in-depth reviews of several different models intended to quantify the benefit of BMPs in urban areas. In addition to this review, the authors reviewed several models deemed most relevant, as related to widespread application, BMP evaluation, and cost analysis, when developing the BMPTRAINS model. The models examined for this study are presented in Table 10. These models are important tools in the evaluation of pollutant removal due to the use of BMPs within a watershed, but each are intended for a specific application. The BMPTRAINS model aims to provide a tool to evaluate a site design which incorporates the use of BMPs for nutrient reduction on an average annual basis and cost. The model has the capability to evaluate complex BMP and/or catchment configurations within a watershed expanding the application and scope compared to existing models.

The similarity in the different models examined was that they all perform evaluation of the effectiveness of BMPs to reduce the pollution generated due to anthropogenic activities. All of the models reviewed evaluated both nitrogen and phosphorus generation within the watershed and removal by BMPs. Some also evaluated other pollutants such as solids, metals, bacterial, etc. The Jordan/Falls Lake Stormwater Nutrient Load Accounting Model (North Carolina Department of Environment and Natural Resources, 2011), The Virginia Runoff Reduction Method Worksheet (Virginia Department of Conservation and Recreation, 2011), and Stormwater Management and Design Aid (SMADA) (Martin Wanielista et al., 1997) evaluate nitrogen and phosphorus. It should be noted that a few of the models reviewed were originally created to evaluate loss of nutrients and top soil from agricultural areas, namely the AVGWLF Model, the Region 5 Model, and the STEPL Model.

Table 10: Models examined for the development of the BMPTRAINS model

Model	Reference
Jordan/Falls Lake Stormwater Nutrient Load Accounting Model	(North Carolina Department of Environment and Natural Resources, 2011)
BMP SELECT Model	(Pomeroy & Rowney, 2013)
Site Evaluation Tool (SET)	(Tetra Tech, 2010)
Virginia Runoff Reduction Method Worksheet	(Virginia Department of Conservation and Recreation, 2011)
Simple Method Pollutant Loading Model	(New Hampshire Department of Environmental Services, 2010)
Stormwater Best Management Practice Design Workbook	(Urban Drainage and Flood Control District, 2010)
STEPL Model	(Tetra Tech, 2011)
AVGWLF Model	(Evans et al., 2008)
P8 Urban Catchment Model	(Walker, 1990)
Region 5 Model	(Michigan Department of Environmental Quality, 1999)
System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN)	(Lee et al., 2012)
Stormwater Management and Design Aid	(Martin Wanielista et al., 1997)

Several of the models had specific treatment volumes that dictated the size of the BMPs used. The Jordan/Falls Lake Stormwater Nutrient Load Accounting Model (North Carolina Department of Environment and Natural Resources, 2011), the Site Evaluation Tool (SET) Model (Tetra Tech, 2010), the Stormwater Best Management Practice Design Workbook (Urban Drainage and Flood Control District, 2010), and the Virginia Runoff Reduction Method Worksheet (Virginia Department of Conservation and Recreation, 2011) will allow a predetermined treatment volume, typically 25.4 or 38.1 mm (1 or 1.5 inches) over the watershed. It should be noted that one can oversize a BMP in the Jordan/Falls Lake Stormwater Nutrient Load Accounting Model to modify the treatment volume provided by a BMP. Additionally, both the SET model (Tetra Tech, 2010) and the Virginia Runoff Reduction Method Worksheet (Virginia Department of Conservation and Recreation, 2011) can take stormwater credits into account potentially reducing the treatment volume. The P8 Urban Catchment Model also has treatment volume specifications that requires predetermined BMP sizes based on user-defined watersheds, storm time series, and target removals (Walker, 1990). The issue of treatment volume specifications becomes problematic when considering catchments which, due to size or degree of impervious cover, are limited in the size of BMP that can be accommodated.

Research on stormwater BMPs is ongoing in the United States, as well as other parts of the world, and methods to quantify the benefits of BMPs on receiving water bodies are important in understanding how these systems interact with the surrounding environment. The use of modeling software is a valuable tool in trying to understand the impact of BMPs in a watershed; while many stormwater models incorporate BMPs, several were developed for limited applications. Most of the models reviewed have specific BMPs pre-programmed into the model without options for the emergence of newer BMPs. However, since BMP research is a constantly evolving research area with new BMPs being introduced in the market, some other models provide the option to have a user defined BMP. The following models: the BMP SELECT Model (Pomeroy & Rowney, 2013), the SET Model (Tetra Tech, 2010), the Simple Method Pollutant Loading Model (New Hampshire Department of Environmental Services, 2010), the STEPL Model (Tetra Tech, 2011), the P8 Urban Catchment Model (Palmstrom & Walker, 1990; Walker, 1990) and the SUSTAIN model (Lee et al., 2012) all have a user defined

BMP option. It should be noted that while both the SUSTAIN model and SET model has a user defined BMP option, the model requires detailed data which may limit the usefulness of this feature (Lee et al., 2012; Tetra Tech, 2010).

Another factor that stormwater models must address is the configuration of the watershed and BMPs within a watershed. A given watershed may be made up of multiple smaller catchments, each with one or more BMPs. Since each watershed or project location is different, models should accommodate the variability of real world projects. All of the models reviewed, with the exception of SMADA (Martin Wanielista et al., 1997) and the Region 5 model (Michigan Department of Environmental Quality, 1999), allow multiple catchments within a watershed. Of the models that allow multiple catchments, several of them are restricted as to the different configurations allowed. There are three basic groups of configurations: series, parallel, and mixed. A series configuration is where the output of one catchment or BMP is the input to a downstream catchment or BMP. A parallel configuration is where each catchment or BMP collect and discharge water from separate areas. A mixed configuration is where some combination of series and parallel configurations exist in the watershed. The BMP SELECT Model allows for multiple catchments and does not evaluate different configurations but rather gives results for each catchment, separately (Pomeroy & Rowney, 2013). The SET Model (Tetra Tech, 2010), Virginia Runoff Reduction Method Worksheet (Virginia Department of Conservation and Recreation, 2011), and the AVGWLF Model (Evans et al., 2008) can evaluate BMPs and/or catchments in series but not in parallel or mixed configurations. The Simple Method Pollutant Loading Model will allow the user to specify BMPs in series; however, the treatment efficiency of the best performing BMP is the only treatment taken into account in determining the catchment or watersheds overall efficiency achieved (New Hampshire Department of Environmental Services, 2010).

Each of the models reviewed aims to evaluate pollutants leaving a watershed and the removal achieved by stormwater BMPs. The models have similar goals, but use different methods to evaluate a watershed design. Several of the models reviewed were initially developed to analyze agricultural applications and modified to include urban stormwater management; such as the AVGWLF Model (Evans et al., 2008) and Region 5 Model (Michigan Department of Environmental Quality, 1999). Both these models assume that all TN and TP is in the solid form, that is particulate bound, which would result in higher efficiency estimations for BMPs that rely more heavily on settling. This assumption could lead to over estimation of true performance since dissolved forms of TN and TP do not behave in the same way as the particulate forms.

Some of the other models also had specific applications with the methodology used to determine pollutant loads and BMP removals. The Jordan/Falls Lake Stormwater Nutrient Load Accounting Model (North Carolina Department of Environment and Natural Resources, 2011) and BMP SELECT Model (Pomeroy & Rowney, 2013) both use median values and event mean concentrations (EMC), respectively, to determine BMP removal rather than a percent reduction. This analysis method will likely result in larger error than using a percent reduction approach, since percent reduction is independent of influent concentrations which will vary from one site to another (Walker, 1990). Additionally, the Jordan/Falls Lake Stormwater Nutrient Load Accounting Model makes the assumption that all rainfall events that occur in a year will generate runoff (North Carolina Department of Environment and Natural Resources, 2011). The assumption of runoff generation is likely true for larger rainfall events; but smaller rainfall events may not generate significant flows or any runoff at all. The generation of runoff will depend strongly on the watershed characteristics, such as the amount of imperviousness. The SUSTAIN model uses algorithms or external models to compute pollutant generation for different land uses. This methodology requires detailed data that may not be available or reliable during the design phase of a project but may be relatively easy to obtain for retrofit applications (Lee et al., 2012).

An important factor to consider when evaluating BMPs in watersheds is cost. Of the models reviewed for this work, three incorporated cost: the BMP SELECT Model (Pomeroy & Rowney, 2013), the AVGWLF Model (Evans et al., 2008), and the SUSTAIN Model (Lee et al., 2012). The BMP SELECT Model provides an option to do a net present worth analysis; however, it does not take into account potential revenues generated by harvesting operations or savings realized by BMPs that do not require the purchase of additional land (Pomeroy & Rowney, 2013). The AVGWLF Model also provides an option to perform net present worth analysis but has cost of BMPs built into the program (Evans et al., 2008). Costs for different construction activities, materials, and BMPs vary spatially and temporally thus, having cost built into the model may limit its use in certain regions and periods. The SUSTAIN model examines cost of BMPs and provides tables with cost data for different components that contribute to cost from the literature (Lee et al., 2012). Additionally, options are available for the user to input their own cost data. This allows for flexibility related to temporal and spatial variability of different construction activities, however net present worth analysis is not included in this model.

Sample et al. (2003) examined cost distributions of BMPs and stormwater infrastructure at the watershed scale based on values reported in the literature and presented a general methodology to analyze this data on a development scale. Based on a lack of available data, the study did not examine operating and maintenance costs. Seters, Grahm, Rocha, Uda, and

Kennedy (2013) also examined cost of BMPs based on literature values as well as from industry. They examined several common BMPs using different scenarios and compared the capital costs as well as life cycle costs using a net present worth analysis. Weiss, Gulliver, and Erickson (2005) evaluated the effectiveness for BMPs to remove TP and TSS from stormwater and the associated cost. They used values from the literature to analyze a variety of BMPs, but did not include land costs in the analysis. The net present cost for several BMPs were presented as functions of water quality volume for a 20-year period.

For model optimization, Chang, Rivera, and Wanielista (2011) developed a grey stochastic programming model to optimize a green roof with beneficial reuse of gray water and stormwater while achieving energy savings for a residential home in Florida. The study showed how synergistic design of water and energy saving features affect the design of a green home under uncertainties. Martin, Ruperd, and Legret (2007) developed a multi-criteria analysis approach to evaluating different BMPs to assist with the decision-making process based on a literature search and survey of practitioners. The ranking of the various BMP alternatives were based on several criteria such as hydraulic performance, environmental performance, social impact, and maintenance, just to name a few (Martin et al., 2007).

Methodologies and Modeling Components of the BMPTRAINS Model

To estimate average annual effectiveness of BMPs, rainfall data that include the volume of rainfall and the inter-event time are available. The runoff from the rainfall is directed to the BMP and the volume of water that is treated as a fraction of the annual volume is recorded. That capture volume contains a mass of nutrients proportional to the volume of rainfall, or there is an average concentration value. A model of the capture methods thus should provide a tool that could allow designers and planners to evaluate site designs for nutrient removal effectiveness.

An example for the state of Florida is presented to illustrate the usefulness of the methodology. Estimates of mass loading, mass removed, and mass discharged are given for a watershed design specified by the user. Additionally, a present worth analysis can also be done. This allows the user to optimize the use of BMPs based on cost as well as nutrient removal. This easy to use, public domain modeling method is accepted by all five water management districts in the state of Florida. It should be noted that the methods used to develop the model called BMPTRAINS are applicable for any geographic region, not just Florida, so long as the proper analysis is performed on the available rainfall data. It has been successfully used with modification for retention effectiveness within other States. The main worksheets of the model are presented below with a short description of the function of each.

General Site Information

The General Site Information worksheet collects information about the project related to rainfall characteristics and the preferred type of analysis for the watershed evaluated. Input data required on the "general site information" worksheet include the selection of the rainfall zone and the mean annual rainfall depth for the project location. The user-friendly interface of the model makes it easy for the user to input their required data by the click of the relevant "button" that will direct the user to the relevant maps. The user has access to view a map showing the different rainfall zones and isopleths of mean annual rainfall depth in the State where the evaluation is performed. For the example study presented in the paper, the maps shown were for the state of Florida and determined in a previous study by Harper and Baker (2007). The maps were developed from long-term study of hourly precipitation data for 11 sites and from 160 meteorological stations across the state of Florida including some near the border in Georgia and Alabama. There are five distinct rainfall zones identified for Florida based on the variability in frequency distributions of rainfall events. Similar studies on rainfall zones are available for other States and can be adapted into the model for use in the respective state. In addition, a help button directs the user to a video explaining the development of the rainfall zone and the mean annual rainfall maps.

The type of analysis is also specified on this worksheet. The user has the choice between the analysis options of specified removal efficiency, net improvement, or BMP analysis. The different analysis options evaluate the nutrient removal efficiency distinctly from the others. The specified removal efficiency option allows the user to specify a target TP and TN removal efficiency, while the net improvement option allows the user to perform an analysis to achieve post-development conditions less than or equal to pre-development conditions. On the other hand, the BMP analysis option allows the user to evaluate the effectiveness of different BMP designs within a watershed for TP and TN removal. Other features on this worksheet include a reset button that clears the model of all input and analysis data, buttons to navigate to other relevant worksheets, buttons that provides information on the methodology used, and a project information cell where the user enters all relevant site identification information.

Watershed Characteristics

The watershed characteristics worksheet is where the user inputs data relevant to the project. There is an option to select the configuration of the watershed, which can contain up to four catchments. The model is capable of performing analysis of up to 15 different catchment configurations in a watershed, ranging from a single catchment to four catchments in series, parallel, or mixed. A button called "View Catchment Configuration" directs users to pictorial representations of the different configurations available. The user is required to select the desired configuration, and thereafter the pre- and post-development land uses for the number of catchments in the project. There are 29 different land uses programmed into the model with event mean concentrations (EMCs) specified (Harper & Baker, 2007). There also exists a user defined land use option. The EMCs for the user-defined option is a required input and done by using the "overwrite the default concentrations" feature. The help button on this worksheet directs the user to a video that provides the background on the different land uses and EMCs.

The user is required to specify the total pre- and post-development catchment areas, in addition to the pre- and post-development non-directly connected impervious area (non-DCIA) curve number (CN) and the DCIA percentage. The input for the estimated area of the BMP is required to allow for its exclusion for the purposes of pollutant generation to meet water management districts or other regulatory requirements. The inputs on this worksheet are used to compute and provide the following information for each catchment: average annual runoff volume in ac-ft/year, pre-development annual mass loading for both TN and TP in kg/year, and post-development annual mass loading for both TN and TP in kg/year.

Stormwater Treatment Analysis

Next the user is directed from the "watershed characteristics" worksheet to the "stormwater treatment analysis" worksheet. Displayed on this worksheet are the required treatment efficiencies based on the desired analysis specified in the general site information worksheet and the selected configuration from the watershed characteristics worksheet. Furthermore, the user is provided access through the displayed buttons to any of the 15 different BMP and user-defined worksheets to input BMP-specific data relevant to the project. The different BMPs included in the BMPTRAINS model are as follows: retention basin, wet detention, exfiltration trench, pervious pavement, stormwater harvesting, filtration including up-flow filters, green roof, rainwater harvesting, floating islands with wet detention, vegetated natural buffer, vegetated filter strip, vegetated area (example tree well), rain (bio) garden, swale, lined reuse pond and underdrain input, and a user defined BMP.

There are two other buttons on this worksheet that directs the user to cost analysis and summary result worksheets namely “Go To Cost Analysis Worksheet” and “Catchment and Treatment Summary Results”, respectively. The “Go To Cost Analysis Worksheet” allows the user to perform cost analysis on the selected BMP configuration, and the “Catchment and Treatment Summary Results” worksheet displays the results from the performed analysis.

BMP Analysis

The model categorizes BMPs into three different types based on the treatment mechanism. The three types of BMP treatment mechanisms are retention, detention, and other. The retention-type BMPs performs treatment by volume reduction through infiltration of stormwater, which removes a specified volume of water from being discharged. The treatment mechanism for the detention-type BMPs is holding and delaying the discharge of water for a specified period, which allows suspended particles settle out of suspension and undergoes biological and chemical processes to remove pollutants before discharge. The other-type BMPs achieve treatment through processes that are different from retention or detention type BMPs. It is worth noting that some BMPs could act as more than one type depending on the design. Thus, the BMPTRAINS model allows for this flexibility by prompting the user to select the treatment type for any BMP used in the project. It is pertinent to note that the BMPTRAINS model is not intended to provide hydraulic design of BMPs but to evaluate the pollution removal capabilities of a watershed design which includes BMPs for pollution removal.

Retention Type BMPs

The retention-type BMPs treat stormwater by the removal of a specified volume of water via infiltration. However, the BMPTRAINS model does not examine groundwater interactions; thus, considers all infiltrated water effectively removed from the stormwater infrastructure and does not discharge to surface water bodies. The resulting reduction in mass of TN or TP achieved is determined by multiplying the volume of water removed, or infiltrated, by the EMC for the specified land use in accordance to the methodology established in a previous study by Harper and Baker (2007). The study developed tables that relate the volume capture efficiency to the DCIA and non-DCIA CN, which generates a curve to show the relationship between retention depth provided and removal efficiency. An example of the retention-type BMP efficiency curve is shown in Figure 17. The retention-type BMPs provided in the BMPTRAINS model are retention basin, exfiltration trench (Martin P Wanielista & Yousef, 1993), pervious pavement, vegetated natural buffer, vegetated area (example tree well), rain (bio) garden (Low Impact Development Center, 2005), swale (Martin P Wanielista & Yousef, 1993), and user defined.

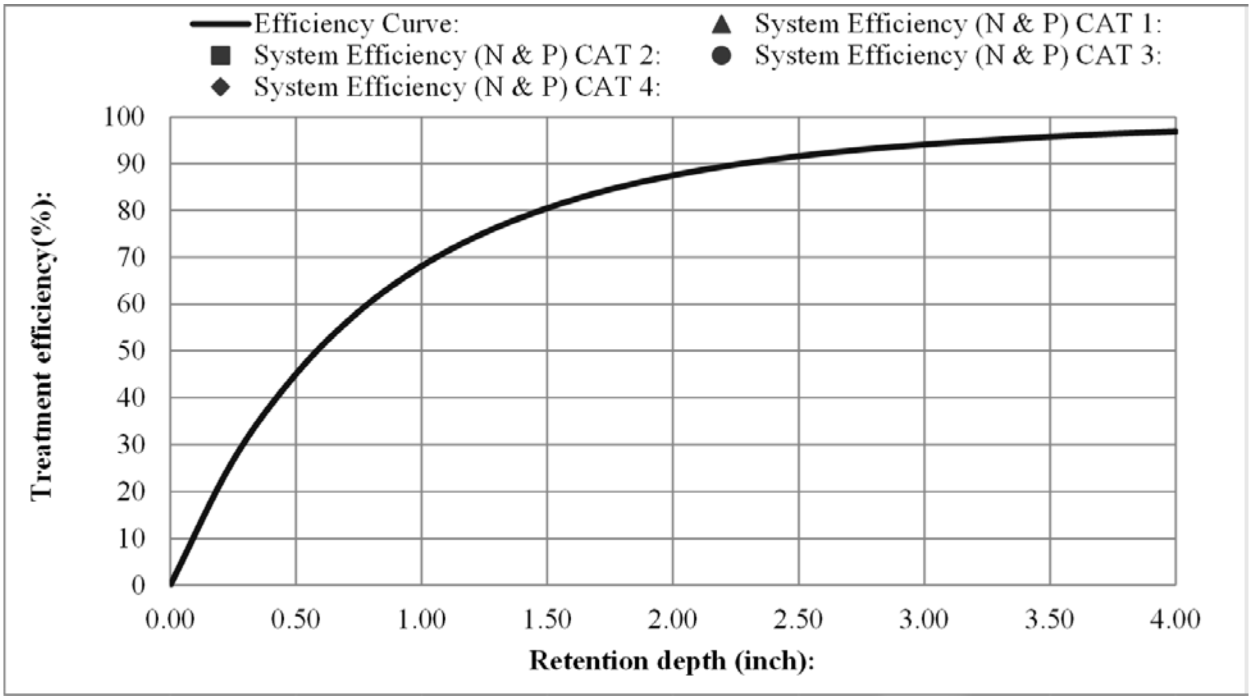


Figure 17: Example curve showing the relationship of achieved treatment efficiency and provided retention depth

There are three factors important to the performance of a retention-type BMP because of its reliance on infiltration for pollutant removal. These factors are the rainfall characteristics, site soils, and provided storage volume. The rainfall characteristics of interest are the intensity of rainfall, duration of rainfall, frequency of rainfall, and frequency of inter-event dry periods. Higher intensity storms will generate large volumes of runoff quickly and potentially overwhelm the provided storage capacity of retention-type BMPs. Long duration storms will tend to fill up the provided storage volume, which indicates that the BMP would attain full capacity and limits its pollutant removal efficiency. The frequency of storms is also important, as frequent storm events will restrict the ability for full recovery of a BMP storage volume and reduces the removal efficiency for subsequent rainfall events. The frequency and duration of inter-event dry events is important for the same reasons. Thus, to determine the overall treatment achieved for multiple retention-type BMPs within a single catchment, the provided retention storage volumes for each

BMP is added and the efficiency is determined from the total storage provided. A similar approach is adopted to compute the removal efficiency for retention-type BMPs in multiple catchments that are in series with one another.

Detention Type BMPs

Detention type BMPs provide a storage volume for stormwater to be held for a designated period and released slowly. These types of BMPs rely on the settling of particles as well as chemical and biological processes to remove pollutants (Harper & Baker, 2007). Harper and Baker (2007) developed equations that predict the efficiency of detention-type BMPs based on average annual residence time. An example of a detention-type BMP removal curve for TN and TP is shown in Figure 18. The detention-type BMPs provided in the BMPTRAINS model are wet detention, floating islands with wet detention (Chang et al., 2012), vegetated area (example tree well), rain (bio) garden (Low Impact Development Center, 2005), and user defined. The wet detention BMP and floating islands with wet detention BMP have an option to claim additional treatment due to a littoral zone. The floating islands with wet detention BMP has an additional removal credit due to the uptake and removal of TN and TP by the floating island plants.

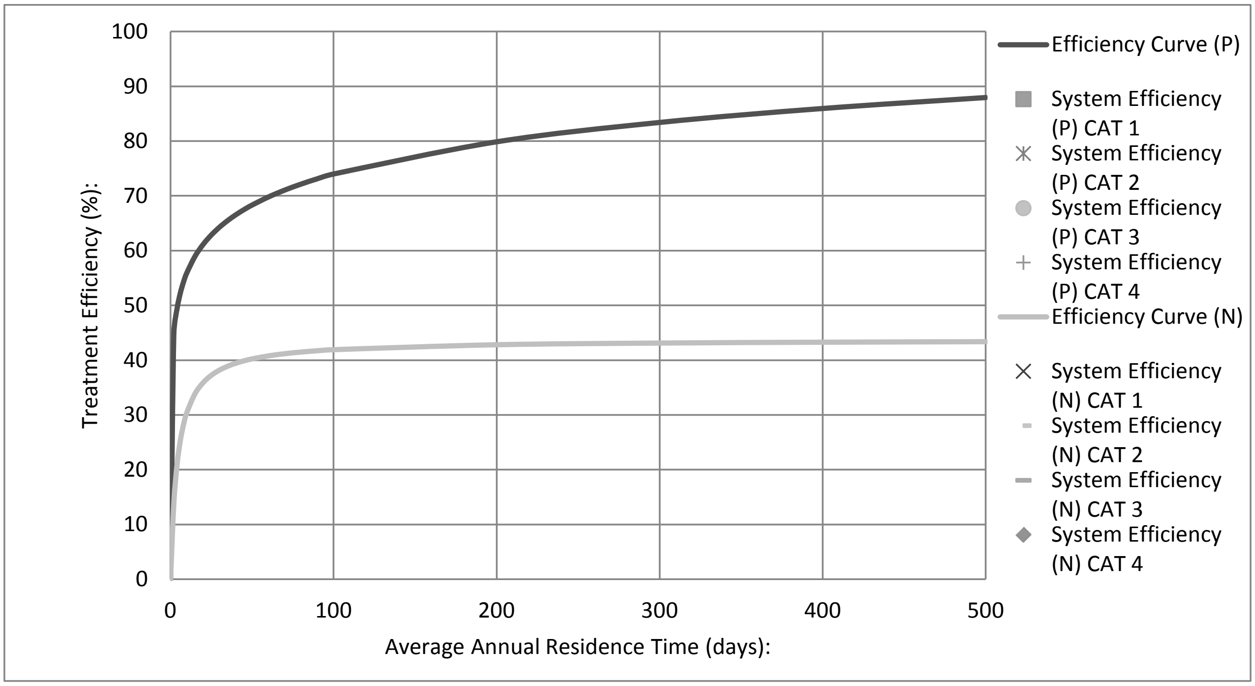


Figure 18: Example curve showing the relationship of provided treatment efficiency for TN and TP for a provided average annual residence time in days

<u>Other Type BMPs</u>

The classification of "other-type BMPs" is for BMPs that achieve treatment by mechanisms different from either retention-type BMPs or detention-type BMPs. The "other-type" BMPs achieve removal of pollutants through a number of mechanisms including, but not limited to, adsorption, chemico-biological interactions, and water capture and reuse. BMPs in this category can behave similar to either retention type or detention type BMPs but are analyzed differently. The different analysis methods can be found in the literature. The BMPs in the model that fall under this category are as follows: stormwater harvesting (M. P. Wanielista et al., 1991), filtration including up-flow filters (Hood et al., 2013; O'Reilly et al., 2012), green roof (M. Hardin, Wanielista, & Chopra, 2012), rainwater harvesting (M. P. Wanielista et al., 1991), vegetated filter strip , lined reuse pond with underdrain input (M. Hardin et al., 2012), and user defined.

Cost Analysis

The BMPTRAINS model performs cost analysis for any given BMP design within the model. This feature allows the user to evaluate either present worth or capital cost for each design scenario considered for a project. The ability to perform the cost analysis on multiple treatment options that can achieve a desired TN and TP reduction goal providers the user with the economic benefits associated with each treatment option. It should be mentioned that in order for this analysis to be relevant, the same removal efficiency should be achieved for each scenario examined.

The cost feature was developed with the goal to find a minimum cost function. The expression for the general form of the equation is shown below in equation 19.

$$Min\ Cost = \sum_{i=1}^{12} C_i X_i \qquad (19)$$

where C_i is the cost per unit size of the i^{th} BMP brought to present value and X_i is the size of the i^{th} BMP. The range of *i* varies from 1 to 12 since a maximum of 12 BMPs, out of the 15 available, can be analyzed within a given watershed. The maximum 12 BMPs achievable is based on a maximum of three BMPs per catchment and four catchments.

The cost component includes the cost of constructing, operating, and maintaining the BMP. Equation 20 describes the components of the overall cost for the i^{th} BMP:

$$C_i = C_{IC} + C_{OM} - C_R \qquad (20)$$

where C_{IC} is the initial cost of the BMP which includes design costs, mobilization costs, land costs, and other capital costs. C_{OM} is the operating and maintenance cost of the BMP. The

C_{OM} is a reoccurring cost, usually yearly, that is required to ensure that the BMP operates as intended. C_R is cost recovery achieved by the BMP. Some BMPs can generate revenues, such as harvesting operations, which generate water that can be utilized instead of potable supplies. This cost recovery results in a reduction of cost for the specific BMP which may lead to it having a lower present worth than a BMP that is not able to recover cost. Additionally, the protection of surface water bodies, as well as other natural resources, should have some cost benefit associated with it. This cost benefit can be incorporated into the cost analysis by subtracting the cost benefit from the operating and maintenance cost. Since the value of money changes with time, money spent in the future may not have the same value as money spent today. Due to this, both the C_{OM} and C_R components must be brought to present value for the desired number of periods to be included in the analysis. The equation used for present worth analysis is that presented by Park (2002) as expressed in equation 21.

$$P = A\left[\frac{(1+i)^N - 1}{i(1+i)^N}\right] \tag{21}$$

where P is present worth, A is annual cost, *i* is the interest rate, and N is the number of periods. The reoccurring costs, C_{OM} and C_{R}, would be used in equation 21 above in place of *A* because each is in terms of annual cost.

Furthermore, the cost analysis can be based on capital cost, not only on the present worth. The capability of the BMPTRAINS model to perform a cost analysis is provided on the Cost Comparison Worksheet, where multiple scenarios can be selected from a drop-down menu. When examining the capital costs, the future costs associated with operation and maintenance, replacement cost, and future revenue generated are not considered. This is because, for a capital cost analysis, only the up-front costs are considered which will be useful if the user is not the owner and thus will not operate or maintain the BMP. Since costs for various activities will vary spatially and temporally, the user inputs all cost data. This allows the designer to use the most relevant and up to date cost information for decision-making.

The cost analysis worksheet allows the user to select between two types of analysis options, capital cost or net present worth. The cost analysis for a net present worth evaluation would require the following information: interest rate, project duration, and cost of water. The cost of water is only relevant for BMPs that harvest stormwater, since these BMPs will greatly reduce potable water usage. The user has the option to split the BMP cost into two components, the fixed cost and the variable cost. An example of fixed cost is the cost of mobilization, and for a variable cost, it is the cost to excavate soil. The user is required to specify the cost of land needed for the BMP, if applicable, the expected life of the BMP in years, the fixed cost portion of the BMP, the variable cost of the BMP, the estimated annual BMP maintenance cost, and the estimated future cost of replacement. The estimated cost of future replacement is only relevant if the project duration is greater than the expected life of the BMP. The model uses the inputs to calculate the net present worth for each scenario specified by the user. An illustration on the use of the cost feature is presented.

Cost Analysis Example

Presented is an example problem to show the usefulness of the cost function provided in the BMPTRAINS model. The selected project location for the example problem is in Jacksonville, Florida, which is in meteorological zone 4 and has a mean annual rainfall depth of 1270 mm (50 inches). At the selected project location, the example problem evaluated six different scenarios of achieving a target specified removal efficiency of 80% for both TN and TP. This analysis focused on a single catchment with an “agricultural – general” pre-development land use and a “low-intensity commercial” post-development land use. The total catchment area was 2.0 acres with a pre-development non-DCIA CN of 78. There was no DCIA in the pre-development condition. The post-development non-DCIA CN is 78 with 90% DCIA. The post development condition was assumed to consist of the following: 40% building, 50% parking lot, 10% green space. The green space is split, with one-half of it around the building and the rest left as natural or available for a retention basin. The two BMPs analyzed for this example were pervious concrete and a retention basin, each of which have an expected life of 20 years.

The pervious concrete section consisted of seven inches of #57 stone compacted and then topped with a six-inch layer of pervious concrete. The soils were assumed to be sandy and free draining, allowing the system to fully recover in 72 hours from a 5 year design storm event. The retention basin was to have a maximum depth of 12 inches. Any additional land required to achieve this restriction was assumed to be purchased at a rate of $1.5 million per acre. The costs to build and maintain the pervious pavement BMP was assumed to be $7.50 per square foot of the pervious concrete section installed and $800 per acre per year, respectively. The cost to build the retention basin was split into a fixed cost portion and a variable cost portion. The fixed cost was assumed to be $4,000.00 for mobilization and the variable cost was assumed to be $44,840.00 per acre-foot. The maintenance cost for the retention basin was assumed to be $6,000.00 per acre per year.

The period of analysis for this example was 20 years. The interest rate was assumed to be 5% for the analysis. Table 11 shows a summary of the different BMP conditions examined for each of the six scenarios. It shows that for the first scenario only a pervious concrete parking lot was used while for the sixth scenario only a retention basin was used. Scenarios two through five have different mixes of the two BMPs, with the pervious concrete in series with the retention basin.

Table 11: Summary of BMP characteristics for the six scenarios evaluated

	BMP Characteristics		
Scenario	Pervious Concrete Area [ac]	Retention Basin Volume [ac-ft]	Additional Land Required [ac]
1	1	0	0
2	0.825	0.0417	0
3	0.65	0.0833	0
4	0.325	0.173	0.073
5	0.15	0.221	0.12
6	0	0.271	0.171

The results of the cost analysis are presented in Table 12. From this table it can be seen that scenario number three gives the minimum cost to achieve the objective of 80% removal of both TN and TP. The overall net present worth cost analysis is shown along with the net present worth cost of TN and TP removal per kilogram per year of removal. This information is displayed in graphical form in Figure 19 and Figure 20, making it easy to identify the minimum cost scenario.

Table 12: Summary of present worth cost analysis for the six scenarios evaluated. Overall net present worth, as well as cost of N and P removed per year presented

Cost Analysis Summary			
	Net Present Worth [$]	Cost of N Removed [$/kg-yr]	Cost of P Removed [$/kg-yr]
Scenario 1	$ 340,408.43	$ 46,538.66	$ 306,791.16
Scenario 2	$ 294,820.38	$ 40,410.86	$ 266,395.63
Scenario 3	$ 237,755.01	$ 32,673.85	$ 215,391.85
Scenario 4	$ 247,387.75	$ 32,797.14	$ 216,204.63
Scenario 5	$ 264,624.43	$ 34,354.25	$ 226,469.33
Scenario 6	$ 292,932.01	$ 36,748.88	$ 242,255.20

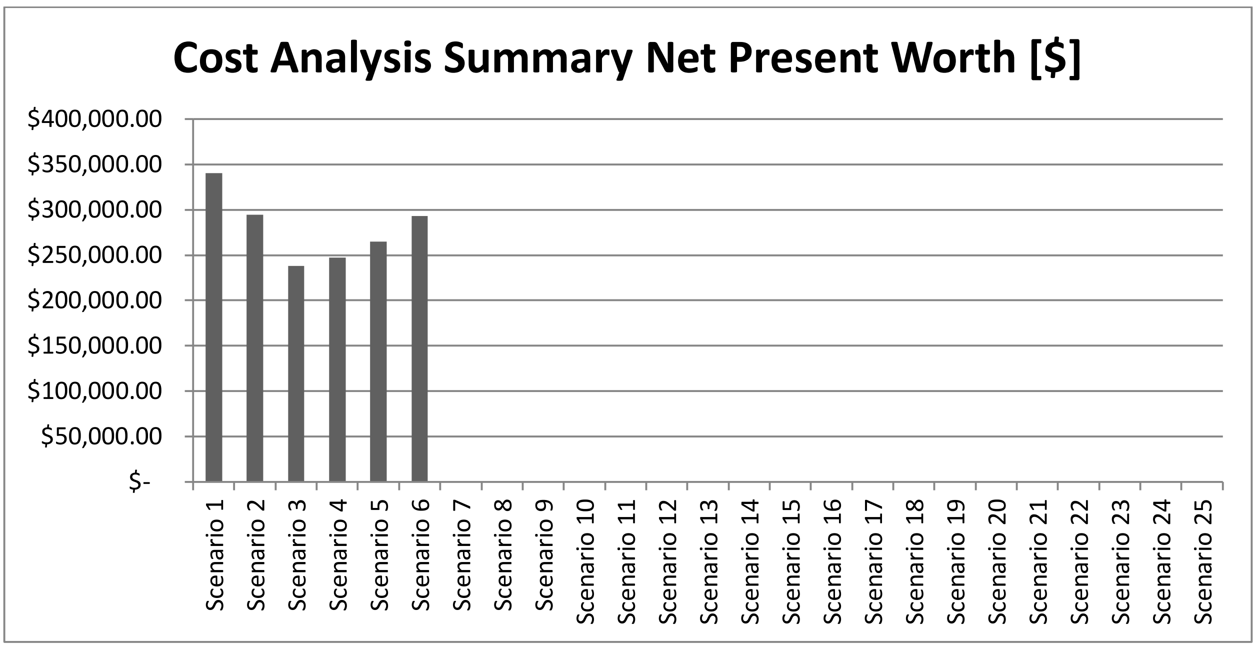


Figure 19: Summary of present worth for the six different scenarios evaluated

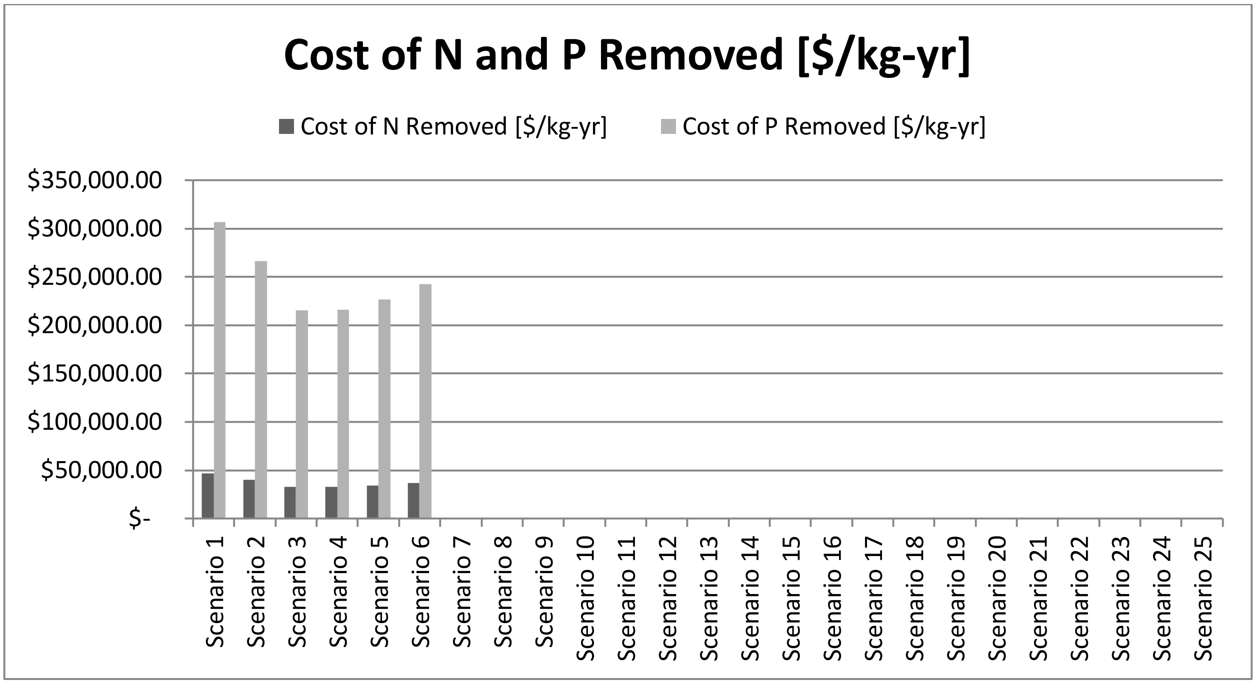


Figure 20: Summary of present worth cost of N and P removed per year for the six different scenarios evaluated

Summary and Conclusions

Presented in this paper is a model developed for estimating the nutrient removal effectiveness and cost of stormwater BMPs. An example application for the state of Florida is presented. The model is used to analyze BMPs to reduce TN and TP to receiving water bodies. The BMPTRAINS model is intended as an analysis tool to assist in the design of stormwater infrastructure. However, the BMPTRAINS model does not address the hydraulic function of a BMP. Therefore, it is expected that the user performs the hydraulic design of a BMP to ensure it functions properly prior to evaluation in the model. The model has the capability to analyze up 29 different land uses as well as a user defined option. Each land use has a programmed EMC for both TN and TP; however these can be overridden with a user-defined EMC. The model allows for up to four catchments in a watershed, which can be configured in series, parallel, or a mixed configuration. The total number of configurations which can be analyzed by this model is 15.

The BMPTRAINS model is a versatile tool allowing for the evaluation of up to 15 different BMPs and one user defined option. This allows for the user to evaluate any BMP where data is available. The model allows for up to three BMPs in each catchment however, multiple BMPs within the same catchment are always treated as in series. BMPs in parallel must be in separate catchments for the purposes of this model. Additionally, if a retention type BMP and a detention type BMP are used within the same catchment the detention type BMP is always treated as downstream of the retention type BMP. This is due to the fact that detention type BMPs frequently also functions as flood control devices; therefore it would not make sense to have it upstream of a water quality device.

The evaluation of a site design based on cost is valuable to designers and planners. Many of the models that currently exist in the literature do not address the cost of building, operating, and maintaining BMPs. This could result in designs being implemented that are not the most efficient as related to cost of pollutants removed. The BMPTRAINS model allows the user to evaluate a site design based on net present worth cost analysis and capital cost. An example problem was presented which showed that a combination of two different BMPs together within a site was able to achieve the desired reduction in TN and TP for less cost than either BMP by itself. The model was applied to show the total net present value for six different scenarios as well as the cost per kilogram of TN and TP removed per year in terms of net present cost.

Disclaimer

The Florida Department of Transportation funded and managed the research described herein. It has been reviewed and accepted for external publication. The views expressed in this

paper are those solely of the authors and in no way reflect the views of the Department. Any mention of trade names or commercial products does not constitute an endorsement or recommendation for use.

CHAPTER 5: GENERAL DISCUSSION AND CONCLUSIONS

General Discussion

The ability to quantify the water quality benefit of stormwater BMPs will allow for designers, planners, and regulators to better protect our precious surface water bodies. While research on stormwater BMPs has been an ongoing area of interest for funding agencies, until recently the overall benefit provided by implementing them as part of a site design has been largely presumptive (Shaver et al., 2007). The work presented here allows for better quantification of the actual benefit that can be expected for specific designs.

Two BMPs needed to be examined further to identify appropriate methods for efficiency determination; these are green roofs and pervious pavements. The method presented by M. Hardin, D. (2006) for determination of green roof hydrologic efficiency needed to be tested for different green roof designs as well as have a method of ET determination established for regions where measured data did not exist. This has been accomplished and is presented above in Chapter 2. Additionally, the storage capacity of pervious pavement systems needed to be examined. The use of porosity to calculate the storage of these systems was examined and suggested values for design were presented. These values were then used to determine the CN for the system. It was noted however that minimum infiltration rates of the parent soils must be maintained for this methodology to be valid. Additionally, it is required that in situ field verification must be performed in accordance to what was presented by Gogo-Abite et al. (2014).

The results of the green roof and pervious pavement study, along with data from the literature on several other common BMPs, were used to develop a site evaluation model called the BMPTRAINS model. In particular, the work of Harper and Baker (2007) was instrumental in the development of this model. They performed a detailed analysis of the historical rainfall data for the entire state of Florida and redefined five distinct rainfall zones. Additionally, they performed long term simulations of retention basins in each of the different rainfall zones with different curve number values. This simulation allowed for the development of several lookup tables which allow for the determination of hydrologic efficiency for any retention type BMP. Since any water collected in the retention system is assumed to be uniform in relation to water quality, the mass of nitrogen and phosphorus removed is directly related to the volume of water that is infiltrated. This concept, along with the efficiency tables presented by Harper and Baker (2007), are the basis for how efficiency is determined for all retention type BMPs.

The efficiency of detention type BMPs are also examined by Harper and Baker (2007). Detention type BMPs capture a design volume of water and slowly release it downstream. These BMPs rely on physical, chemical, and biological processes to achieve nutrient removal. A majority of the removal occurs through particle settling with chemical and biological processes accounting for a small amount of removal. All removal processes are dependent on the average annual residence time. The equations developed by Harper and Baker (2007) are used to determine the efficiency of these type of BMPs.

The ability to analyze a site design not only for nutrient removal efficiency but also cost of treatment is part of what makes the BMPTRAINS model such a powerful tool. The cost analysis feature allows users to analyze several different design scenarios to identify the most cost efficient design. Cost can be analyzed in capital cost of the project or using a net present worth analysis. Additionally, the results of the analysis can be viewed in graphical form showing a comparison of either capital cost or net present worth for each scenario. A graph is also shown which displays the cost of removing each kg of N and P in terms of either capital cost or net present worth. This ability gives the user more information to base design decisions on.

Additional Information

The BMPTRAINS model allows for a watershed to be divided into up to four different catchments, each with its distinct pre- and post-development conditions. Each catchment can have up to three different BMPs in series. BMPs in parallel must be in separate catchments. The catchments can be analyzed in up to 15 different configurations including in series, parallel, and mixed. The overall nitrogen and phosphorus removal efficiency is determined using a treatment train approach.

There are several different scenarios that can be examined in this model. First is a single catchment with multiple retention type BMPs; for this scenario all the provided retention volumes for each BMP are added up and the resulting total volume provided is used to determine the treatment efficiency based on the relationship developed by Harper and Baker (2007). The next scenario is a single catchment with multiple detention type BMPs; for this scenario all the provided average yearly retention times for each BMP are added up and the resulting total average annual retention time is used to determine the treatment efficiency based on the relationship developed by Harper and Baker (2007).

The next scenario is a single catchment with both a retention type BMP and detention type BMP; for this scenario the detention type BMP is always treated as downstream. It should be noted that since settling plays a primary role in the removal of nitrogen and phosphorus for detention type BMPs the relationship described by Harper and Baker (2007) needs to be modified. Since the upstream retention BMP will likely remove much of the suspended sediment prior to discharging to the detention BMP the efficiency of the detention BMP will be reduced, however this reduction will be dependent on the volume of treatment achieved by the retention system. The equation used to determine the modified efficiency of nitrogen and phosphorus for the detention type BMP is shown below in equations 22, 23 and 24. First, for both nitrogen and phosphorus, if the provided retention efficiency is greater than the non-adjusted provided detention efficiency then the adjusted detention efficiency is as shown below in equations 22 and 23 for nitrogen and phosphorus, respectively.

$$\varepsilon_a = \varepsilon_n - 22 \tag{22}$$

$$\varepsilon_a = \varepsilon_n - 12 \tag{23}$$

Where ε_a is the adjusted detention efficiency, ε_n is the non-adjusted detention efficiency. When the provided retention efficiency is less than the non-adjusted provided detention efficiency, the adjusted detention efficiency is as shown below in equation 24 for nitrogen and phosphorus.

$$\varepsilon_a = \varepsilon_n - \frac{\varepsilon_p}{7} \tag{24}$$

Where ε_a is the adjusted detention efficiency, ε_n is the non-adjusted detention efficiency, and εp is the provided retention efficiency. This adjusted detention treatment efficiency can then be applied to the water leaving the retention system to get the overall treatment efficiency.

The ability to analyze catchments in different configurations allows for many more possible scenarios. The calculation of overall treatment efficiency for multiple catchments in different configurations is similar in concept to how multiple BMPs are handled within a single catchment. When two or more catchments are in series, the provided treatment efficiency of each catchment is converted to an equivalent retention depth. Additionally, for catchments in series, it is recognized that water from upstream catchments will be treated in BMPs in downstream catchments. This volume of water should be taken into account when determining the overall treatment efficiency. In an effort to address this volume of water, a new factor is introduced that represents the volume of upstream water that is treated downstream. This factor, called the lag factor, should increase with time of concentration since the longer the time of concentration the more time available for the downstream BMP treatment volume to recover. This factor is multiplied by the product of the downstream provided treatment volume and the upstream catchment area. The result of this is multiplied by the smaller of one or the ratio of the downstream catchment area and the upstream catchment area. This allows for the model to address the issue of time of concentration between catchments and the additional treatment that occurs. The lag factor needs to be examined further so that an appropriate value can be assigned depending on the site geometry and degree of connectedness. The default value for this factor is 0.5 for the current version of the model. The general form of the equation for multiple catchments in series is presented below in equation 25.

$$V_e = \frac{\sum_{i=1}^{n} V_i\, A_i + \sum_{i=1}^{n} \sum_{j=1}^{n} L_j V_{i+1} A_i * min\left(1, \frac{A_{i+1}}{A_i}\right)}{\sum_{i=1}^{n} A_i} \tag{25}$$

Where V_e is the equivalent treatment volume of the watershed, V_i is the equivalent treatment volume of the ith catchment, A_i is the ith catchment area, and L_j is the jth lag factor which must be between 0 and 1. The equivalent treatment volume for the watershed is then used to determine the overall achieved treatment efficiency by using the appropriate retention efficiency relationship based on the site of interest.

The calculation of the overall treatment efficiency of a watershed for catchments in parallel is done by taking an area weighted average. The general form of the equation to calculate multiple catchments in parallel is presented below as equation 26.

$$V_e = \frac{\sum_{i=1}^{n} V_i A_i}{\sum_{i=1}^{n} A_i} \tag{26}$$

Where V_e is the equivalent treatment volume of the watershed, V_i is the equivalent treatment volume of the ith catchment, and A_i is the ith catchment area. The equivalent treatment volume for the watershed is then used to determine the overall achieved treatment efficiency by using the appropriate retention efficiency relationship based on the site of interest.

Conclusions

The information presented within this work shows that using a treatment train approach to stormwater BMPs are an effective way to reduce the volume of stormwater runoff generated from a site and improve the quality of receiving water bodies. The widespread use of BMPs will protect our surface water bodies allowing them to be of a quality acceptable for beneficial use. While several BMPs were examined for this work, additional data were needed to quantify the benefit of two BMPs, green roofs and pervious pavements.

Green Roofs

This work showed that green roofs are a sustainable solution to stormwater management in urban areas. It was shown that irrigated green roofs with cisterns to capture and reuse filtrate were able to significantly reduce the volume of runoff generated from roof tops. Also shown was that the mass balance method presented by M. Hardin, D. (2006) is effective at predicting the filtrate off green roofs. The evapotranspiration (ET) was shown to not be dependent on drainage layer or growth media depth, for the depths examined in this work which were up to 203.2 mm (8 in). The filtrate factor was shown to be dependent on the depth of growth media but not on the type of drainage layer used (M. Wanielista et al., 2008).

The hydrologic efficiency of green roofs was examined for several geographic regions within the state of Florida. The efficiency was shown to vary with geographic region. It was shown that in the Orlando Florida region, hydrologic efficiency can be as high as 87% if a cistern is used to capture and reuse the filtrate for irrigation of the roof. This result is assuming that the cistern is sized to capture 127 mm (5 in) of runoff over the green roof area. It should be noted that this efficiency could be increased with added reuse of the captured water, such as irrigation of ground level landscaping. Without a cistern, the efficiency for the same region is 43%. Additionally, the Blaney-Criddle equation was examined as a possible method to determine ET losses for regions where reliable data did not exist. Based on the comparisons to collected data presented within this work, the Blaney-Criddle equation was shown to be an acceptable method to determine ET.

Pervious Pavements

The total and effective porosities of several pervious pavements and common materials used for sub-base layers were examined. Based on the porosities measured and the design of the pavement systems examined, water storage was able to be determined. From this curve numbers could be calculated, however this is only relevant for systems placed over well-draining sandy soils that can maintain an infiltration rate of 50 mm/hr (2 in/hr). The results of this analysis showed that, even after extreme sediment loading, the storage capacity of these systems still result in curve numbers that are less than those for impervious pavements. It should be noted that infiltration into the pavement system must be maintained and monitored in accordance with the methods presented by Gogo-Abite et al. (2014).

The determination of effective porosity was examined further with an emphasis on drying time before measurement. It was found that there was no significant difference (α=0.05) between effective porosity values determined after a 6 hour drying time and 24 hour drying time. This indicates that a six hour drying time is sufficient for determining effective porosity using the gravimetric method presented here. The results for a one hour dry time however, showed that there was insufficient evidence to conclude that there is no difference compared to both the six and 24 hour dry time.

As there are many different possible combinations of sub-base materials, sub-base material depths, pervious pavement, and pervious pavement depths, it was desired to examine if taking a depth weighted average of the individual components of a pervious pavement system would give an accurate representation of the true porosity of the whole system. It was found that depth weighted average porosity did provide a reasonable measure of the whole system; however, for systems with multiple layers, interstitial mixing may reduce the true porosity value. This could result in over estimation of true storage. Additionally, the effect of sediment loading on porosity and subsequent rejuvenation due to vacuum sweeping was examined. It was observed that the poured in place systems, pervious concrete and FlexiPave, were able to take much more sediment than the permeable paver systems. These systems also did not rejuvenate as effectively as the permeable paver systems. This is likely due to the pore structure allowing more sediment deeper into the system below the effective force of the vacuum.

A new porosity term was defined based on the results of the sediment loading and rejuvenation portion of the study. This term was called the operational porosity and is defined as the average value between the clean effective porosity and the sediment loaded effective porosity. The value is introduced as a more appropriate design value for pervious pavements as sediment will fill up voids within the system over time and vacuuming was shown to only be effective at removing sediment close to the pavement surface. Therefore after many years of service the clean effective porosity will overestimate the true storage and result in systems that do not perform as intended during design events. Several operational porosity values were listed for materials examined in this study. These operational porosity values can then be used to calculate a storage volume and subsequent curve number using a depth weighted average of the system components.

BMPTRAINS Model

A model was developed based on the work performed on green roofs and pervious pavements presented here as well as from data from the literature. The model is called the BMPTRAINS model and was developed for estimating the nitrogen and phosphorus removal effectiveness using a treatment train approach as well as cost of BMPs. The model is meant to be an analysis tool, meaning that it does not design the hydraulic functions of BMPs but analyzes the achieved efficiency of already designed BMPs. The model has the ability to analyze up to 29 different land uses and has a user defined option. Event mean concentration (EMC) data is programmed into the model for the provided land uses but there is also a user defined option to override the default values.

The model evaluates a single watershed at a time. The watershed can be divided into up to four distinct catchments. These catchments can be analyzed in up to 15 different configurations including series, parallel, and mixed configurations. There are 15 different BMPs programmed into the model as well as a user defined option. This allows for new BMPs to be analyzed as data becomes available. The model allows up to three different BMPs in each catchment. When multiple BMPs are within the same catchment, the model always treats them as in series with one another, if BMPs are to be in parallel, they must be placed in different catchments. It should be noted that when retention type BMPs and detention type BMPs are used together within a single catchment, the detention type BMP is always assumed to be downstream of the retention type BMP. This is due to the fact that detention type BMPs are often used for flood control, as well as water quality, while retention type BMPs are only used for water quality. Placement of a water quality BMP downstream of a flood control BMP is not considered good engineering practice.

The model also has the ability to analyze a site design based on cost. Both capital cost and net present worth can be analyzed in this model. The user can create up to 25 different scenarios to analyze the cost of different BMP treatment options. The capital cost or net present worth for each scenario is presented in graphical form allowing the user to easily see the most cost efficient solution. Additionally, the cost, in either capital cost or net present worth, per kg of both nitrogen and phosphorus is plotted for each scenario.

Recommendations for Future Work

Green Roofs

While green roofs have been used for more than 30 years they have only just recently been seen as a way of retaining water near the rainfall area. Throughout the course of this work the authors have noted the following areas needing further work. The use of different vegetation and the resulting effects on evapotranspiration rates i.e. does the Blaney-Criddle equation still hold up with a different vegetative cover. Additionally, more work needs to be done to quantify the increase in waterproof membrane life when using a green roof.

Pervious Pavements

The use of pervious pavements for the control of stormwater is becoming more common place. This is leading to the introduction of new materials and designs being used. While this work examined several common materials, both surface pavement and sub-base layer materials, new materials need to be examined as they are introduced. It is also recommended that pervious pavement systems that have been in use for several years be examined for the degree of clogging and how deep sediment has traveled into the system. This will give further insight to the values that should be used for water storage determination. Additionally, rejuvenation techniques and equipment should continue to be researched. While the vacuum trucks seem to work well for sediments close to the pavement surface, methods that would allow removal of sediment deeper in the system would be of benefit to the industry.

BMPTRAINS Model

While the BMPTRAINS model addresses many shortcomings of existing models, there are a few areas of additional work that would improve the model. First, examine the ability of infiltration BMPs to remove pollutants prior to discharge to groundwater. Since groundwater and surface water bodies are connected, there is a possibility that pollutants that seep into the groundwater may be transported to adjacent surface water bodies. The event mean concentrations provided for the different land uses should continue to be examined and updated as needed. Also, different land uses should be added as necessary. The time lag that occurs between catchments in series should be examined further as this will affect the overall treatment efficiency achieved. This lag factor is related to the time of concentration and recovery of downstream BMPs. Further research needs to be done to determine this relationship and how to apply it to the model. Finally, as new BMPs are developed or their efficiency is described in the literature they should be added to the model. This will allow for easier approval by regulatory agencies since the efficiency determination will be standardized.

APPENDIX A: GREEN ROOF RAW DATA

Table 13: Raw Data for Green Roof ET Comparison of the Shallow Blanket System

ET Comparison of all the Chambers

Date	Rainfall (in.)	A	B	C
5/24/2010	0.00	-	-	-
5/25/2010	0.00	0.36	0.32	0.30
5/26/2010	0.00	0.13	0.11	0.08
5/27/2010	0.00	0.25	0.22	0.24
5/28/2010	0.00	0.28	0.25	0.24
5/29/2010	0.00	0.17	0.18	0.12
5/30/2010	0.37	0.15	0.04	0.07
5/31/2010	0.35	0.04	0.06	0.03
6/1/2010	0.40	0.03	0.02	0.02
6/3/2010	0.28	0.14	0.13	0.10
6/4/2010	1.02	0.09	0.06	0.05
6/5/2010	0.38	0.13	0.04	0.07
6/7/2010	0.00	0.00	0.00	0.00
6/9/2010	0.03	0.17	0.14	0.15
6/11/2010	0.00	0.15	0.15	0.13
6/13/2010	0.00	0.16	0.16	0.15
6/15/2010	0.00	0.16	0.15	0.14
6/17/2010	0.00	0.16	0.14	0.13
6/18/2010	0.90	0.23	0.26	0.21
6/19/2010	1.41	0.25	0.26	0.22
6/20/2010	0.15	0.02	0.01	0.06
6/21/2010	2.54	1.21	0.44	0.69
6/23/2010	0.00	0.00	0.00	0.00
6/25/2010	0.00	0.16	0.12	0.15
6/27/2010	0.00	0.15	0.14	0.13
6/29/2010	0.00	0.16	0.15	0.14
7/1/2010	0.00	0.13	0.12	0.12
7/2/2010	1.70	0.90	0.53	0.53
7/3/2010	0.05	0.05	0.04	0.05
7/4/2010	0.01	0.10	0.10	0.10
7/5/2010	0.35	0.11	0.10	0.06
7/7/2010	0.00	0.00	0.00	0.00
7/9/2010	0.00	0.14	0.13	0.14
7/11/2010	0.00	0.15	0.13	0.12
7/13/2010	0.00	0.13	0.16	0.14

ET Comparison of all the Chambers

Date	Rainfall (in.)	A	B	C
7/15/2010	1.15	0.17	0.12	0.10
7/16/2010	0.05	0.05	0.05	0.05
7/17/2010	0.00	0.00	0.00	0.00
7/19/2010	0.00	0.14	0.14	0.12
7/21/2010	0.00	0.15	0.15	0.15
7/23/2010	0.00	0.15	0.09	0.13
7/24/2010	0.16	0.43	0.40	0.43
7/25/2010	0.12	0.10	0.08	0.07
7/27/2010	0.00	0.09	0.09	0.09
7/29/2010	0.00	0.15	0.15	0.15
7/30/2010	0.19	0.42	0.44	0.40
7/31/2010	0.00	0.00	0.00	0.00
8/2/2010	0.92	0.33	0.33	0.32
8/4/2010	0.00	0.00	0.00	0.00
8/9/2010	1.30	0.15	0.14	0.13
8/12/2010	1.62	0.14	0.14	0.15
8/14/2010	0.50	0.12	0.13	0.14
8/16/2010	0.00	0.00	0.00	0.00
8/19/2010	0.43	0.29	0.22	0.22
8/20/2010	1.92	0.36	0.23	0.29
8/24/2010	0.88	0.07	0.08	0.64
8/25/2010	0.19	0.06	0.04	0.08
8/26/2010	0.81	0.10	0.01	0.08
8/30/2010	0.18	0.17	0.04	0.03
9/1/2010	0.00	0.12	0.06	0.11
9/3/2010	0.00	0.13	0.13	0.15
9/7/2010	0.10	0.04	0.11	0.11
9/9/2010	0.50	0.24	0.22	0.27
9/13/2010	0.40	0.09	0.09	0.09
9/15/2010	0.00	0.00	0.00	0.00
9/17/2010	0.00	0.15	0.14	0.13
9/20/2010	0.00	0.08	0.09	0.10
9/21/2010	0.00	0.31	0.30	0.27
9/22/2010	0.00	0.21	0.22	0.22
9/23/2010	0.00	0.15	0.16	0.14
9/24/2010	0.64	0.25	0.28	0.29
9/27/2010	0.60	0.00	0.02	0.06

ET Comparison of all the Chambers

Date	Rainfall (in.)	A	B	C
9/29/2010	1.35	0.21	0.21	0.24
9/30/2010	0.00	0.00	0.00	0.00
10/1/2010	0.00	0.15	0.11	0.15
10/2/2010	0.00	0.12	0.17	0.14
10/3/2010	0.00	0.17	0.20	0.18
10/4/2010	0.00	0.20	0.20	0.17
10/5/2010	0.00	0.11	0.12	0.12
10/6/2010	0.00	0.19	0.11	0.14
10/7/2010	0.00	0.15	0.14	0.12
10/9/2010	0.00	0.10	0.11	0.11
10/12/2010	0.00	0.09	0.09	0.09
10/22/2010	0.00	0.08	0.08	0.07
10/24/2010	0.00	0.16	0.15	0.14
10/26/2010	0.00	0.16	0.15	0.15
10/28/2010	0.00	0.15	0.14	0.13
10/30/2010	0.00	0.12	0.14	0.16
11/1/2010	0.00	0.12	0.13	0.13
11/3/2010	0.00	0.09	0.04	0.07
11/5/2010	0.40	0.07	0.15	0.11
11/8/2010	0.00	0.00	0.00	0.00
11/10/2010	0.00	0.11	0.13	0.12
11/12/2010	0.00	0.15	0.13	0.13
11/14/2010	0.00	0.06	0.07	0.08
11/17/2010	0.00	0.15	0.16	0.14
11/18/2010	0.00	0.09	0.12	0.09
11/21/2010	0.10	0.08	0.09	0.08
11/24/2010	0.00	0.05	0.05	0.04
11/26/2010	0.00	0.09	0.09	0.09
11/28/2010	0.05	0.07	0.04	0.07
11/30/2010	1.45	0.09	0.12	0.10
12/2/2010	0.00	0.00	0.00	0.00
12/6/2010	0.00	0.07	0.07	0.04
12/8/2010	0.00	0.04	0.09	0.06
12/10/2010	0.00	0.07	0.07	0.05
12/13/2010	0.05	0.05	0.04	0.04
12/15/2010	0.00	0.06	0.07	0.08

ET Comparison of all the Chambers				
Date	Rainfall (in.)	A	B	C
12/17/2010	0.00	0.08	0.09	0.09
12/20/2010	0.45	0.06	0.04	0.06
12/21/2010	0.00	0.00	0.00	0.00
12/23/2010	0.00	0.05	0.06	0.05
12/27/2010	0.10	0.06	0.06	0.06
12/29/2010	0.00	0.08	0.06	0.06
12/31/2010	0.00	0.04	0.03	0.02
1/2/2011	0.00	0.06	0.06	0.06
1/4/2011	0.00	0.07	0.06	0.06
1/6/2011	0.45	0.10	0.23	0.10
1/8/2011	0.00	0.00	0.06	0.00
1/11/2011	0.35	0.09	0.08	0.06
1/13/2011	0.00	0.00	0.00	0.00
1/15/2011	0.00	0.06	0.06	0.05
1/18/2011	1.76	0.08	0.06	0.23
1/20/2011	0.00	0.00	0.00	0.00
1/23/2011	1.70	0.07	0.07	0.20
1/25/2011	0.00	0.00	0.00	0.00
1/27/2011	1.28	0.08	0.10	0.11
1/29/2011	0.00	0.00	0.00	0.00
1/31/2011	0.00	0.06	0.04	0.05
2/2/2011	0.00	0.05	0.05	0.04
2/4/2011	0.00	0.05	0.05	0.04
2/8/2011	0.36	0.10	0.11	0.10
2/10/2011	0.09	0.05	0.05	0.05
2/14/2011	0.00	0.03	0.03	0.05
2/16/2011	0.00	0.07	0.07	0.03
2/18/2011	0.00	0.04	0.06	0.08
2/20/2011	0.00	0.06	0.05	0.08
2/22/2011	0.00	0.05	0.06	0.06
2/25/2011	0.00	0.04	0.05	0.04
2/27/2011	0.00	0.08	0.11	0.11
3/2/2011	0.21	0.11	0.15	0.19
3/4/2011	0.00	0.09	0.12	0.08
3/6/2011	0.10	0.14	0.12	0.04
3/8/2011	0.00	0.12	0.11	0.11

ET Comparison of all the Chambers

Date	Rainfall (in.)	A	B	C
3/13/2011	1.00	0.09	0.09	0.09
3/15/2011	0.00	0.00	0.00	0.00
3/17/2011	0.00	0.12	0.00	0.11
3/19/2011	0.00	0.16	0.14	0.16
3/21/2011	0.00	0.16	0.14	0.15
3/23/2011	0.00	0.15	0.15	0.16
3/25/2011	0.00	0.17	0.14	0.16
4/2/2011	5.20	0.04	0.07	0.06
Average		0.12	0.11	0.12

Table 14: Raw Data for Green Roof ET Monthly Average Comparisons for the Shallow Blanket System

ET Monthly Average Comparison of all the Chambers			
Date	A	B	C
May-10	0.20	0.17	0.15
Jun-10	0.19	0.13	0.14
Jul-10	0.17	0.14	0.14
Aug-10	0.15	0.11	0.17
Sep-10	0.13	0.14	0.15
Oct-10	0.14	0.13	0.13
Nov-10	0.09	0.09	0.09
Dec-10	0.05	0.05	0.05
Jan-11	0.05	0.06	0.07
Feb-11	0.06	0.06	0.06
Mar-11	0.12	0.11	0.11
Avg	0.12	0.11	0.11

Table 15: Raw Data for Green Roof f Factor Comparison for the Shallow Blanket System

f Factor Comparison of all the Chambers

Date	Rainfall (in.)	A	B	C
5/24/2010	0.00	-	-	-
5/25/2010	0.00	0.37	0.44	0.48
5/26/2010	0.00	0.78	0.81	0.85
5/27/2010	0.00	0.56	0.62	0.58
5/28/2010	0.00	0.43	0.48	0.53
5/29/2010	0.00	0.67	0.63	0.77
5/30/2010	0.37	0.83	0.95	0.92
5/31/2010	0.35	0.87	0.83	0.90
6/1/2010	0.40	0.97	0.98	0.97
6/3/2010	0.28	0.53	0.56	0.66
6/4/2010	1.02	0.93	0.95	0.96
6/5/2010	0.38	0.67	0.89	0.80
6/7/2010	0.00	0.00	0.00	0.00
6/9/2010	0.03	0.06	0.18	0.18
6/11/2010	0.00	0.06	0.12	0.23
6/13/2010	0.00	0.00	0.00	0.03
6/15/2010	0.00	0.00	0.06	0.10
6/17/2010	0.00	0.06	0.13	0.18
6/18/2010	0.90	0.81	0.79	0.82
6/19/2010	1.41	0.82	0.82	0.85
6/20/2010	0.15	0.88	0.91	0.62
6/21/2010	2.54	0.52	0.83	0.73
6/23/2010	0.00	0.00	0.00	0.00
6/25/2010	0.00	0.03	0.15	0.10
6/27/2010	0.00	0.03	0.10	0.17
6/29/2010	0.00	0.00	0.03	0.13
7/1/2010	0.00	0.14	0.24	0.28
7/2/2010	1.70	0.56	0.74	0.74
7/3/2010	0.05	0.00	0.11	0.00
7/4/2010	0.01	0.67	0.68	0.70
7/5/2010	0.35	0.69	0.71	0.83
7/7/2010	0.00	0.00	0.00	0.00
7/9/2010	0.00	0.04	0.17	0.18
7/11/2010	0.00	0.03	0.17	0.21
7/13/2010	0.00	0.11	0.03	0.07
7/15/2010	1.15	0.77	0.83	0.87

f Factor Comparison of all the Chambers

Date	Rainfall (in.)	A	B	C
7/16/2010	0.05	0.00	0.00	0.00
7/17/2010	0.00	0.00	0.00	0.00
7/19/2010	0.00	0.10	0.13	0.19
7/21/2010	0.00	0.03	0.03	0.07
7/23/2010	0.00	0.09	0.19	0.18
7/24/2010	0.16	0.11	0.15	0.13
7/25/2010	0.12	0.18	0.35	0.44
7/27/2010	0.00	0.38	0.43	0.44
7/29/2010	0.00	0.03	0.03	0.03
7/30/2010	0.19	0.19	0.22	0.21
7/31/2010	0.00	0.00	0.00	0.00
8/2/2010	0.92	0.46	0.47	0.48
8/4/2010	0.00	0.00	0.00	0.00
8/9/2010	1.30	0.53	0.57	0.61
8/12/2010	1.62	0.74	0.74	0.73
8/14/2010	0.50	0.53	0.46	0.42
8/16/2010	0.00	0.00	0.00	0.00
8/19/2010	0.43	0.14	0.15	0.11
8/20/2010	1.92	0.81	0.88	0.85
8/24/2010	0.88	0.51	0.62	0.46
8/25/2010	0.19	0.67	0.78	0.56
8/26/2010	0.81	0.94	0.99	0.93
8/30/2010	0.18	0.23	0.18	0.23
9/1/2010	0.00	0.22	0.25	0.34
9/3/2010	0.00	0.24	0.25	0.18
9/7/2010	0.10	0.00	0.00	0.00
9/9/2010	0.50	0.40	0.47	0.35
9/13/2010	0.40	0.05	0.13	0.05
9/15/2010	0.00	0.00	0.00	0.00
9/17/2010	0.00	0.04	0.04	0.11
9/20/2010	0.00	0.16	0.13	0.06
9/21/2010	0.00	0.10	0.10	0.13
9/22/2010	0.00	0.39	0.30	0.25
9/23/2010	0.00	0.53	0.44	0.57
9/24/2010	0.64	0.72	0.72	0.70
9/27/2010	0.60	1.02	0.88	0.70
9/29/2010	1.35	0.70	0.69	0.64

f Factor Comparison of all the Chambers

Date	Rainfall (in.)	A	B	C
9/30/2010	0.00	0.00	0.00	0.00
10/1/2010	0.00	0.53	0.67	0.53
10/2/2010	0.00	0.63	0.56	0.59
10/3/2010	0.00	0.42	0.42	0.45
10/4/2010	0.00	0.41	0.41	0.45
10/5/2010	0.00	0.77	0.63	0.65
10/6/2010	0.00	0.41	0.67	0.59
10/7/2010	0.00	0.60	0.62	0.63
10/9/2010	0.00	0.35	0.35	0.35
10/12/2010	0.00	0.09	0.17	0.22
10/22/2010	0.00	0.00	0.00	0.00
10/24/2010	0.00	0.03	0.09	0.13
10/26/2010	0.00	0.03	0.07	0.12
10/28/2010	0.00	0.10	0.16	0.23
10/30/2010	0.00	0.13	0.10	0.06
11/1/2010	0.00	0.27	0.24	0.20
11/3/2010	0.00	0.50	0.73	0.53
11/5/2010	0.40	0.77	0.59	0.71
11/8/2010	0.00	0.00	0.00	0.00
11/10/2010	0.00	0.23	0.17	0.26
11/12/2010	0.00	0.10	0.17	0.20
11/14/2010	0.00	0.45	0.52	0.48
11/17/2010	0.00	0.10	0.12	0.10
11/18/2010	0.00	0.43	0.33	0.40
11/21/2010	0.10	0.44	0.39	0.46
11/24/2010	0.00	0.52	0.55	0.62
11/26/2010	0.00	0.43	0.40	0.43
11/28/2010	0.05	0.60	0.76	0.61
11/30/2010	1.45	0.89	0.86	0.88
12/2/2010	0.00	0.00	0.00	0.00
12/6/2010	0.00	0.04	0.13	0.25
12/8/2010	0.00	0.32	0.26	0.43
12/10/2010	0.00	0.38	0.38	0.57
12/13/2010	0.05	0.45	0.57	0.48
12/15/2010	0.00	0.51	0.42	0.45
12/17/2010	0.00	0.77	0.82	0.82
12/20/2010	0.45	0.75	0.81	0.75

f Factor Comparison of all the Chambers

Date	Rainfall (in.)	A	B	C
12/21/2010	0.00	0.00	0.00	0.00
12/23/2010	0.00	0.52	0.50	0.52
12/27/2010	0.10	0.29	0.30	0.31
12/29/2010	0.00	0.27	0.45	0.48
12/31/2010	0.00	0.65	0.70	0.79
1/2/2011	0.00	0.50	0.50	0.50
1/4/2011	0.00	0.43	0.50	0.48
1/6/2011	0.45	0.65	0.20	0.65
1/8/2011	0.00	0.00	0.00	0.00
1/11/2011	0.35	0.43	0.49	0.56
1/13/2011	0.00	0.00	0.00	0.00
1/15/2011	0.00	0.00	0.00	0.00
1/18/2011	1.76	0.87	0.90	0.76
1/20/2011	0.00	0.00	0.00	0.00
1/23/2011	1.70	0.89	0.88	0.67
1/25/2011	0.00	0.00	0.00	0.00
1/27/2011	1.28	0.89	0.86	0.84
1/29/2011	0.00	0.00	0.00	0.00
1/31/2011	0.00	0.00	0.00	0.00
2/2/2011	0.00	0.00	0.00	0.00
2/4/2011	0.00	0.00	0.00	0.00
2/8/2011	0.36	0.17	0.13	0.18
2/10/2011	0.09	0.00	0.00	0.00
2/14/2011	0.00	0.00	0.00	0.00
2/16/2011	0.00	0.00	0.00	0.00
2/18/2011	0.00	0.00	0.00	0.00
2/20/2011	0.00	0.00	0.00	0.00
2/22/2011	0.00	0.00	0.00	0.00
2/25/2011	0.00	0.00	0.00	0.00
2/27/2011	0.00	0.00	0.00	0.00
3/2/2011	0.21	0.00	0.00	0.00
3/4/2011	0.00	0.05	0.04	0.21
3/6/2011	0.10	0.32	0.43	0.67
3/8/2011	0.00	0.23	0.30	0.29
3/13/2011	1.00	0.66	0.67	0.66
3/15/2011	0.00	0.00	0.00	0.00
3/17/2011	0.00	0.00	0.00	0.00

f Factor Comparison of all the Chambers

Date	Rainfall (in.)	A	B	C
3/19/2011	0.00	0.00	0.04	0.03
3/21/2011	0.00	0.03	0.04	0.03
3/23/2011	0.00	0.07	0.03	0.03
3/25/2011	0.00	0.06	0.10	0.06
4/2/2011	5.20	0.94	0.89	0.92
Average		0.31	0.34	0.34

Table 16: Raw Data for Green Roof f Factor Monthly Average Comparison of the Shallow Blanket System

f Factor Monthly Average Comparison of all the Chambers			
Date	A	B	C
May-10	0.64	0.68	0.72
Jun-10	0.35	0.42	0.42
Jul-10	0.20	0.25	0.26
Aug-10	0.46	0.49	0.45
Sep-10	0.30	0.29	0.27
Oct-10	0.32	0.35	0.36
Nov-10	0.41	0.35	0.42
Dec-10	0.38	0.41	0.45
Jan-11	0.33	0.31	0.32
Feb-11	0.02	0.07	0.02
Mar-11	0.13	0.15	0.18
Avg	0.32	0.34	0.35

APPENDIX B: POROSITY RAW DATA

Table 17: Raw Data for Component Total Porosity

Pre-Load

TOTAL POROSITY (pre-loading)

S/NO.	MATERIAL	TEST SERIES 1	2	3	4	5	AVERAGE POROSITY
1	Pervious Concrete PC	30.0	31.3	35.4	31.3	31.3	**31.9**
2	Flexi-pave FP	35.4	35.4	35.4	40.9	39.5	**37.3**
3	Permeable Pavers PP	10.0	8.1	8.8	9.5		**9.1**
4	Black&Gold		23.2	23.2	25.9		**24.1**
5	(#89) Pea rock	35.4	42.8	40.9	43.6	45.0	**41.5**
6	HPF	45.0	45.0	43.6	43.6	45.0	**44.4**
7	Crushed concrete (#57)	46.3	46.3	47.7	49.1	46.3	**47.1**
8	Limestone (#4)	50.4	53.1	49.1	50.4	49.1	**50.4**
9	Granite (#4)	42.2	45.0	46.3	45.0	47.7	**45.2**

Post Load

TOTAL POROSITY (post loading)

S/NO.	MATERIAL	TEST SERIES 1	2	3	4	5	AVERAGE POROSITY
1	Pervious concrete	28.6	27.3	34.1	30.0	25.9	**29.2**
2	Flexi-pave	15.0	25.9	23.2	4.1	9.5	**15.5**
4	Pea rock (#89)	24.5	24.5	24.5	19.1	15.0	**21.5**
5	HPF	23.2		23.2			**23.2**
6	Crushed concrete (#57)	12.3	9.5	10.9	8.2	8.2	**9.8**
7	Limestone (#4)	5.5	6.8	9.5	6.8	10.9	**7.9**
8	Granite (#4)	8.2	12.3	8.2	5.5	10.9	**9.0**

Post Vacuum

TOTAL POROSITY TEST RESULTS SUMMARY

S/NO.	MATERIAL	TEST SERIES 1	2	3	4	5	AVERAGE POROSITY
1	Pervious concrete	30.0	25.9	38.2	32.7	27.3	**30.8**
2	Flexi-pave	12.3	27.3	24.5	8.2	15.0	**17.4**

Table 18: Raw Data for Component Effective Porosity

Pre-Load

EFFECTIVE POROSITY (pre-loading)

S/NO.	MATERIAL	TEST SERIES 1	2	3	4	5	AVERAGE POROSITY
1	**Pervious concrete**	24.5	25.9	30.0	27.3	28.6	**27.2**
2	**Flexi-pave**	27.3	31.3	28.6	35.4	32.7	**31.1**
4	**Black & Gold**		8.2	5.5	13.6		**9.1**
5	**Pea rock (#89)**	31.1	38.2	36.8	38.2	38.2	**36.5**
6	**HPF**	39.5	38.2	38.2	39.5	39.5	**39.0**
7	**Crushed concrete (#57)**	43.6	31.3	43.6	45.0	43.6	**41.4**
8	**Limestone (#4)**	45.9	47.7	45.0	46.3	41.0	**45.2**
9	**Granite (#4)**	40.9	43.6	45.0	43.6	45.0	**43.6**

Post Load

EFFECTIVE POROSITY (post loading)

S/NO.	MATERIAL	TEST SERIES 1	2	3	4	5	AVERAGE POROSITY
1	**Pervious concrete**	21.8	21.8	28.6	24.5	20.4	**23.4**
2	**Flexi-pave**	6.8	20.4	17.7	1.4	5.5	**10.4**
5	**Pea rock (#89)**	12.3	10.9	21.8	9.5	8.2	**12.5**
6	**HPF**	13.6		16.4			**15.0**
7	**Crushed concrete (#57)**	1.4	1.4	1.4	1.4	1.4	**1.4**
8	**Limestone (#4)**	2.7	4.1	1.4	4.1	2.7	**3.0**
9	**Granite (#4)**	2.7	4.1	2.7	1.4	4.1	**3.0**

Post Vacuum

EFFECTIVE POROSITY TEST RESULTS SUMMARY

S/NO.	MATERIAL	TEST SERIES 1	2	3	4	5	AVERAGE POROSITY
1	**Pervious concrete**	25.9	21.8	35.4	31.3	24.5	**27.8**
2	**Flexi-pave**	5.5	21.8	16.4	1.4	4.1	**9.8**

Table 19: Raw Data for Pervious Concrete System Porosity

		PERVIOUS CONCRETE				POROSITY	
Date	Test #	Height [In]	V added [liters]	V barell [liters]	V [liters]	Vv [liters]	n [%] = (Vv / V)
7/9/2008	1	15.75	25	104.1	103.0	24.2	23.5
7/17/2008	2	16	22	105.8	104.6	21.2	20.2
7/21/2008	3	15.875	19.04	104.9	103.8	18.2	17.6
AVERAGE							20.4
7/22/2008		Loading:	10 Liters	Sand			
7/30/2008	1	16	13.32	105.8	104.6	12.5	11.9
7/31/2008	2	16	13.84	105.8	104.6	13.0	12.4
8/4/2008	3	16	15.88	105.8	104.6	15.0	14.4
8/5/2008	4	16	14.82	105.8	104.6	14.0	13.4
8/5/2008	5	16	14	105.8	104.6	13.1	12.6
8/6/2008	6	16.5	14.5	109.1	107.9	13.6	12.6
AVERAGE							12.9
8/7/2008		VACUUM					VACUUM
8/7/2008	1	16	14.94	105.8	104.6	14.1	13.5
8/8/2008	2	16	15.26	105.8	104.6	14.4	13.8
8/12/2008	3	16	14.94	105.8	104.6	14.1	13.5
8/13/2008	4	16	14.39	105.8	104.6	13.5	12.9
AVERAGE							13.4

Table 20: Raw Data for FlexiPave System Porosity

FLEXIPAVE						POROSITY	
Date	Test #	Height [In]	V added [liters]	V barell [liters]	V [liters]	Vv [liters]	n [%] = (Vv / V)
2/4/2009	1	16.25	33.36	107.4	106.4	32.9	30.9
2/4/2009	2	16.25	19.36	107.4	106.4	18.9	17.8
2/4/2009	3	16.25	19.84	107.4	106.4	19.4	18.2
2/5/2009	4	16.25	23.62	107.4	106.4	23.2	21.8
2/6/2009	5	16.25	22.72	107.4	106.4	22.3	20.9
2/12/2009	6	16.25	23.15	107.4	106.4	22.7	21.3
4/8/2009	7	16.25	23.84	107.4	106.4	23.4	22.0
Average							21.8
Loaded with Sand (Date: 05-06-09)							
5/12/2009	1	16.25	7.52	107.4	106.4	7.1	6.6
5/18/2009	2	16.25	8.90	107.4	106.4	8.4	7.9
6/2/2009	3	16.25	10.00	107.4	106.4	9.5	9.0
6/23/2009	4	16.25	8.71	107.4	106.4	8.2	7.8
6/25/2009	5	16.25	9.21	107.4	106.4	8.7	8.2
Average							7.9
Vaccumed							
6/26/2009	1	16.25	8.00	107.4	106.4	7.5	7.1
7/1/2009	2	16.25	10.62	107.4	106.4	10.2	9.5
8/3/2009	3	16.25	11.25	107.4	106.4	10.8	10.1
9/16/2009	4	16.25	6.00	107.4	106.4	5.5	5.2
10/23/2009	5	16.25	6.00	107.4	106.4	5.5	5.2
1/12/2010	6	16.25	12.56	107.4	106.4	12.1	11.4
1/14/2010	7	16.25	5.48	107.4	106.4	5.5	5.2
Average							7.7

Table 21: Raw Data for Permeable Pavers (Limestone) System Porosity

Permeable Pavers (Limestone)					POROSITY		
Date	Test #	Height [In]	V added [liters]	V barell [liters]	V [liters]	Vv [liters]	n [%] = (Vv / V)
7/17/2008	1	16.5	30.90	109.1	107.9	30.1	27.9
7/21/2008	2	16.5	29.52	109.1	107.9	28.7	26.6
7/25/2008	3	16.5	29.08	109.1	107.9	28.2	26.2
7/28/2008	4	16.5	28.64	109.1	107.9	27.8	25.8
7/30/2008	5	16.5	27.60	109.1	107.9	26.8	24.8
Average							26.2
7/30/2008		Loading:	2 Liters	Sand			
7/31/2008	1	16.75	24.92	110.7	109.5	24.0	21.9
8/4/2008	2	17	29.22	112.4	111.2	28.3	25.5
8/5/2008	3	17	28.70	112.4	111.2	27.8	25.0
8/5/2008	4	17	27.50	112.4	111.2	26.6	23.9
8/6/2008	5	17	24.56	112.4	111.2	23.7	21.3
8/7/2008	6	17	27.30	112.4	111.2	26.4	23.7
8/8/2008	7	17	28.00	112.4	111.2	27.1	24.4
8/12/2008	8	17	28.68	112.4	111.2	27.8	25.0
Average							23.8
8/12/2008		VACUUM					VACUUM
8/14/2008	1	16.625	29.10	109.9	108.7	28.2	26.0
8/14/2008	2	16.625	27.10	109.9	108.7	26.2	24.1
8/15/2008	3	16.625	28.00	109.9	108.7	27.1	24.9
8/20/2008	4	16.875	31.00	111.6	110.3	30.1	27.3
Average							25.6

Table 22: Raw Data for Permeable Pavers (Granite) System Porosity

Permeable Pavers (Granite)					POROSITY		
Date	Test #	Height [In]	V added [liters]	V barell [liters]	V [liters]	Vv [liters]	n [%] = (Vv / V)
7/17/2008	1	16.5	31.00	109.1	107.9	30.2	27.9
7/21/2008	2	16.5	29.80	109.1	107.9	29.0	26.8
7/25/2008	3	16.75	27.28	110.7	109.5	26.4	24.1
7/28/2008	4	16.25	28.98	107.4	106.2	28.1	26.5
7/30/2008	5	16.5	30.00	109.1	107.9	29.2	27.0
Average							26.5
7/30/2008		Loading:	4 Liters	Sand			
7/31/2008	1	16.75	23.80	110.7	109.5	22.9	20.9
8/4/2008	2	16.75	25.80	110.7	109.5	24.9	22.7
8/5/2008	3	16.75	26.70	110.7	109.5	25.8	23.6
8/5/2008	4	16.75	25.66	110.7	109.5	24.8	22.6
8/6/2008	5	16.75	24.50	110.7	109.5	23.6	21.6
8/7/2008	6	16.75	23.78	110.7	109.5	22.9	20.9
8/8/2008	7	16.75	26.24	110.7	109.5	25.3	23.1
8/12/2008	8	16.75	22.32	110.7	109.5	21.4	19.6
Average							21.9
8/12/2008		VACUUM					VACUUM
8/14/2008	1	16.375	25.18	108.3	107.1	24.3	22.7
8/14/2008	2	16.5	25.50	109.1	107.9	24.6	22.8
8/15/2008	3	16.5	24.56	109.1	107.9	23.7	22.0
8/20/2008	4	16.6875	25.10	110.3	109.1	24.2	22.2
Average							22.4

Table 23: Raw Data for Hanson Pavers (HP) System Porosity

Hanson Pavers					POROSITY		
Date	Test #	Height [In]	V added [liters]	V barell [liters]	V [liters]	Vv [liters]	n [%] = (Vv / V)
7/21/2008	1	16.5	27.66	109.1	107.9	26.8	24.9
7/25/2008	2	16.25	27.44	107.4	106.2	26.6	25.0
7/28/2008	3	16	26.89	105.8	104.6	26.1	24.9
7/30/2008	4	16	29.44	105.8	104.6	28.6	27.4
7/31/2008	5	16.25	28.76	107.4	106.2	27.9	26.3
Average							25.7
7/31/2008		Loading:	1 Liters	Sand			
8/4/2008	1	16.25	29.02	107.4	106.2	28.2	26.5
8/5/2008	2	16.75	29.02	110.7	109.5	28.1	25.7
8/5/2008	3	16.75	28.00	110.7	109.5	27.1	24.8
8/6/2008	4	16.5	26.82	109.1	107.9	25.9	24.0
8/7/2008	5	16.75	27.34	110.7	109.5	26.4	24.2
8/8/2008	6	16.75	28.56	110.7	109.5	27.7	25.3
8/12/2008	7	16.4375	24.44	108.7	107.5	23.6	21.9
Average							24.6
8/12/2008		VACUUM					VACUUM
8/14/2008	1	16.5	28.62	109.1	107.9	27.7	25.7
8/14/2008	2	16.25	28.00	107.4	106.2	27.1	25.5
8/15/2008	3	16.125	27.34	106.6	105.4	26.5	25.1
8/20/2008	4	16.75	29.80	110.7	109.5	28.9	26.4
Average							25.7

Table 24: Raw Data for #89 Limestone Effective Porosity with Respect to Drying Time

#89 Limestone Effective Porosity				
	89 L1	89 L2	89 L3	89 L4
1 HR Dry Time		0.434	0.423	
	0.467	0.420	0.449	0.408
	0.388	0.402	0.403	0.402
	0.374	0.366	0.410	0.401
Average	0.410	0.405	0.421	0.404
6 HR Dry Time	0.408	0.389	0.392	0.380
	0.441	0.442	0.482	0.441
	0.433	0.429	0.450	0.452
Average	0.427	0.420	0.441	0.424
24 HR Dry Time	0.427	0.403	0.419	0.426
	0.503	0.425	0.401	0.392
	0.432	0.425	0.433	0.414
	0.500	0.461	0.450	0.429
Average	0.466	0.429	0.426	0.415

Table 25: Raw Data for #89 Granite Effective Porosity with Respect to Drying Time

	#89 Granite Effective Porosity			
	89 G1	89 G2	89 G3	89 G4
1 HR Dry Time	0.449	0.459	0.427	0.437
	0.435	0.433	0.422	0.463
	0.415	0.387	0.425	0.446
	0.406	0.461	0.406	0.428
	0.426	0.435	0.420	0.444
Average	0.426	0.435	0.420	0.444
6 HR Dry Time	0.391	0.407	0.429	0.403
	0.448	0.492	0.467	0.479
	0.413	0.468	0.429	0.433
	0.417	0.456	0.442	0.438
Average	0.419	0.451	0.437	0.439
24 HR Dry Time	0.454	0.431	0.422	0.436
	0.468	0.529	0.445	0.439
	0.448	0.490	0.446	0.465
	0.442	0.487	0.432	0.400
	0.453	0.484	0.436	0.435
Average	0.453	0.484	0.436	0.435

Table 26: Raw Data for #57 Limestone Effective Porosity with Respect to Drying Time

#57 Limestone Effective Porosity				
	57 L1	57 L2	57 L3	57 L4
1 HR Dry Time	0.439	0.409	0.380	0.390
	0.488	0.441	0.429	0.441
	0.415	0.417	0.426	0.353
	0.459	0.469	0.433	0.393
	0.497	0.447	0.483	0.504
	0.442	0.461	0.438	0.460
	0.457	0.441	0.432	0.423
Average	0.457	0.441	0.432	0.423
6 HR Dry Time	0.422	0.401	0.392	0.408
	0.507	0.486	0.503	0.476
	0.521	0.506	0.491	0.468
	0.483	0.464	0.462	0.451
Average	0.483	0.464	0.462	0.451
24 HR Dry Time	0.453	0.452	0.435	0.513
	0.475	0.433	0.373	0.433
	0.523	0.485	0.488	0.482
	0.476	0.383	0.395	0.465
	0.482	0.438	0.423	0.473
Average	0.482	0.438	0.423	0.473

Table 27: Raw Data for #57 Granite Effective Porosity with Respect to Drying Time

	#57 Granite Effective Porosity			
	57 G1	57 G2	57 G3	57 G4
1 HR Dry Time	0.392	0.411	0.381	0.424
	0.431	0.432	0.428	0.461
	0.406	0.398	0.383	0.416
	0.424	0.389	0.379	0.406
	0.411	0.413	0.411	0.471
	0.392	0.426	0.413	0.445
	0.409	0.411	0.399	0.437
Average	0.409	0.407	0.397	0.435
6 HR Dry Time	0.407	0.369	0.361	0.407
	0.452	0.492	0.465	0.497
	0.465	0.484	0.476	0.480
	0.442	0.448	0.434	0.461
Average	0.435	0.440	0.427	0.456
24 HR Dry Time	0.417	0.421	0.441	0.466
	0.405	0.472		0.486
	0.457	0.455	0.431	0.483
	0.426	0.412	0.407	0.471
	0.426	0.440	0.426	0.477
Average	0.426	0.440	0.426	0.477

Table 28: Mann-Whitney U Test for #89 Limestone, 6 and 24 Hour Dry Times

	6-HR	24-HR
Count	24	32
rank sum	658	938
U	410	358

Mean	384
Variance	3648
Std dev	60.3987
z-score	-0.4305
p-value	0.33343
sig	no

6-HR	24-HR
0.40769	0.42703
0.43684	0.41076
0.44104	0.50308
0.42224	0.43891
0.43347	0.43223
0.42342	0.42957
0.38888	0.50012
0.4236	0.45878
0.4424	0.40284
0.43903	0.41963
0.4288	0.42525
0.39775	0.45216
0.39154	0.42519
0.42034	0.42969
0.48202	0.46097
0.47439	0.42265
0.45015	0.4191
0.42774	0.4356
0.3796	0.40106
0.46907	0.45429
0.44134	0.43282
0.46067	0.44991
0.45222	0.44962
0.40633	0.47144
	0.42555
	0.43235
	0.39225
	0.43962
	0.41425
	0.40053
	0.42939
	0.4751

Ranked Data		
0.3796	6-HR	1
0.38888	6-HR	2
0.39154	6-HR	3
0.39225	24-HR	4
0.39775	6-HR	5
0.40053	24-HR	6
0.40106	24-HR	7
0.40284	24-HR	8
0.40633	6-HR	9
0.40769	6-HR	10
0.41076	24-HR	11
0.41425	24-HR	12
0.4191	24-HR	13
0.41963	24-HR	14
0.42034	6-HR	15
0.42224	6-HR	16
0.42265	24-HR	17
0.42342	6-HR	18
0.4236	6-HR	19
0.42519	24-HR	20
0.42525	24-HR	21
0.42555	24-HR	22
0.42703	24-HR	23
0.42774	6-HR	24
0.4288	6-HR	25
0.42939	24-HR	26
0.42957	24-HR	27
0.42969	24-HR	28
0.43223	24-HR	29
0.43235	24-HR	30
0.43282	24-HR	31
0.43347	6-HR	32
0.4356	24-HR	33
0.43684	6-HR	34
0.43891	24-HR	35
0.43903	6-HR	36
0.43962	24-HR	37
0.44104	6-HR	38
0.44134	6-HR	39
0.4424	6-HR	40
0.44962	24-HR	41
0.44991	24-HR	42
0.45015	6-HR	43
0.45216	24-HR	44
0.45222	6-HR	45
0.45429	24-HR	46
0.45878	24-HR	47
0.46067	6-HR	48
0.46097	24-HR	49
0.46907	6-HR	50
0.47144	24-HR	51
0.47439	6-HR	52
0.4751	24-HR	53
0.48202	6-HR	54
0.50012	24-HR	55
0.50308	24-HR	56

U for 6-HR	U for 24-HR
658	938
Total	Check
1596	1596
Count 6-HR	Count 24-HR
24	32
U1	410
U2	358

Table 29: Mann-Whitney U Test for #89 Limestone, 1 and 6 Hour Dry Times

	1-HR	6-HR
Count	40	24
rank sum	1227	853
U	553	407

Mean	480
Variance	5200
Std dev	72.111026
z-score	-1.0123279
p-value	0.1556907
sig	no

1-HR	6-HR
0.513424	0.3913661
0.4027203	0.4274394
0.4493199	0.4479598
0.512123	0.4845653
0.435068	0.4126552
0.4105263	0.4467771
0.4147842	0.4066233
0.4505618	0.4153755
0.4057954	0.49178
0.4252513	0.5073329
0.4630988	0.4683028
0.3922531	0.4469545
0.4591957	0.4293318
0.464932	0.46233
0.4334713	0.4668244
0.3983442	0.4562389
0.3870491	0.4286221
0.4552336	0.4706091
0.4607924	0.403016
0.4471319	0.4319929
0.5034891	0.4790065
0.4760497	0.4222945
0.4273211	0.4331165
0.4236546	0.4529864
0.4223536	
0.4067416	
0.4254287	
0.3940863	
0.405618	
0.4116499	
0.5290952	
0.4566529	
0.4366647	
0.47534	
0.4629805	
0.4002957	
0.4461857	
0.3769959	
0.4283856	
0.4507983	

Ranked Data		
0.3769959	1-HR	1
0.3870491	1-HR	2
0.3913661	6-HR	3
0.3922531	1-HR	4
0.3940863	1-HR	5
0.3983442	1-HR	6
0.4002957	1-HR	7
0.4027203	1-HR	8
0.403016	6-HR	9
0.405618	1-HR	10
0.4057954	1-HR	11
0.4066233	6-HR	12
0.4067416	1-HR	13
0.4105263	1-HR	14
0.4116499	1-HR	15
0.4126552	6-HR	16
0.4147842	1-HR	17
0.4153755	6-HR	18
0.4222945	6-HR	19
0.4223536	1-HR	20
0.4236546	1-HR	21
0.4252513	1-HR	22
0.4254287	1-HR	23
0.4273211	1-HR	24
0.4274394	6-HR	25
0.4283856	1-HR	26
0.4286221	6-HR	27
0.4293318	6-HR	28
0.4319929	6-HR	29
0.4331165	6-HR	30
0.4334713	1-HR	31
0.435068	1-HR	32
0.4366647	1-HR	33
0.4461857	1-HR	34
0.4467771	6-HR	35
0.4469545	6-HR	36
0.4471319	1-HR	37
0.4479598	6-HR	38
0.4493199	1-HR	39
0.4505618	1-HR	40
0.4507983	1-HR	41
0.4529864	6-HR	42
0.4552336	1-HR	43
0.4562389	6-HR	44
0.4566529	1-HR	45
0.4591957	1-HR	46
0.4607924	1-HR	47
0.46233	6-HR	48
0.4629805	1-HR	49
0.4630988	1-HR	50
0.464932	1-HR	51
0.4668244	6-HR	52
0.4683028	6-HR	53
0.4706091	6-HR	54
0.47534	1-HR	55
0.4760497	1-HR	56
0.4790065	6-HR	57
0.4845653	6-HR	58
0.49178	6-HR	59
0.5034891	1-HR	60
0.5073329	6-HR	61
0.512123	1-HR	62
0.513424	1-HR	63
0.5290952	1-HR	64

U for 1-HR	U for 6-HR
1227	853
Total	Check
2080	2080
Count 1-HR	Count 6-HR
40	24
U1	553
U2	407

Table 30: Mann-Whitney U Test for #89 Limestone, 1 and 24 Hour Dry Times

	1-HR	24-HR
Count	40	32
rank sum	1245	1383
U	855	425

Mean	640
Variance	7786.6667
Std dev	88.242091
z-score	-2.436479
p-value	0.0074155
sig	yes

1-HR	24-HR
0.513424	0.4536369
0.4027203	0.4124187
0.4493199	0.4683619
0.512123	0.4586044
0.435068	0.4481963
0.4105263	0.4544057
0.4147842	0.441573
0.4505618	0.4708457
0.4057954	0.4305145
0.4252513	0.4332939
0.4630988	0.52945
0.3922531	0.4879361
0.4591957	0.4895328
0.464932	0.4645772
0.4334713	0.4872856
0.3983442	0.4661147
0.3870491	0.4217623
0.4552336	0.4363099
0.4607924	0.4445299
0.4471319	0.4546422
0.5034891	0.4457717
0.4760497	0.4620934
0.4273211	0.4318155
0.4236546	0.4669426
0.4223536	0.4356002
0.4067416	0.4506801
0.4254287	0.4385571
0.3940863	0.4553519
0.405618	0.4646954
0.4116499	0.4730928
0.5290952	0.4003548
0.4566529	0.472738
0.4366647	
0.47534	
0.4629805	
0.4002957	
0.4461857	
0.3769959	
0.4283856	
0.4507983	

Ranked Data		
0.3769959	1-HR	1
0.3870491	1-HR	2
0.3922531	1-HR	3
0.3940863	1-HR	4
0.3983442	1-HR	5
0.4002957	1-HR	6
0.4003548	24-HR	7
0.4027203	1-HR	8
0.405618	1-HR	9
0.4057954	1-HR	10
0.4067416	1-HR	11
0.4105263	1-HR	12
0.4116499	1-HR	13
0.4124187	24-HR	14
0.4147842	1-HR	15
0.4217623	24-HR	16
0.4223536	1-HR	17
0.4236546	1-HR	18
0.4252513	1-HR	19
0.4254287	1-HR	20
0.4273211	1-HR	21
0.4283856	1-HR	22
0.4305145	24-HR	23
0.4318155	24-HR	24
0.4332939	24-HR	25
0.4334713	1-HR	26
0.435068	1-HR	27
0.4356002	24-HR	28
0.4363099	24-HR	29
0.4366647	1-HR	30
0.4385571	24-HR	31
0.441573	24-HR	32
0.4445299	24-HR	33
0.4457717	24-HR	34
0.4461857	1-HR	35
0.4471319	1-HR	36
0.4481963	24-HR	37
0.4493199	1-HR	38
0.4505618	1-HR	39
0.4506801	24-HR	40
0.4507983	1-HR	41
0.4536369	24-HR	42
0.4544057	24-HR	43
0.4546422	24-HR	44
0.4552336	1-HR	45
0.4553519	24-HR	46
0.4566529	1-HR	47
0.4586044	24-HR	48
0.4591957	1-HR	49
0.4607924	1-HR	50
0.4620934	24-HR	51
0.4629805	1-HR	52
0.4630988	1-HR	53
0.4645772	24-HR	54
0.4646954	24-HR	55
0.464932	1-HR	56
0.4661147	24-HR	57
0.4669426	24-HR	58
0.4683619	24-HR	59
0.4708457	24-HR	60
0.472738	24-HR	61
0.4730928	24-HR	62
0.47534	1-HR	63
0.4760497	1-HR	64
0.4872856	24-HR	65
0.4879361	24-HR	66
0.4895328	24-HR	67
0.5034891	1-HR	68
0.512123	1-HR	69
0.513424	1-HR	70
0.5290952	1-HR	71
0.52945	24-HR	72

U for 1-HR	U for 24-HR
1245	1383
Total	Check
2628	2628
Count 1-HR	Count 24-HR
40	32
U1	855
U2	425

Table 31: Mann-Whitney U Test for #89 Granite, 6 and 24 Hour Dry Times

	6-HR	24-HR
Count	24	32
rank sum	606	990
U	462	306

Mean	384
Variance	3648
Std dev	60.3987
z-score	-1.2914
p-value	0.09828
sig	no

6-HR	24-HR
0.39137	0.45364
0.42744	0.41242
0.44796	0.46836
0.48457	0.4586
0.41266	0.4482
0.44678	0.45441
0.40662	0.44157
0.41538	0.47085
0.49178	0.43051
0.50733	0.43329
0.4683	0.52945
0.44695	0.48794
0.42933	0.48953
0.46233	0.46458
0.46682	0.48729
0.45624	0.46611
0.42862	0.42176
0.47061	0.43631
0.40302	0.44453
0.43199	0.45464
0.47901	0.44577
0.42229	0.46209
0.43312	0.43182
0.45299	0.46694
	0.4356
	0.45068
	0.43856
	0.45535
	0.4647
	0.47309
	0.40035
	0.47274

Ranked Data		
0.39137	6-HR	1
0.40035	24-HR	2
0.40302	6-HR	3
0.40662	6-HR	4
0.41242	24-HR	5
0.41266	6-HR	6
0.41538	6-HR	7
0.42176	24-HR	8
0.42229	6-HR	9
0.42744	6-HR	10
0.42862	6-HR	11
0.42933	6-HR	12
0.43051	24-HR	13
0.43182	24-HR	14
0.43199	6-HR	15
0.43312	6-HR	16
0.43329	24-HR	17
0.4356	24-HR	18
0.43631	24-HR	19
0.43856	24-HR	20
0.44157	24-HR	21
0.44453	24-HR	22
0.44577	24-HR	23
0.44678	6-HR	24
0.44695	6-HR	25
0.44796	6-HR	26
0.4482	24-HR	27
0.45068	24-HR	28
0.45299	6-HR	29
0.45364	24-HR	30
0.45441	24-HR	31
0.45464	24-HR	32
0.45535	24-HR	33
0.45624	6-HR	34
0.4586	24-HR	35
0.46209	24-HR	36
0.46233	6-HR	37
0.46458	24-HR	38
0.4647	24-HR	39
0.46611	24-HR	40
0.46682	6-HR	41
0.46694	24-HR	42
0.4683	6-HR	43
0.46836	24-HR	44
0.47061	6-HR	45
0.47085	24-HR	46
0.47274	24-HR	47
0.47309	24-HR	48
0.47901	6-HR	49
0.48457	6-HR	50
0.48729	24-HR	51
0.48794	24-HR	52
0.48953	24-HR	53
0.49178	6-HR	54
0.50733	6-HR	55
0.52945	24-HR	56

U for 6-HR	U for 24-HR
606	990

Total	Check
1596	1596

Count 6-HR	Count 24-HR
24	32

U1	462
U2	306

Table 32: Mann-Whitney U Test for #89 Granite, 1 and 6 Hour Dry Times

	1-HR	6-HR
Count	40	24
rank sum	1227	853
U	553	407

Mean	480
Variance	5200
Std dev	72.111026
z-score	-1.0123279
p-value	0.1556907
sig	no

1-HR	6-HR
0.513424	0.3913661
0.4027203	0.4274394
0.4493199	0.4479598
0.512123	0.4845653
0.435068	0.4126552
0.4105263	0.4467771
0.4147842	0.4066233
0.4505618	0.4153755
0.4057954	0.49178
0.4252513	0.5073329
0.4630988	0.4683028
0.3922531	0.4469545
0.4591957	0.4293318
0.464932	0.46233
0.4334713	0.4668244
0.3983442	0.4562389
0.3870491	0.4286221
0.4552336	0.4706091
0.4607924	0.403016
0.4471319	0.4319929
0.5034891	0.4790065
0.4760497	0.4222945
0.4273211	0.4331165
0.4236546	0.4529864
0.4223536	
0.4067416	
0.4254287	
0.3940863	
0.405618	
0.4116499	
0.5290952	
0.4566529	
0.4366647	
0.47534	
0.4629805	
0.4002957	
0.4461857	
0.3769959	
0.4283856	
0.4507983	

Ranked Data		
0.3769959	1-HR	1
0.3870491	1-HR	2
0.3913661	6-HR	3
0.3922531	1-HR	4
0.3940863	1-HR	5
0.3983442	1-HR	6
0.4002957	1-HR	7
0.4027203	1-HR	8
0.403016	6-HR	9
0.405618	1-HR	10
0.4057954	1-HR	11
0.4066233	6-HR	12
0.4067416	1-HR	13
0.4105263	1-HR	14
0.4116499	1-HR	15
0.4126552	6-HR	16
0.4147842	1-HR	17
0.4153755	6-HR	18
0.4222945	6-HR	19
0.4223536	1-HR	20
0.4236546	1-HR	21
0.4252513	1-HR	22
0.4254287	1-HR	23
0.4273211	1-HR	24
0.4274394	6-HR	25
0.4283856	1-HR	26
0.4286221	6-HR	27
0.4293318	6-HR	28
0.4319929	6-HR	29
0.4331165	6-HR	30
0.4334713	1-HR	31
0.435068	1-HR	32
0.4366647	1-HR	33
0.4461857	1-HR	34
0.4467771	6-HR	35
0.4469545	6-HR	36
0.4471319	1-HR	37
0.4479598	6-HR	38
0.4493199	1-HR	39
0.4505618	1-HR	40
0.4507983	1-HR	41
0.4529864	6-HR	42
0.4552336	1-HR	43
0.4562389	6-HR	44
0.4566529	1-HR	45
0.4591957	1-HR	46
0.4607924	1-HR	47
0.46233	6-HR	48
0.4629805	1-HR	49
0.4630988	1-HR	50
0.464932	1-HR	51
0.4668244	6-HR	52
0.4683028	6-HR	53
0.4706091	6-HR	54
0.47534	1-HR	55
0.4760497	1-HR	56
0.4790065	6-HR	57
0.4845653	6-HR	58
0.49178	6-HR	59
0.5034891	1-HR	60
0.5073329	6-HR	61
0.512123	1-HR	62
0.513424	1-HR	63
0.5290952	1-HR	64

U for 1-HR	U for 6-HR
1227	853
Total	Check
2080	2080
Count 1-HR	Count 6-HR
40	24
U1	553
U2	407

Table 33: Mann-Whitney U Test for #89 Granite, 1 and 24 Hour Dry Times

	1-HR	24-HR
Count	40	32
rank sum	1245	1383
U	855	425

Mean	640
Variance	7786.6667
Std dev	88.242091
z-score	-2.436479
p-value	0.0074155
sig	yes

1-HR	24-HR
0.513424	0.4536369
0.4027203	0.4124187
0.4493199	0.4683619
0.512123	0.4586044
0.435068	0.4481963
0.4105263	0.4544057
0.4147842	0.441573
0.4505618	0.4708457
0.4057954	0.4305145
0.4252513	0.4332939
0.4630988	0.52945
0.3922531	0.4879361
0.4591957	0.4895328
0.464932	0.4645772
0.4334713	0.4872856
0.3983442	0.4661147
0.3870491	0.4217623
0.4552336	0.4363099
0.4607924	0.4445299
0.4471319	0.4546422
0.5034891	0.4457717
0.4760497	0.4620934
0.4273211	0.4318155
0.4236546	0.4669426
0.4223536	0.4356002
0.4067416	0.4506801
0.4254287	0.4385571
0.3940863	0.4553519
0.405618	0.4646954
0.4116499	0.4730928
0.5290952	0.4003548
0.4566529	0.472738
0.4366647	
0.47534	
0.4629805	
0.4002957	
0.4461857	
0.3769959	
0.4283856	
0.4507983	

Ranked Data		
0.3769959	1-HR	1
0.3870491	1-HR	2
0.3922531	1-HR	3
0.3940863	1-HR	4
0.3983442	1-HR	5
0.4002957	1-HR	6
0.4003548	24-HR	7
0.4027203	1-HR	8
0.405618	1-HR	9
0.4057954	1-HR	10
0.4067416	1-HR	11
0.4105263	1-HR	12
0.4116499	1-HR	13
0.4124187	24-HR	14
0.4147842	1-HR	15
0.4217623	24-HR	16
0.4223536	1-HR	17
0.4236546	1-HR	18
0.4252513	1-HR	19
0.4254287	1-HR	20
0.4273211	1-HR	21
0.4283856	1-HR	22
0.4305145	24-HR	23
0.4318155	24-HR	24
0.4332939	24-HR	25
0.4334713	1-HR	26
0.435068	1-HR	27
0.4356002	24-HR	28
0.4363099	24-HR	29
0.4366647	1-HR	30
0.4385571	24-HR	31
0.441573	24-HR	32
0.4445299	24-HR	33
0.4457717	24-HR	34
0.4461857	1-HR	35
0.4471319	1-HR	36
0.4481963	24-HR	37
0.4493199	1-HR	38
0.4505618	1-HR	39
0.4506801	24-HR	40
0.4507983	1-HR	41
0.4536369	24-HR	42
0.4544057	24-HR	43
0.4546422	24-HR	44
0.4552336	1-HR	45
0.4553519	24-HR	46
0.4566529	1-HR	47
0.4586044	24-HR	48
0.4591957	1-HR	49
0.4607924	1-HR	50
0.4620934	24-HR	51
0.4629805	1-HR	52
0.4630988	1-HR	53
0.4645772	24-HR	54
0.4646954	24-HR	55
0.464932	1-HR	56
0.4661147	24-HR	57
0.4669426	24-HR	58
0.4683619	24-HR	59
0.4708457	24-HR	60
0.472738	24-HR	61
0.4730928	24-HR	62
0.47534	1-HR	63
0.4760497	1-HR	64
0.4872856	24-HR	65
0.4879361	24-HR	66
0.4895328	24-HR	67
0.5034891	1-HR	68
0.512123	1-HR	69
0.513424	1-HR	70
0.5290952	1-HR	71
0.52945	24-HR	72

U for 1-HR	U for 24-HR
1245	1383

Total	Check
2628	2628

Count 1-HR	Count 24-HR
40	32

U1	855
U2	425

Table 34: Mann-Whitney U Test for #57 Limestone, 6 and 24 Hour Dry Times

	6-HR	24-HR
Count	24	32
rank sum	729.5	866.5
U	338.5	429.5

Mean	384
Variance	3648
Std dev	60.3987
z-score	0.75333
p-value	0.77437
sig	no

6-HR	24-HR
0.42229	0.45316
0.44766	0.49527
0.50733	0.4754
0.54536	0.50308
0.52082	0.5233
0.53306	0.50869
0.40095	0.47623
0.47794	0.54163
0.48587	0.45169
0.51739	0.46854
0.5058	0.43335
0.46446	0.48746
0.39202	0.48474
0.456	0.46404
0.50349	0.38285
0.51041	0.48717
0.4906	0.4353
0.49296	0.4437
0.40816	0.37286
0.44447	0.46647
0.47635	0.48764
0.49379	0.47723
0.46842	0.39539
0.45441	0.51041
	0.51336
	0.4686
	0.43282
	0.4699
	0.4819
	0.47061
	0.46546
	0.49113

Ranked Data		
0.37286	24-HR	1
0.38285	24-HR	2
0.39202	6-HR	3
0.39539	24-HR	4
0.40095	6-HR	5
0.40816	6-HR	6
0.42229	6-HR	7
0.43282	24-HR	8
0.43335	24-HR	9
0.4353	24-HR	10
0.4437	24-HR	11
0.44447	6-HR	12
0.44766	6-HR	13
0.45169	24-HR	14
0.45316	24-HR	15
0.45441	6-HR	16
0.456	6-HR	17
0.46404	24-HR	18
0.46446	6-HR	19
0.46546	24-HR	20
0.46647	24-HR	21
0.46842	6-HR	22
0.46854	24-HR	23
0.4686	24-HR	24
0.4699	24-HR	25
0.47061	24-HR	26
0.4754	24-HR	27
0.47623	24-HR	28
0.47635	6-HR	29
0.47723	24-HR	30
0.47794	6-HR	31
0.4819	24-HR	32
0.48474	24-HR	33
0.48587	6-HR	34
0.48717	24-HR	35
0.48746	24-HR	36
0.48764	24-HR	37
0.4906	6-HR	38
0.49113	24-HR	39
0.49296	6-HR	40
0.49379	6-HR	41
0.49527	24-HR	42
0.50308	24-HR	43
0.50349	6-HR	44
0.5058	6-HR	45
0.50733	6-HR	46
0.50869	24-HR	47
0.51041	6-HR	48.5
0.51041	24-HR	48.5
0.51336	24-HR	50
0.51739	6-HR	51
0.52082	6-HR	52
0.5233	24-HR	53
0.53306	6-HR	54
0.54163	24-HR	55
0.54536	6-HR	56

U for 6-HR	U for 24-HR
729.5	866.5
Total	Check
1596	1596
Count 6-HR	Count 24-HR
24	32
U1	338.5
U2	429.5

Table 35: Mann-Whitney U Test for #57 Limestone, 1 and 6 Hour Dry Times

	1-HR	6-HR
Count	48	24
rank sum	1416	1212
U	912	240

Mean	576
Variance	7008
Std dev	83.71
z-score	-4.01
p-value	0.00
sig	yes

1-HR	6-HR
0.4390893	0.4222945
0.3843879	0.4476641
0.4877587	0.5073329
0.4699586	0.5453578
0.4146067	0.5208161
0.4564163	0.5330574
0.4593732	0.4009462
0.4631579	0.477942
0.4966884	0.4858664
0.3035482	0.5173862
0.4423418	0.5057954
0.4980485	0.4644589
0.4087522	0.3920166
0.3713187	0.4560024
0.4405086	0.5034891
0.4273802	0.510408
0.417327	0.4905973
0.399586	0.4929627
0.4687759	0.4081609
0.4250739	0.4444707
0.4473684	0.4763454
0.1894737	0.4937907
0.461029	0.4684211
0.4180367	0.4544057
0.3798936	
0.3767002	
0.42945	
0.4276759	
0.4261384	
0.4086339	
0.4329982	
0.4345358	
0.4832052	
0.3035482	
0.4376109	
0.4816677	
0.3896511	
0.3463631	
0.4406268	
0.4665287	
0.3534004	
0.4570077	
0.3927853	
0.4553519	
0.5043761	
0.2224719	
0.4600237	
0.3830278	

Ranked Data		
0.1894737	1-HR	1
0.2224719	1-HR	2
0.3035482	1-HR	3
0.3035482	1-HR	4
0.3463631	1-HR	5
0.3534004	1-HR	6
0.3713187	1-HR	7
0.3767002	1-HR	8
0.3798936	1-HR	9
0.3830278	1-HR	10
0.3843879	1-HR	11
0.3896511	1-HR	12
0.3920166	6-HR	13
0.3927853	1-HR	14
0.399586	1-HR	15
0.4009462	6-HR	16
0.4081609	6-HR	17
0.4086339	1-HR	18
0.4087522	1-HR	19
0.4146067	1-HR	20
0.417327	1-HR	21
0.4180367	1-HR	22
0.4222945	6-HR	23
0.4250739	1-HR	24
0.4261384	1-HR	25
0.4273802	1-HR	26
0.4276759	1-HR	27
0.42945	1-HR	28
0.4329982	1-HR	29
0.4345358	1-HR	30
0.4376109	1-HR	31
0.4390893	1-HR	32
0.4405086	1-HR	33
0.4406268	1-HR	34
0.4423418	1-HR	35
0.4444707	6-HR	36
0.4473684	1-HR	37
0.4476641	6-HR	38
0.4544057	6-HR	39
0.4553519	1-HR	40
0.4560024	6-HR	41
0.4564163	1-HR	42
0.4570077	1-HR	43
0.4593732	1-HR	44
0.4600237	1-HR	45
0.461029	1-HR	46
0.4631579	1-HR	47
0.4644589	6-HR	48
0.4665287	1-HR	49
0.4684211	6-HR	50
0.4687759	1-HR	51
0.4699586	1-HR	52
0.4763454	6-HR	53
0.477942	6-HR	54
0.4816677	1-HR	55
0.4832052	1-HR	56
0.4858664	6-HR	57
0.4877587	1-HR	58
0.4905973	6-HR	59
0.4929627	6-HR	60
0.4937907	6-HR	61
0.4966884	1-HR	62
0.4980485	1-HR	63
0.5034891	6-HR	64
0.5043761	1-HR	65
0.5057954	6-HR	66
0.5073329	6-HR	67
0.510408	6-HR	68
0.5173862	6-HR	69
0.5208161	6-HR	70
0.5330574	6-HR	71
0.5453578	6-HR	72

U for 1-HR	U for 6-HR
1416	1212
Total	Check
2628	2628
Count 1-HR	Count 6-HR
48	24
U1	912
U2	240

Table 36: Mann-Whitney U Test for #57 Limestone, 1 and 24 Hour Dry Times

	1-HR	24-HR
Count	48	32
rank sum	1511	1729
U	1201	335

Mean	768
Variance	10368
Std dev	101.82
z-score	-4.25
p-value	0.00
sig	yes

1-HR	24-HR
0.4390893	0.4531638
0.3843879	0.4952691
0.4877587	0.4753992
0.4699586	0.5030751
0.4146067	0.5232998
0.4564163	0.5086931
0.4593732	0.4762271
0.4631579	0.5416322
0.4966884	0.4516854
0.3035482	0.4685393
0.4423418	0.433353
0.4980485	0.487463
0.4087522	0.4847428
0.3713187	0.4640449
0.4405086	0.3828504
0.4273802	0.4871674
0.417327	0.4353046
0.399586	0.443702
0.4687759	0.3728563
0.4250739	0.4664695
0.4473684	0.4876404
0.1894737	0.4772324
0.461029	0.3953873
0.4180367	0.510408
0.3798936	0.5133649
0.3767002	0.4685985
0.42945	0.4328208
0.4276759	0.4698995
0.4261384	0.4819042
0.4086339	0.4706091
0.4329982	0.4654642
0.4345358	0.4911295
0.4832052	
0.3035482	
0.4376109	
0.4816677	
0.3896511	
0.3463631	
0.4406268	
0.4665287	
0.3534004	
0.4570077	
0.3927853	
0.4553519	
0.5043761	
0.2224719	
0.4600237	
0.3830278	

Ranked Data		
0.1894737	1-HR	1
0.2224719	1-HR	2
0.3035482	1-HR	3
0.3035482	1-HR	4
0.3463631	1-HR	5
0.3534004	1-HR	6
0.3713187	1-HR	7
0.3728563	24-HR	8
0.3767002	1-HR	9
0.3798936	1-HR	10
0.3828504	24-HR	11
0.3830278	1-HR	12
0.3843879	1-HR	13
0.3896511	1-HR	14
0.3927853	1-HR	15
0.3953873	24-HR	16
0.399586	1-HR	17
0.4086339	1-HR	18
0.4087522	1-HR	19
0.4146067	1-HR	20
0.417327	1-HR	21
0.4180367	1-HR	22
0.4250739	1-HR	23
0.4261384	1-HR	24
0.4273802	1-HR	25
0.4276759	1-HR	26
0.42945	1-HR	27
0.4328208	24-HR	28
0.4329982	1-HR	29
0.433353	24-HR	30
0.4345358	1-HR	31
0.4353046	24-HR	32
0.4376109	1-HR	33
0.4390893	1-HR	34
0.4405086	1-HR	35
0.4406268	1-HR	36
0.4423418	1-HR	37
0.443702	24-HR	38
0.4473684	1-HR	39
0.4516854	24-HR	40
0.4531638	24-HR	41
0.4553519	1-HR	42
0.4564163	1-HR	43
0.4570077	1-HR	44
0.4593732	1-HR	45
0.4600237	1-HR	46
0.461029	1-HR	47
0.4631579	1-HR	48
0.4640449	24-HR	49
0.4654642	24-HR	50
0.4664695	24-HR	51
0.4665287	1-HR	52
0.4685393	24-HR	53
0.4685985	24-HR	54
0.4687759	1-HR	55
0.4698995	24-HR	56
0.4699586	1-HR	57
0.4706091	24-HR	58
0.4753992	24-HR	59
0.4762271	24-HR	60
0.4772324	24-HR	61
0.4816677	1-HR	62
0.4819042	24-HR	63
0.4832052	1-HR	64
0.4847428	24-HR	65
0.4871674	24-HR	66
0.487463	24-HR	67
0.4876404	24-HR	68
0.4877587	1-HR	69
0.4911295	24-HR	70
0.4952691	24-HR	71
0.4966884	1-HR	72
0.4980485	1-HR	73
0.5030751	24-HR	74
0.5043761	1-HR	75
0.5086931	24-HR	76
0.510408	24-HR	77
0.5133649	24-HR	78
0.5232998	24-HR	79
0.5416322	24-HR	80

U for 1-HR	U for 24-HR
1511	1729
Total	Check
3240	3240
Count 1-HR	Count 24-HR
48	32
U1	1201
U2	335

Table 37: Mann-Whitney U Test for #57 Granite, 6 and 24 Hour Dry Times

	6-HR	24-HR
Count	24	32
rank sum	708	888
U	360	408

Mean	384
Variance	3648
Std dev	60.4
z-score	-0.4
p-value	0.3
sig	no

6-HR	24-HR
0.40739	0.41685
0.43767	0.44009
0.45222	0.4052
0.4521	0.47321
0.46493	0.45683
0.46582	0.46286
0.36854	0.42643
0.44636	0.48232
0.49208	0.42123
0.49273	0.44867
0.48421	0.47244
0.46866	0.47451
0.36132	0.45458
0.51922	0.45305
0.46464	0.41206
0.41555	0.47759
0.47623	0.44134
0.44701	0.46109
0.40668	0.35724
0.43862	0.46907
0.49651	0.43063
0.47989	0.45216
0.48037	0.4071
0.49911	0.47794
	0.4657
	0.45996
	0.4864
	0.49196
	0.48326
	0.47244
	0.47096
	0.50237

Ranked Data		
0.35724	24-HR	1
0.36132	6-HR	2
0.36854	6-HR	3
0.4052	24-HR	4
0.40668	6-HR	5
0.4071	24-HR	6
0.40739	6-HR	7
0.41206	24-HR	8
0.41555	6-HR	9
0.41685	24-HR	10
0.42123	24-HR	11
0.42643	24-HR	12
0.43063	24-HR	13
0.43767	6-HR	14
0.43862	6-HR	15
0.44009	24-HR	16
0.44134	24-HR	17
0.44636	6-HR	18
0.44701	6-HR	19
0.44867	24-HR	20
0.4521	6-HR	21
0.45216	24-HR	22
0.45222	6-HR	23
0.45305	24-HR	24
0.45458	24-HR	25
0.45683	24-HR	26
0.45996	24-HR	27
0.46109	24-HR	28
0.46286	24-HR	29
0.46464	6-HR	30
0.46493	6-HR	31
0.4657	24-HR	32
0.46582	6-HR	33
0.46866	6-HR	34
0.46907	24-HR	35
0.47096	24-HR	36
0.47244	24-HR	37.5
0.47244	24-HR	37.5
0.47321	24-HR	39
0.47451	24-HR	40
0.47623	6-HR	41
0.47759	24-HR	42
0.47794	24-HR	43
0.47989	6-HR	44
0.48037	6-HR	45
0.48232	24-HR	46
0.48326	24-HR	47
0.48421	6-HR	48
0.4864	24-HR	49
0.49196	24-HR	50
0.49208	6-HR	51
0.49273	6-HR	52
0.49651	6-HR	53
0.49911	6-HR	54
0.50237	24-HR	55
0.51922	6-HR	56

U for 6-HR	U for 24-HR
708	888

Total	Check
1596	1596

Count 6-HR	Count 24-HR
24	32

U1	360
U2	408

Table 38: Mann-Whitney U Test for #57 Granite, 1 and 6 Hour Dry Times

	1-HR	6-HR
Count	48	24
rank sum	1382	1246
U	946	206

Mean	576
Variance	7008
Std dev	83.7
z-score	-4.4
p-value	0.0
sig	yes

1-HR	6-HR
0.39178	0.4073921
0.3756949	0.43767
0.4312833	0.4522176
0.4297457	0.4520993
0.4062685	0.464932
0.3879361	0.465819
0.4238321	0.3685393
0.4269663	0.4463631
0.4114134	0.4920757
0.257126	0.4927262
0.3918983	0.4842105
0.3920166	0.4686576
0.4105263	0.3613247
0.4006505	0.5192194
0.4316972	0.4646363
0.4077469	0.4155529
0.3979894	0.4762271
0.4168539	0.4470136
0.3889415	0.4066824
0.3895328	0.4386162
0.4127144	0.4965109
0.3723241	0.4798936
0.425961	0.4803666
0.4262567	0.499113
0.381372	
0.3976345	
0.4284447	
0.4166765	
0.3826138	
0.4136606	
0.3792431	
0.413424	
0.4105263	
0.3010053	
0.4127735	
0.4160852	
0.4244234	
0.377942	
0.4606742	
0.4551745	
0.4164991	
0.4446481	
0.4062093	
0.4695446	
0.4707274	
0.415139	
0.4451212	
0.4224128	

Ranked Data		
0.257126	1-HR	1
0.3010053	1-HR	2
0.3613247	6-HR	3
0.3685393	6-HR	4
0.3723241	1-HR	5
0.3756949	1-HR	6
0.377942	1-HR	7
0.3792431	1-HR	8
0.381372	1-HR	9
0.3826138	1-HR	10
0.3879361	1-HR	11
0.3889415	1-HR	12
0.3895328	1-HR	13
0.39178	1-HR	14
0.3918983	1-HR	15
0.3920166	1-HR	16
0.3976345	1-HR	17
0.3979894	1-HR	18
0.4006505	1-HR	19
0.4062093	1-HR	20
0.4062685	1-HR	21
0.4066824	6-HR	22
0.4073921	6-HR	23
0.4077469	1-HR	24
0.4105263	1-HR	25.5
0.4105263	1-HR	25.5
0.4114134	1-HR	27
0.4127144	1-HR	28
0.4127735	1-HR	29
0.413424	1-HR	30
0.4136606	1-HR	31
0.415139	1-HR	32
0.4155529	6-HR	33
0.4160852	1-HR	34
0.4164991	1-HR	35
0.4166765	1-HR	36
0.4168539	1-HR	37
0.4224128	1-HR	38
0.4238321	1-HR	39
0.4244234	1-HR	40
0.425961	1-HR	41
0.4262567	1-HR	42
0.4269663	1-HR	43
0.4284447	1-HR	44
0.4297457	1-HR	45
0.4312833	1-HR	46
0.4316972	1-HR	47
0.43767	6-HR	48
0.4386162	6-HR	49
0.4446481	1-HR	50
0.4451212	1-HR	51
0.4463631	6-HR	52
0.4470136	6-HR	53
0.4520993	6-HR	54
0.4522176	6-HR	55
0.4551745	1-HR	56
0.4606742	1-HR	57
0.4646363	6-HR	58
0.464932	6-HR	59
0.465819	6-HR	60
0.4686576	6-HR	61
0.4695446	1-HR	62
0.4707274	1-HR	63
0.4762271	6-HR	64
0.4798936	6-HR	65
0.4803666	6-HR	66
0.4842105	6-HR	67
0.4920757	6-HR	68
0.4927262	6-HR	69
0.4965109	6-HR	70
0.499113	6-HR	71
0.5192194	6-HR	72

U for 1-HR	U for 6-HR
1382	1246
Total	Check
2628	2628
Count 1-HR	Count 6-HR
48	24
U1	946
U2	206

Table 39: Mann-Whitney U Test for #57 Granite, 1 and 24 Hour Dry Times

	1-HR	24-HR
Count	48	32
rank sum	1401	1839
U	1311	225

Mean	768
Variance	10368
Std dev	101.8
z-score	-5.3
p-value	0.0
sig	yes

1-HR	24-HR
0.39178	0.4168539
0.3756949	0.4400946
0.4312833	0.405204
0.4297457	0.4732111
0.4062685	0.4568303
0.3879361	0.4628622
0.4238321	0.4264341
0.4269663	0.4823182
0.4114134	0.42123
0.257126	0.4486694
0.3918983	0.4724423
0.3920166	0.4745121
0.4105263	0.4545831
0.4006505	0.4530455
0.4316972	0.4120639
0.4077469	0.4775872
0.3979894	0.4413365
0.4168539	0.4610881
0.3889415	0.3572442
0.3895328	0.4690716
0.4127144	0.4306328
0.3723241	0.4521585
0.425961	0.4070964
0.4262567	0.477942
0.381372	0.4657008
0.3976345	0.4599645
0.4284447	0.4863986
0.4166765	0.4919574
0.3826138	0.4832643
0.4136606	0.4724423
0.3792431	0.4709639
0.413424	0.5023655
0.4105263	
0.3010053	
0.4127735	
0.4160852	
0.4244234	
0.377942	
0.4606742	
0.4551745	
0.4164991	
0.4446481	
0.4062093	
0.4695446	
0.4707274	
0.415139	
0.4451212	
0.4224128	

Ranked Data		
0.257126	1-HR	1
0.3010053	1-HR	2
0.3572442	24-HR	3
0.3723241	1-HR	4
0.3756949	1-HR	5
0.377942	1-HR	6
0.3792431	1-HR	7
0.381372	1-HR	8
0.3826138	1-HR	9
0.3879361	1-HR	10
0.3889415	1-HR	11
0.3895328	1-HR	12
0.39178	1-HR	13
0.3918983	1-HR	14
0.3920166	1-HR	15
0.3976345	1-HR	16
0.3979894	1-HR	17
0.4006505	1-HR	18
0.405204	24-HR	19
0.4062093	1-HR	20
0.4062685	1-HR	21
0.4070964	24-HR	22
0.4077469	1-HR	23
0.4105263	1-HR	24.5
0.4105263	1-HR	24.5
0.4114134	1-HR	26
0.4120639	24-HR	27
0.4127144	1-HR	28
0.4127735	1-HR	29
0.413424	1-HR	30
0.4136606	1-HR	31
0.415139	1-HR	32
0.4160852	1-HR	33
0.4164991	1-HR	34
0.4166765	1-HR	35
0.4168539	24-HR	36
0.4168539	1-HR	37
0.42123	24-HR	38
0.4224128	1-HR	39
0.4238321	1-HR	40
0.4244234	1-HR	41
0.425961	1-HR	42
0.4262567	1-HR	43
0.4264341	24-HR	44
0.4269663	1-HR	45
0.4284447	1-HR	46
0.4297457	1-HR	47
0.4306328	24-HR	48
0.4312833	1-HR	49
0.4316972	1-HR	50
0.4400946	24-HR	51
0.4413365	24-HR	52
0.4446481	1-HR	53
0.4451212	1-HR	54
0.4486694	24-HR	55
0.4521585	24-HR	56
0.4530455	24-HR	57
0.4545831	24-HR	58
0.4551745	1-HR	59
0.4568303	24-HR	60
0.4599645	24-HR	61
0.4606742	1-HR	62
0.4610881	24-HR	63
0.4628622	24-HR	64
0.4657008	24-HR	65
0.4690716	24-HR	66
0.4695446	1-HR	67
0.4707274	1-HR	68
0.4709639	24-HR	69
0.4724423	24-HR	70.5
0.4724423	24-HR	70.5
0.4732111	24-HR	72
0.4745121	24-HR	73
0.4775872	24-HR	74
0.477942	24-HR	75
0.4823182	24-HR	76
0.4832643	24-HR	77
0.4863986	24-HR	78
0.4919574	24-HR	79
0.5023655	24-HR	80

U for 1-HR	U for 24-HR
1401	1839
Total	Check
3240	3240
Count 1-HR	Count 24-HR
48	32
U1	1311
U2	225

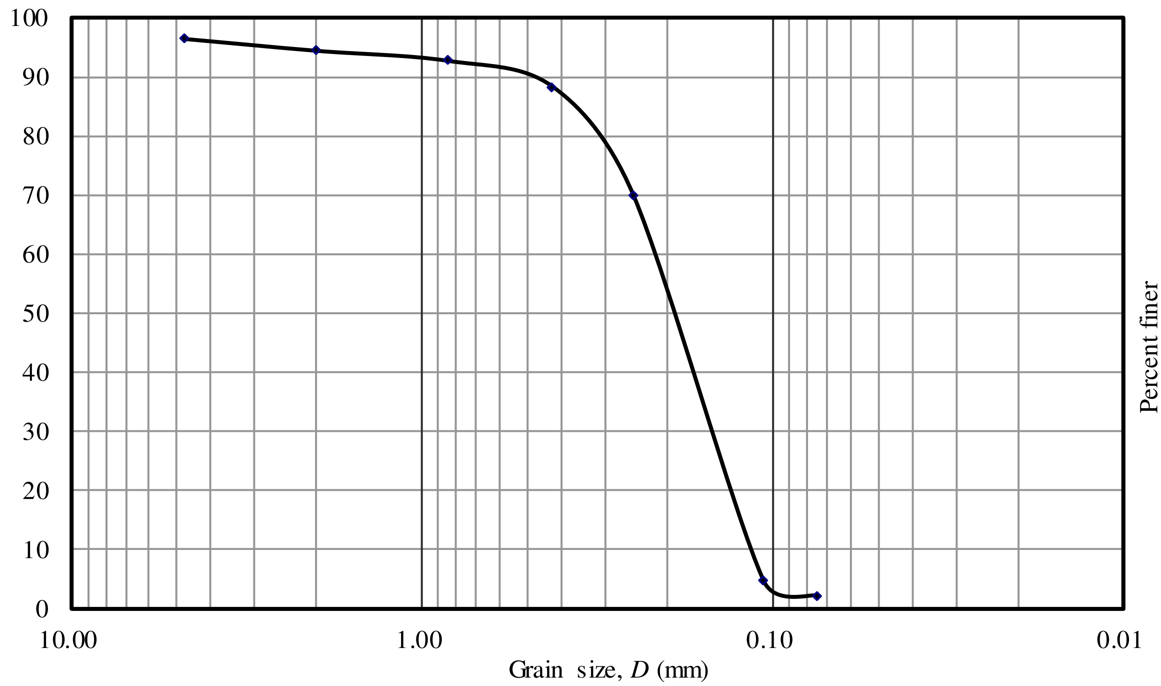
Description of soil	Poorly graded fine SAND (A3)			Sample No.	1
				Mass of oven dry sample, W	554.73 g

Sieve No.	Sieve opening (*mm*)	Mass of soil retained on each sieve, W_n (*g*)	Percent of mass retained on each sieve, R_n	Cumulative percent retained, $\sum R_n$	Percent finer, 100 - $\sum R_n$
4	4.750	20.1	3.6	3.6	96.4
10	2.000	11.1	2.0	5.6	94.4
20	0.850	9.3	1.7	7.3	92.7
40	0.425	24.2	4.4	11.6	88.4
60	0.250	101.5	18.3	29.9	70.1
140	0.106	362.7	65.4	95.3	4.7
200	0.075	13.4	2.4	97.7	2.3
Pan	--	11.7			

$W_1 = \sum$ 553.9 g

Mass loss during sieve analysis = $[(W - W_1) \div W] \times 100 =$ 0.15 % (OK if less than 2%)

Plot of percent finer vs. grain size (Sample: 1)



$D_{60} =$ 0.21
$D_{30} =$ 0.16
$D_{10} =$ 0.12

(Determined from graph, corresponding to percents finer of 60%, 30%, *and* 10%)

Uniformity coefficient, $C_u = (D_{60} / D_{10}) =$ **1.75**

Coefficient of gradation, $C_c = [D^2_{30} \div (D_{60} \times D_{10})] =$ **1.02**

Effective size of soil sample, $D_{10} =$ **0.12** ***mm***

AASHTO Classification System:- **A3 (Fine sand)**

Unified Classification System:- **SP (Poorly graded sand)**

Figure 21: Sieve Analysis Results for Clogging Sand

REFERENCES

ASTM C29/C29M. (2009). Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate. West Conshohocken, PA: ASTM International.

Burack, T., S., Walls, M., J., & Stewart, H. (2008). *New Hampshire Stormwater Manual*.

Chang, N.-B., Islam, K., Marimon, Z., & Wanielista, M. P. (2012). Assessing biological and chemical signatures related to nutrient removal by floating islands in stormwater mesocosms. *Chemosphere, 88*(6), 736-743.

Chang, N.-B., Rivera, B. J., & Wanielista, M. P. (2011). Optimal design for water conservation and energy savings using green roofs in a green building under mixed uncertainties. *Journal of Cleaner Production, 19*(11), 1180-1188.

Chopra, M., Wanielista, M., Kakuturu, S., Hardin, M., & Stuart, E. (2010). Evaluation of Pollution Levels Due to the Use of Consumer Fertilizers under Florida Conditions. Florida Department of Transportation.

Chopra, M., Wanielista, M., Spence, J., Ballock, C., & Offenberg, M. (2006). Hydraulic Performance of Pervious Concrete Pavements *2006 Concrete Technology Forum*: National Ready Mix Concrete Association.

Colandini, V., & Legret, M. (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), 111-117.

Das, B. M. (2011). *Principles of geotechnical engineering / Braja M. Das* (7th ed. ed.). Stamford, CT.: Cengage Learning.

Davis, A. P., Shokouhian, M., Sharma, H., Minami, C., & Winogradoff, D. (2003). Water Quality Improvement through Bioretention: Lead, Copper, & Zinc Removal. *Water Environment Research, 75*(1), 73 - 82.

Green Infrastructure Standards (2014).

Douglas, E., M., Jacobs, J., M., Sumner, D., M., & Ray, R., L. (2009). A Comparison of Models for Estimating Potential Evapotranspiration for Florida Land Cover Types. *Journal of Hydrology, 373*, 366-376.

Elliott, A., & Trowsdale, S. (2007). A review of models for low impact urban stormwater drainage. *Environmental Modelling & Software, 22*(3), 394-405.

Ellis, J. B. (2000). Infiltration Systems: A Sustainable Source-Control Option for Urban Stormwater Quality Management? *Water & Environment Management, 14*(1), 27 - 34.

Evans, B., M., Lehning, D., W., & Corradini, K., J. (2008). AVGWLF Version 7.1 Users Guide: Penn State Institutes of Energy and the Environment.

FLL. (2002). *Guideline for the Planning, Execution and Upkeep of Green-Roof Sites* (January 2002 Edition ed.): Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau E. V.

Gogo-Abite, I., Hardin, M., Chopra, M., Wanielista, M., & Stuart, E. (2014). In Situ Permeability Determination Device for Porous Pavement Systems. *Journal of irrigation and drainage engineering*.

Good, J. C. (1993). Roof Stormwater runoff as a Diffuse Source of Metals and Aquatic Toxicity in Storm Water. *Water Science Technology, 28*(No 3 - 5), 317 - 322.

Guo, Y., & Baetz, B., W. (2007). Sizing of Rainwater Storage Units for Green Building Applications. *Journal of Hydrologic Engineering, 12*(2), 197-205.

Hagan, G. (2012, September 14, 2012).

Hardin, M., D. (2006). *The Effectiveness of a Specifically Designed Green Roof Stormwater Treatment System Irrigated with Recycled Stormwater Runoff to Achieve Pollutant Removal and Stormwater Volume Reduction.* (Master of Science in Environmental Engineering), University of Central Florida.

Hardin, M., & Wanielista, M. (2007). Stormwater Effectiveness of an Operating Green Roof Stormwater Treatment System and Comparison to a Scaled Down Green Roof Stormwater Treatment System Chambers: Florida Department of Environmental Protection.

Hardin, M., Wanielista, M., & Chopra, M. (2012). A Mass Balance Model for Designing Green Roof Systems that Incorporate a Cistern for Re-Use. *Water, 4*(4), 914-931.

Harper, H. H., & Baker, D. (2007). *Evaluation of Current Stormwater Design Criteria within the State of Florida*. (SO108). Retrieved from http://www.dep.state.fl.us/water/nonpoint/docs/nonpoint/SW_TreatmentReportFinal_71907.pdf.

Haselbach, L., & Freeman, R. (2006). Vertical porosity distributions in pervious concrete pavement. *ACI Material Journal, 103*(6), 452-458.

Haselbach, L., & Freeman, R. (2006). Vertical porosity distributions in pervious concrete pavement. *ACI materials journal, 103*(6).

Haselbach, L., M., Valavala, S., & Montes, F. (2006). Permeability predictions for sand-clogged Portland cement pervious concrete pavement systems. *Journal of Environmental Management, 81*, 42 - 49. doi: 10.1016/j.jenvman.2005.09.019

Haselbach, L. M., Valavala, S., & Montes, F. (2006). Permeability predictions for sand-clogged Portland cement pervious concrete pavement systems. *J Environ Manage, 81*(1), 42-49. doi: 10.1016/j.jenvman.2005.09.019

Hilten, R., N., Lawrence, T., M, & Tollner, E., W. (2008). Modeling Stormwater Runoff from Green Roofs with HYDRUS-1D. *Journal of Hydrology, 358*, 288-293.

Hoffman, L. (2006, May 11 - 12). *The Earth Pledge Green Roof Stormwater Modeling System.* Paper presented at the Greening Rooftops for Sustainable Communities.

Hood, A., Chopra, M., & Wanielista, M. (2013). Assessment of Biosorption Activated Media under Roadside Swales for the Removal of Phosphorus from Stormwater. *Water, 5*(1), 53-66.

Hunt, B., & Moran, A. (2004, Feb). *Bioretention and Green Roof Field Research in North Carolina.* Paper presented at the 1st Annual Stormwater Management Research Symposium Proceedings, Orlando, FL.

Jones, M., P., & Hunt, W., F. (2010). Performance of rainwater harvesting systems in the southeastern United States. *Resources, Conservation and Recycling, 54*, 623-629.

Kelly, M., Hardin, M., & Wanielista, M. (2007). A Stormwater Management Evaluation of the 2007 New American Home Stormwater Treatment System and the Stormwater Academy Green Roof. Florida Department of Environmental Protection.

Kosareo, L., & Ries, R. (2007). Comparative environmental life cycle assessment of green roofs. *Building and Environment, 42*, 2606 - 2613.

Lee, J. G., Selvakumar, A., Alvi, K., Riverson, J., Zhen, J. X., Shoemaker, L., & Lai, F.-h. (2012). A watershed-scale design optimization model for stormwater best management practices. *Environmental Modelling & Software, 37*, 6-18.

Legret, M., Colandini, V., & Le Marc, C. (1996). Effects of porous pavement with reservoir structure on the quality of runoff water and soil. *Science of The Total Environment, 189-190*, 335-340.
Liaw, C.-H., & Tsai, Y.-L. (2004). Optimum Storage Volume of Rooftop Rain Water Harvesting Systems for Domestic Use. *Journal of the American Water Resources Association, 40*(4), 901-912.
Low Impact Development Center. (2005). Rain Garden Design Templates. Retrieved 6/11/2014, 2014, from http://www.lowimpactdevelopment.org/raingarden_design/whatisaraingarden.htm#PDFs
MacMillan, G. (2004). *York University Rooftop Garden Stormwater Quantity and Quality Performance Monitoring Report*. Paper presented at the Greening Rooftops for Sustainable Communities.
Martin, C., Ruperd, Y., & Legret, M. (2007). Urban Stormwater Drainage Management: The Development of a Multicriteria Decision Aid Approach for Best Management Practices. *European Journal of Operational Research, 181*, 338 - 349.
Meiarashi, S., Nakashiba, F., Niimi, H., Hasebe, M., & Nakatsuji, T. (1995). Quantitative comparison between noise reduction factors of drainage asphalt pavement. *Applied Acoustics, 44*(2), 165-179. doi: 10.1016/0003-682X(95)91371-9
Michigan Department of Environmental Quality. (1999). *Pollutants Controlled - Calculation and Documentation for Section 319 Watersheds Training Manual*. Retrieved from http://it.tetratech-ffx.com/steplweb/STEPLmain_files/Region%205%20manual05.pdf.
Miller, C. (2000). Use of Vegetated Roof Covers in Runoff Management. 2005, from http://www.roofmeadow.com/technical/publications/Runoff_Management_wit~0011.pdf
Miller, C. (2006). Mathematical Simulation Methods, A Foundation for Developing a General-Purpose Green Roof Simulation Model. 2006, from http://www.roofmeadow.com/technical/publications/Hydrologic_models2.pdf
Montes, F., Valaval, S., & Haselbach, L. M. (2005). A new test method for porosity measurements of Portland cement pervious concrete. *Journal of ASTM International, 2*(1), 12931-12944.
Moran, A., Hunt, B., & Jennings, G. (2004). *A North Carolina Field Study to Evaluate Greenroof Runoff Quantity, Runoff Quality, and Plant Growth*. Paper presented at the Greening Rooftops for Sustainable Communities.
New Hampshire Department of Environmental Services. (2010). *Guidance for Estimation Pre- and Post-Development Stormwater Pollutant Loads*. http://des.nh.gov/organization/commissioner/pip/publications/wd/documents/wd-10-11.pdf: New Hampshire Department of Environmental Services.
North Carolina Department of Environment and Natural Resources. (2011). *Jordan/Falls Lake Stormwater Load Accounting Tool (Version 1.0) User's Manual*. North Carolina Department of Environment and Natural Resources Retrieved from http://portal.ncdenr.org/c/document_library/get_file?uuid=c54894f6-4d95-43d3-bdc5-c1c694253b24&groupId=38364.
O'Reilly, A. M., Wanielista, M. P., Chang, N.-B., Xuan, Z., & Harris, W. G. (2012). Nutrient removal using biosorption activated media: Preliminary biogeochemical assessment of an innovative stormwater infiltration basin. *Science of the Total Environment, 432*, 227-242.

Palmstrom, N., & Walker, W. (1990). The P8 urban catchment model for evaluating nonpoint source controls at the local level. *Enhancing States' Lake Management Programs, US EPA*.
Park, C. S. (2002). *Contemporary Engineering Econonics* (3rd ed.): Prentice-Hall, Inc.
Pomeroy, C. A., & Rowney, A. C. (2013). User's Guide to the BMP SELECT Model Version 2.0: Water Environment Research Foundation.
Saiz, S., Kennedy, C., Bass, B., & Pressnail, K. (2006). Comparative life cycle assessment of standard and green roofs. *Environmental Science & Technology, 40*(13), 4312 – 4316.
Sample, D., J., Heaney, J., P., Wright, L., T., Fan, C., Lai, F., & Field, R. (2003). Costs of Best Management Practives and Associated Land for Urban Stormwater Control. *Journal of Water Resources Planning and Management, 129*, 59 - 68.
Sansalone, J., Kuang, X., & Ranieri, V. (2008). Permeable pavement as a hydraulic and filtration interface for urban drainage. *Journal of irrigation and drainage engineering, 134*(5), 666-674.
Sansalone, J., Kuang, X., Ying, G., & Ranieri, V. (2012). Filtration and clogging of permeable pavement loaded by urban drainage. *Water research, 46*(20), 6763-6774.
Sansalone, J. J., & Buchberger, S. G. (1995). An infiltration device as a best management practice for immobilizing heavy metals in urban highway runoff. *Water Science and Technology, 32*(1), 119-125.
Schlüter, W., & Jefferies, C. (2002). Modelling the outflow from a porous pavement. *Urban Water, 4*(3), 245-253. doi: 10.1016/S1462-0758(01)00065-6
Scholz, M., & Grabowiecki, P. (2007). Review of permeable pavement systems. *Building and Environment, 42*(11), 3830-3836.
Seters, T., V., Grahm, C., Rocha, L., Uda, M., & Kennedy, C. (2013). Assessment of Life Cycle Costs for Low Impact Development Stormwater Management Practices: Toronto and Region Conservation Authority.
Shaver, E., Horner, R., Skupien, J., May, C., & Ridley, G. (2007). Fundamentals of Urban Runoff Management: Technical and Institutional Issues. *Lake County Water Authority*. http://www.lake.wateratlas.usf.edu/upload/documents/Fundamentals%20of%20Urban%20Runoff%20Management%20Technical%20and%20Institutional%20Issues.pdf
Sonne, J. (2006). Evaluating green roof energy performance. *ASHRAE Journal, 48*.
Teemusk, A., & Mander, U. (2009). Greenroof potential to reduce temperature fluctuations of a roof membrane: A case study from Estonia. *Building and Environment, 44*, 643 – 650.
Tennis, P. D., Leming, M. L., & Akers, D. J. (2004). *Pervious concrete pavements* PCA Serial No. 2828, (pp. 32). Retrieved from https://www.dnr.state.sc.us/marine/NERR/pdf/PerviousConcrete_pavements.pdf
Tetra Tech. (2010). Macomb County Site Evaluation Tool - User's Manual and Guidance. from http://www.macombgov.org/PUBLICWORKS/documents/MacombCountySETUserManualandGuidanceDec2010.pdf
Tetra Tech. (2011). *User's Guide: Spreadsheet Tool for the Estimation of Pollutant Load (STEPL) Version 4.1*. U.S. Environmental Protection Agency Retrieved from http://it.tetratech-ffx.com/steplweb/STEPLmain_files/STEPLGuide401.pdf.
Tsihrintzis, V. A., & Hamid, R. (1997). Modeling and management of urban stormwater runoff quality: a review. *Water Resources Management, 11*(2), 136-164.
Underground, W. (2012). Retrieved September, 2012, from http://www.wunderground.com/history/

Urban Drainage and Flood Control District. (2010). *Urban Storm Drainage Criteria Manual Volume 3 - Best Management Practices*. Denver, Colorado: Water Resources Publications, LLC Retrieved from http://www.udfcd.org/downloads/pdf/critmanual/Volume%203%20PDFs/USDCM%20Volume%203.pdf.

USEPA. (1994). *The quality of our nation's water*. Washington, D.C.: United States Environmental Proctection Agency.

USEPA. (2008). *TMDLs to Stormwater Permits Handbook (Draft)*. Retrieved from http://water.epa.gov/lawsregs/lawsguidance/cwa/tmdl/stormwater_index.cfm.

USEPA. (2009). *Effluent Limitations Guidelines and Standards for the Construction and Development Point Source Category*. (40 CFR Part 450). Environmental Protection Agency Retrieved from http://www.gpo.gov/fdsys/pkg/FR-2009-12-01/pdf/E9-28446.pdf.

Vaze, J., & Chiew, F. H. S. (2004). Nutrient Loads Associated with Different Sediment Sizes in Urban Stormwater & Surface Pollutants. *Journal of Environmental Engineering, 130*(4), 391 - 396.

Virginia Department of Conservation and Recreation. (2011). *Virginia Runoff Reduction Method Instructions & Documentation*. Virginia Department of Conservation and Recreation Retrieved from http://leg5.state.va.us/reg_agent/frmView.aspx?Viewid=13631000587~1&typ=40&actno=000587&mime=application/pdf.

Walker, W. (1990). P8 Urban Catchment Model Program Documentation.

Wanielista, M., & Hardin, M. (2006). *A Stormwater Management Assessment of Green Roofs with Irrigation*. Paper presented at the 2nd Biennal Stormwater Management Research Symposium, Orlando, FL.

Wanielista, M., & Hardin, M. (2011). A Comparative Analysis of Greenroof Depth as it Affects Retention of Rainfall. Florida Department of Environmental Protection.

Wanielista, M., Kelly, M., & Hardin, M. (2008). A Comparative Analysis of Greenroof Designs Including Depth of Media, Drainage Layer Materials, and Pollution Control Media. Florida Department of Environmental Protection.

Wanielista, M., Kersten, R., & Eaglin, R. (1997). *Hydrology: Water Quantity and Quality Control*. New York: John Wiley & Sons, Inc.

Wanielista, M. P. (1990). *Hydrology and water quantity control*.

Wanielista, M. P., Yousef, A. Y., Harper, G. M., & Dansereau, L. (1991). *Design Curves for the Reuse of Stormwater*. Florida Department of Environmental Regulation Retrieved from http://www.stormwater.ucf.edu/research/FILES/Wanielista%20-%20design%20curves%20for%20the%20reuse%20of%20stormwater.pdf.

Wanielista, M. P., & Yousef, Y. A. (1993). *Stormwater management*: John Wiley & Sons.

Weiss, P., T., Gulliver, J., S., & Erickson, A., J. (2005). The Cost and Effectiveness of Stormwater Management Practices. Minnesota Department of Transportation.