Implementation of a non-parametric rainfall simulation method to size rainwater harvesting systems for stormwater management and irrigation of urban agricultural facilities

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Dedications

I would like to dedicate this in loving memory of my grandmother Mahalakshmi Narsimhamoorthy. She was a great person and has taught me invaluable lessons that will continue to add value to my life. I would also like to dedicate this to my parents, R. Shyam Sunder and Gandhini Shyam who has been always there for me, supporting me every step of my life with their unconditional support and also my brother Rahul Sunder who has shown me the path towards light during my entire life and taught me to live life to the fullest.

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Abstract

Implementation of a non-parametric rainfall simulation method to size rainwater harvesting systems for stormwater management and irrigation of urban agricultural facilities

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Combined Sewer Overflows (CSOs) are one of the biggest problems associated with stormwater runoff in Philadelphia. Rainwater harvesting (RWH) for the purpose of storage and non-potable reuse is one of several highly advocated solutions for reduction of stormwater runoff especially in urban areas. Various RWH systems have been designed based on simple supply vs. demand water balance concepts and somewhat more complex parametric rainfall simulation methods.

This project involves the use of a non-parametric rainfall simulation method incorporated in the Storage and Reliability Estimation Tool (SARET) developed by Basinger, Montalto, & Lall (2010) to size a RWH system collecting stormwater runoff from residential roofs at an urban agricultural facility situated at 53rd and Wyalusing Avenue, Philadelphia. Two methods were used to obtain the irrigation requirements for the urban agricultural facility, one uses the Blaney-Criddle method (Blaney & Criddle, 1950) while the second uses water consumption bills obtained at the site. SARET then uses historical daily precipitation data for Philadelphia to develop storage vs. catchment area reliability curves based on which the desired volume of the storage facility as well as the catchment area are chosen. During the design phase, a bioretention facility was preferred as a treatment facility to improve the water quality of runoff collected from the roofs before application to the crops. Analyzing various options, StormChamber® developed by Hydrologic Solutions was chosen as a underground water storage facility. The specifications and construction plans for the

bioretention facility, storage facility and other aspects of the system were then laid out to enable the final construction.

Once the construction was complete, a preliminary assessment was performed by estimating the depth vs. volume relationship of the storage facility and conducting a statistical test on the observed data, based on which it was concluded tentatively that the system was working as designed. A more in depth analysis, based on a longer observation period is, however, required for a more conclusive assessment. Finally, a GIS analysis was performed using planimetrics data in ArcGIS 10.1 that looks at other residential sites within Philadelphia where a similar system can be replicated consisting of both the RWH system as well as the agricultural facility.

CHAPTER 1: INTRODUCTION

1.1 Combined Sewer Systems

Stormwater runoff is an integral part of the hydrologic cycle; its volume is determined on the size of the storm as well as the land cover characteristics (MA Department of Environmental Protection, MA Office of Coastal Zone Management, 1997). Properties of the surface such as size of the drainage area, the slope as well as the type of land affect both the quantity and quality of runoff. Urbanization has resulted in an increase in impervious area (rooftops, roads and parking lots), reducing the amount of precipitation that can infiltrate and simultaneously increasing runoff. It was observed that a development that contains 10-20% paved surfaces would result in an increase in runoff volume by 10% when compared to natural ground cover, while in the case of 75-100% paved surfaces, an increase of 45% in runoff volume was observed (Minnesota Pollution Control Agency, 1989). In addition to quantity, water quality (WQ) is also affected by urbanization. Since impervious areas reduce the opportunity to treat water by natural processes, various pollutants such as lead, copper, hydrocarbons and other organics contaminate stormwater runoff from residential, commercial and industrial areas (Massachussets Department of Environmental Protection, 1989). Therefore, runoff must be controlled and treated to reduce pollutants before it is discharged to water bodies.

Many old cities in the United States especially in the Northeast employ the combined sewer system that consist of a single collection system that conveys both sanitary sewage and stormwater to municipal wastewater treatment plants where the combined effluent is discharged to receiving water bodies. When flow within the collection system exceeds the system capacity, direct discharges of untreated combined flows to receiving water bodies occur, events known as Combined Sewer

Overflows (CSOs). CSOs are relatively common since they take place even due to small (<30 mm) storms (Novotny & Olem, 1994). Though, water quality (WQ) has improved through the containment of point source pollution since the Clean Water Act of 1970, Non-Point Source (NPS) pollution, including stormwater runoff especially in urban areas, remains a major WQ problem. To reduce the WQ impacts of stormwater runoff, EPA expanded the Clean Water Act in 1987 to require municipalities to obtain permits for discharging stormwater runoff (Center for Watershed Protection, 2011). Based on this new legislation, EPA advocated the release of the Stormwater Best Management Practices (BMP) manual for many states (EPA, 2012), a method to reduce the adverse impacts of development that are defined in each states stormwater manual. For example the Pennsylvania Stormwater Best Management Practices (BMP) manual addresses two basic issues using a stormwater management approach to the land development process: first to prevent or minimize stormwater runoff through planning, and secondly to employ various structural and non-structural BMPs to mitigate any potential problems (Pennsylvania Department of Enironmental Protection, 2006).

One recommended approach for the abatement of CSOs is the use of Low Impact Development (LID) including Green Infrastructure (GI) such as bioretention facilities and bioswales that have gained increasing importance as an alternative to stormwater design in the recent decade (Dietz, 2007). One of the oldest stormwater management practices is rainwater harvesting that refers to the collection and reuse of rainfall for potable and non-potable purposes. This practice is also listed as one of the acceptable stormwater BMPs in Pennsylvania (Pennsylvania Department of Enironmental Protection, 2006), and is being employed as an efficient method of stormwater management especially in densely populated urban settings on both large-scale projects employed in industrial areas and small-scale single-family projects employed at residential areas.

In urban areas impervious surfaces such as rooftops and pavements are a major source of the pollutant loads associated with stormwater runoff, though pollutant concentrations originating on trafficked areas (particularly roads) are much higher than those originating on residential roofs (Grottker, 1987). For this reason, stormwater runoff originating on residential rooftops requires simpler treatment than would be required of runoff originating from trafficked areas such as streets (EPA, 1999).

1.2 Stormwater Management in the City of Philadelphia

Like many other cities in the country, the collection system in the City of Philadelphia is 60% combined (Madden, 2010) and is plagued by the same stormwater problems faced by many other cities. During dry weather conditions and during very small storm events, combined sewers are efficient in conveying combined flows to one of the city’s three Water Pollution Control Plants (WPCP); under heavier rainfall conditions, the flow in these combined sewers may exceed the capacity of the sewer system or the treatment facility, resulting in CSOs wherein some portion of the wastewater and stormwater may be diverted directly to nearby rivers (Schuylkill and Delaware) to avoid flooding of residential buildings and streets. These CSOs may occur at any of the 164 permitted combined sewer outfalls situated within the city (Philadelphia Water Department, 2008).

On September 1, 2009, the Philadelphia Water Department (PWD) submitted the Combined Sewer Overflow Long Term Control Plan Update (LTCPU) to the EPA that illustrated how PWD would invest $1.6 billion over 20 years to develop a citywide network of GIs in order to address and mitigate the problem of CSOs

(Madden, 2010). In order to evaluate and justify such an approach, PWD performed comprehensive analysis on a number of implementation approaches such as complete sewer preparation, treatment plant expansion and GIs. It was observed that the GI approach was the best alternative primarily based on its effectiveness to handle CSOs in a cost effective manner (Philadelphia Water Department , 2009).

In 2008, through a joint venture between the Temple-Villanova Sustainable Stormwater Initiative (T-VSSI) and PWD, a regional BMP database was developed as an online resource of stormwater BMPs implemented in Southeastern Pennsylvania. This database groups BMPs into various categories such as Bioretention/Bioretention facilities, catch basins and rain barrels to name a few, that had been implemented through various regional projects (T-VSSI, PWD, 2006). Bioretention facilities (also referred to as rain gardens) seem to be one of the most popular BMP to be implemented at various locations in the region with each differing in sizing and inlet specifications to address the problem of runoff overflow at these sites. Green roofs and rain barrels are also popular at residential and commercial locations (T-VSSI, PWD, 2006). Through various analysis and case studies, these projects showcased that through proper design and implementation, BMPs can be utilized towards abatement of CSOs as well as provide various other direct benefits to the community.

1.3 Urban Agriculture and their role in Stormwater Management

Since its conception through various community garden programs, the practice of subdividing urban land into plots for individuals to garden for food appears simple, but actually carries many urban planning challenges. These programs have been encouraged throughout the last century to provide spaces for individuals and families to garden for food and to use for recreation (Lawson, 2004). Community gardens and urban farming projects in Philadelphia date back to as early as 1897, when the

Philadelphia Vacant Lot Cultivation Association divided 56th & Haverford into various plots to make gardening space affordable in the city to address the problems of unemployment. Although in existence since the 1900's, urban agriculture in the form of community gardens only really took off in the 1970's, triggered by the effects of deindustrialization on both availability of jobs, as well as the population density of neighborhoods. Since then various locations across the city have seen an explosion of urban farming. By the 1990s, more than 1000 such vacant plots had been converted to for-profit community gardens for the purpose of urban farming. (Goldstein, 1997). By then it was acknowledged that community gardens were not only a source of food but also a strategy for neighborhood development. Since community gardens are pervious, one of their major contributions towards neighborhood development is towards stormwater runoff reduction and groundwater recharge (Levy, 2009). It was not until recently that community gardens were analyzed in order to properly understand their role in urban stormwater management in the City of Philadelphia through which it was found that they are a viable means for promoting the decentralization of stormwater management in the city (Levy, 2009).

1.4 Rainwater Harvesting

A Rainwater Harvesting (RWH) system is essentially a rainwater capture and reuse systems that can be implemented for various purposes such as stormwater reuse and for stormwater runoff reduction. Some rainfall reuse systems employ the use of rain barrels and cisterns for the purpose of storage and reuse at a later time (T-VSSI, PWD, 2006). For instance since 1980, Germany has seen an explosion of RWH systems mostly in single-family houses primarily reusing stormwater for the purpose of toilet flushing, gardening and other non-potable purposes (Nolde, 2006). Rainwater harvesting systems have been widely used in community gardens such as those in

New York City that have collected an estimate of around a million gallons of rainwater from nearby roofs thus making water collection convenient and reducing demand on the public water system (Grow NYC, 2011). Community gardens, although popular in Philadelphia, have not been quick and efficient in employing a RWH system to capture rainwater. Programs such as the Philadelphia Green's Garden Tenders have been assisting various community gardens such as Warrington by proving materials such as rain barrels to collect rainwater (PHS, 2011). With impervious surfaces such as rooftops occupying a large proportion of the city's landscape, rainwater harvesting for irrigation purposes offer substantial incentives. However, water quality concerns associated with the pollutants in roof runoff must be addressed through onsite treatment facilities before non-potable reuse of rainwater can be practiced (Nicholson, Clark, Long, Spicher, & Steele, 2009).

1.5 RWH system sizing

The basic rule for sizing any RWH system is that the potential volume of water that can be captured (the supply) must equal or exceed the volume of water used (Texas Water Development Board, 2005). A very simple method for sizing the system employs a water-balance method that compares monthly demand and supply using average monthly precipitation amounts. This is one of the simplest approaches to system design since it only considers annual variability in precipitation amounts, thus establishing an easy to understand catchment vs. storage relationship (Gould & Nissen-Petersen, 1999). The major drawback of this method, however, is that the relationship is not based on the actual distribution of precipitation amounts during the month and hence a user could incorrectly conclude that a storage to reliability information would hold true for two different locations that have similar annual precipitation amounts but different monthly or daily precipitation patterns.

Another sizing method employs historical precipitation data but this method may not be robust since it considers only one historical period when in fact various precipitation combinations are possible (Basinger, Montalto, & Lall, 2010). Furthermore, inaccurate system reliability may be estimated if the useful life of the RWH system is greater than that of the historical period of precipitation observation used in the design of the system (Taulis & Milke, 2005).

Some more sophisticated RWH system sizing methods employ probability distribution theory and longer historical precipitation records. Although they are analytically robust, they are virtually impossible to be adopted at various locations since the statistical characteristic of the precipitation record is hardwired into the results (Lee, Lee, Yang, & Yu, 2000). Other RWH systems have been sized based on the use of stochastic precipitation generators, though their application at different locations is contingent on the ability of the rainfall generation algorithm to produce statistical ensembles to match observations of interest. Thus, for such an approach to be useful, these models must be computationally robust, relatively easy to understand and exercise ease of implementation (Basinger, Montalto, & Lall, 2010).

Stochastic precipitation generators can be further categorized into parametric and non-parametric. Similar to the probabilistic approach, parametric approaches require specific statistical relationships be used to describe the precipitation records of interest. On the other hand, non-parametric models can be used as stochastic precipitation generators that do not have rigid adherence to any statistical form of precipitation thus making them more portable then their counterpart (Basinger, Montalto, & Lall, 2010). The core of non-parametric models consists of the use of Probability Distribution Functions (PDFs) to describe rainfall occurrence (dry and wet spells) that are derived directly from local observations. Synthetic time series ensembles can be created as a sequence of wet and dry spell states with precipitation amounts resampled with replacement from historical record using the K nearest neighbors in state space, making the process equivalent to a non-parametric approximation of a multivariate first order Markov process. This method produces random sequences of daily precipitation that adhere to the statistical property of the historical data (Lall, Rajagopalan, & Tarboton, 1996). Seasonal variations can also be directly considered by developing a future state (wet or dry) based on the previous time step using a moving window or nearest neighbor approach (Lall & Sharma, 1996) (Lall, Rajagopalan, & Tarboton, 1996). Conditional probabilities can be also computed and used with exogenous datasets such as sea surface temperatures to further refine realization based on other climatic conditions (Cowden, Watkins, & Mihelcic, 2008). Non-parametric models have also been implemented for other purposes in the field of hydrology such as the synthesis of monthly stream flow (Sharma, Tarboton, & Lall, 1997).

Although, non-parametric models have seen a growing widespread use as stochastic precipitation generators, the only application of non-parametric precipitation simulations methods to RWH system sizing found in literature was in estimating the reliability with which domestic RWH systems without storage tanks could yield at least 20 liters per capita per day in cities of West Africa (Cowden, Watkins, & Mihelcic, 2008).

1.6 Project Summary

The site at the 53rd street block of Wyalusing Avenue, Philadelphia is the location of an urban agricultural facility founded by the members of Urban Tree Connection (UTC), a grass-roots community development organization. Over the last 10 years, UTC has developed various urban agriculture sites around the Haddington neighborhood in which vacant lots are converted into various types of parks and gardens (UTC; NF, 2012).

The urban agricultural facility consists of a total area of 853 square meters of growing area space. Due to the farm's need for a consistent water supply and the cost that would be associated with acquiring this from the municipal water system, a RWH harvesting system was proposed for the site to store runoff from residential roofs located within the block that would be available for irrigation. The entire project roughly consisted a period of two years that includes various aspects of the project such as the design, construction and field monitoring to analyze the performance of the system. This in turn forms the crux of the thesis.

The thesis is divided into several sections to describe various aspects of the design as well as the construction of the system. Chapter 2 summarizes the RWH system design process including the use of a non-parametric rainfall simulation model to size the storage facility and the design of a bioretention facility that acts as a bio-filtration pre-treatment device for the roof runoff. Chapter 3 addresses the construction of the RWH system and discusses the changes that were made to the design due to constraints encountered at the site during construction. To analyze the performance of the system, field monitoring was performed on the RWH system, details and analysis of which are provided in Chapter 4. In Chapter 5, a GIS analysis is performed based on planimetric data in an attempt to identify other sites within the municipal boundary of Philadelphia where a similar system could be constructed. As an addendum, various abbreviations and nomenclatures used throughout the text are listed in Appendix A.

CHAPTER 2: DESIGNING THE RAIN WATER HARVESTING SYSTEM

2.1 Introduction

The RWH system designed at the project site harvests roof runoff that is directed via gravity to an underground storage facility, passing through a bioretention facility (also referred as a rain garden) for treatment along the way. A non-submersible pump connected to the drip irrigation system distributes this water throughout the urban agriculture facility. The site that includes the area that became the agricultural space and the roof catchment area is shown in Figure 1.

Figure 1. Google Satellite roof imagery depicting the rooftop catchments in blue and the urban agricultural facility in green (Google, 2010)

The total roof catchment area was estimated be 850 – 1020 square meters (10-12 roofs), depending on property owner willingness to participate, while the area of the irrigation facility was estimated to be 853 square meters (Figure 2). In addition to irrigation demand and residential roof area constraints, several other design considerations were needed to be satisfied. Decisions such as connecting the RWH system to the closest roofs (to minimize the length of pipe that needed to be purchased) were made throughout the design process in order to maintain the projects limited budget. This chapter elaborates methods employed to estimate the volume of the storage facility and to design the bioretention facility.

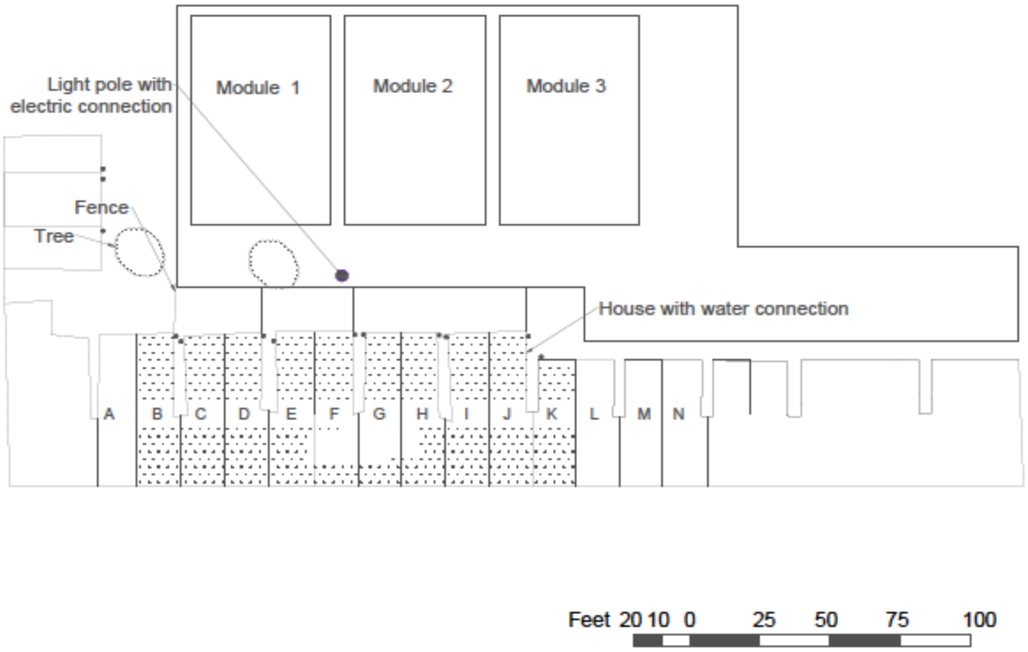


Figure 2. Site Layout at 53rd and Wyalusing Avenue

In order to design the RWH system, the Storage and Reliability Estimation Tool (SARET) is employed. SARET provides an alternative approach to the simplistic RWH system methods previously described (Basinger, Montalto, & Lall, 2010). SARET first sizes the RWH system using a fully non-parametric precipitation generator and then estimates the reliability with which the system can meet various non-portable urban water demands. The precipitation generator works on the basis of bootstrapping user specified historical precipitation values using Markov chain transition probabilities that are derived from the local rainfall observations.

2.2 Non-parametric rainfall simulation model

As previously stated, unlike their parametric counterparts, non-parametric models do not exhibit rigid adherence to any assumed statistical characteristics of precipitation. One of the major strengths of these models is that different sets of historical observations can be used without violating any of the model assumptions. This allows the model to be portable and be used with precipitation data for different climatological regions (Basinger, Montalto, & Lall, 2010). Though true, this was not relevant here since no other city other than Philadelphia was considered during the entire analysis. The non-parametric model utilized in SARET generates precipitation occurrence probabilities and amounts from a user-specified historical record of daily observation, in this case Philadelphia daily precipitation (1964-1995). Figure 3 shows the 32-year rainfall record obtained from the Philadelphia International Airport (PHL) that was used in this analysis. The average annual precipitation over this period was observed to be 1003 mm, with the annual totals as low as 717 mm and as high as 1311 mm.

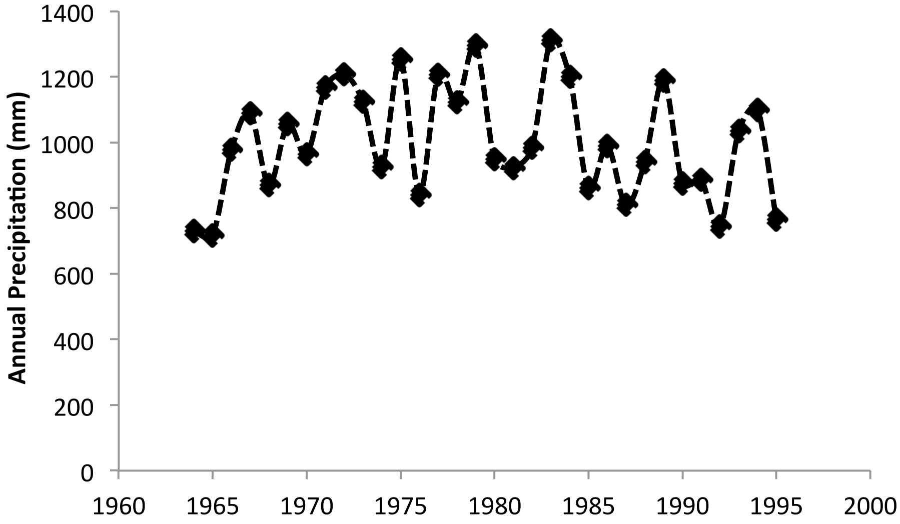


Figure 3. Annual precipitation for the City of Philadelphia (PHL) 1964-1995.

The model then categorizes each day within the historical day as either “wet” (W) or “dry ” (D) (“wet” being a positive precipitation value and “dry” being a value of zero). A detailed description of the non-parametric model employed in SARET (Basinger, Montalto, & Lall, 2010) is shown in Appendix B. Once these flags were assigned to all days in the historical record (Appendix B), the model creates synthetic precipitation sequences by sampling with replacement from the actual historical daily precipitation amounts using the array of daily historical precipitation amounts corresponding to that particular day (within the “moving window” that consists a total of 30 days that is centered on the target day). It was observed that this method of choosing values from within a “moving window” rather than randomly choosing values from the entire range of historical observations results in a more accurate depiction of seasonality (Basinger, Montalto, & Lall, 2010). Since the Storage and Reliability Estimation Tool (SARET) was developed to process only 25 years daily precipitation data (reprograming the model to accommodate 32 years daily precipitation data (1964-1995) was beyond the scope of this thesis), only historical precipitation sequence for the period 1964-1988 was considered for the analysis. By comparing the box and whisker plots for the synthesized rainfall time series using the non-parametric model in SARET to that of the historical daily precipitation series for Philadelphia (1964-1988), it was observed that the median and the extreme values match the historical data consistently (Figure 4).

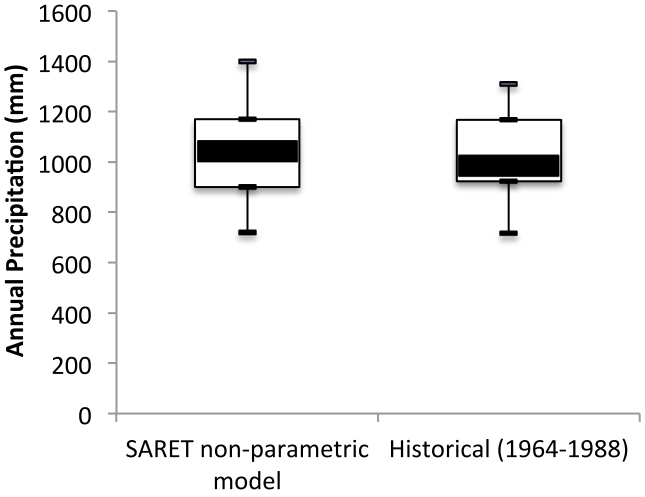


Figure 4. Box and Whisker plot comparing the SARET non-parametric model and the Historical observations for Philadelphia (1964-1988)

To better understand the robust nature of the non-parametric model employed in SARET and in an attempt to verify the synthetic precipitation sequences generated by SARET, a separate analysis was performed using a customized model developed in MATLAB that employs the Hidden Markov Model (HMM) Tool developed by The International Research Institute for Climate and Society (IRICS, Columbia University, 2007).

The HMM tool with its Graphic User Interface (GUI) implementation is a program developed in MATLAB that provides a framework for modeling daily precipitation occurrences by fitting a model to observed rainfall records realized through the introduction of a small number of discrete rainfall states. These states allow a diagnostic interpretation of observed daily rainfall variability in terms of few rainfall patterns, though these are not directly observable and are hidden from the observer. The time sequence of which state is active follows a first order Markov chain wherein the state active “today” depends only on the state that was active “yesterday”. The HMM tool has the capability to perform three different operations: the first estimates the model parameters (“learn”), the second estimate the most likely state sequence (“viterbi”) while the third generates rainfall simulations (“simulate”). Since we use the output of the HMM tool as an input to the customized model created in MATLAB, the “learn” action is selected in order to estimate the rainfall probability and mean rainfall amount on “wet” days (IRICS, Columbia University, 2007). The HMM tool can thus be used to synthesize various rainfall sequences based on the observed data.

For this purpose, daily precipitation for 25 years (1964-1988) for the month of January was used to synthesize precipitation sequences using the HMM tool and the customized model in MATLAB. The precipitation data for the month of January is used as the input data, and using the “learn” action, the HMM tool provides the transition probability matrix. In this case, we select only two hidden states; state 1 is the dry state while state 2 is the wet state each of which is defined similarly to that in SARET. The length of the sequence is 775 days (31 days for a period of 25 years). Once the transition probability matrix is obtained, the program developed in MATLAB (Appendix C) is employed that uses the probability matrix to synthesize precipitation sequences (Appendix B). The programs core is based on bootstrapping that is similar to the one implemented in SARET. Using the transition probability matrix, ten such precipitation sequences are synthesized. Compared to the model in SARET, the program is a much simpler non-parametric method since it does not employ the complicated "moving-window" method as described previously instead based on the transition probability matrix, the program decides whether the subsequent day is a "wet" or a "dry" day. If it's a "wet" day then the value is bootstrapped from the sequence of state 2 ("wet" state) values from the historic observation and for a "dry" day the value is set as zero. This is repeated for each day throughout the month and the whole process is performed to synthesize five precipitation sequences each for the month of January for the entire 25-year period.

The two methods are compared with the historic precipitation sequence for the month of January using a box and whisker plot as shown in Figure 5. It is evident that the non-parametric methods (SARET and customized model) are similar in their total precipitation values for the month of January for the period 1964-1988 and also adheres to the statistical properties of the historical observations. Furthermore, since SARET uses the "moving-window" method that encapsulates the seasonality of the historic precipitation sequence, it is used more effectively to generate annual precipitation sequences as seen in the previous section.

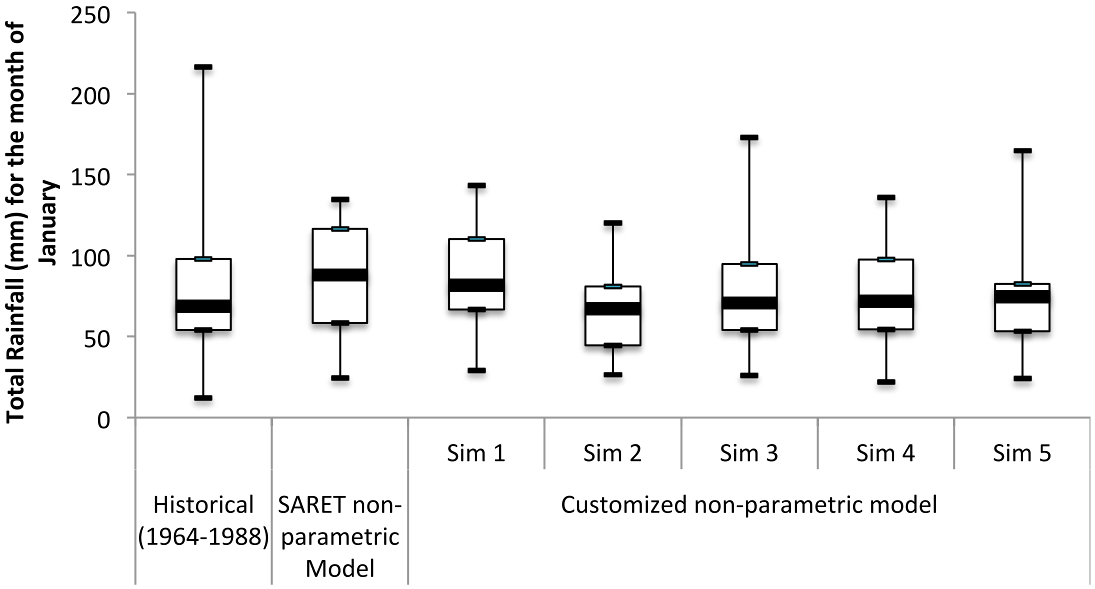


Figure 5. Box and Whisker plot comparing the SARET non-parametric model, the customized non-parametric model (sequence 1-5) and the Historical observations for Philadelphia (1964-1988)

Therefore, it was confirmed that SARET was able to generate precipitation sequences that adhere to the statistical property of the historical observations which leads us to the following step where SARET is employed in sizing the storage facility of the RWH system. Before implementing SARET though, the irrigation demand of the agricultural facility, a required input for the model was estimated that is illustrated in the following section.

2.3 Estimation of irrigation demand

The current growing year 2011-12 has seen an increase in the growing area from that of 2010-11. According to the data obtained at the site, the old growing area (2010-11) was estimated to be 390 square meters while the new growing area (2011-12) was estimated to be 853 square meters. Due to an increase in the area, irrigation demand calculations were first based on the old growing area and then those of the new growing area were estimated. We used two different approaches to determine the amount of water needed per week for irrigation of the crops. The first method employed water bills obtained from the property owners at the site to estimate irrigation usage during 2010-11 the growing season. The second method uses the Blaney-Criddle method to directly estimate the water consumption by specific crops grown at the site to derive supplemental irrigation needs. These two methods are described in detail below.

2.3.1 Water Bills to determine irrigation usage

For the first method, the water bills from the previous growing season (2010-11) were used to determine how much water was actually used to irrigate the crops. An average domestic consumption amount of sixty gallons (0.26 cubic meters) per capita per day was subtracted from the total billed usage to derive the estimated irrigation usage. The domestic consumption amount was dependent on the number of days in each month (Table 1). Next, the ratio of the new growing area to the old growing area (2.19) was calculated. This ratio was multiplied to the 2010-11 monthly irrigation usages to obtain the theoretical irrigation demand for 2011-12. Table 1 shows the four growing months: June, July, August and September that were used to calculate the irrigation demand. Once the irrigation demand for the new growing area for each of the four growing months was estimated, the amount of irrigation per week for each month was estimated by assuming that the irrigation requirements for each week of the month remained constant.

Table 1. Irrigation usages calculated from water bills

Month	**Total Usage (cubic meters)**	**Homeowner usage (cubic meters)**	**Irrigation Usage (Cubic meters)**	**New Usage (cubic meters)**	**New Usage (mm/wk)**
June	48.14	20.45	27.7	60.57	17.8
July	116.1	21.12	94.97	207.70	60.9
August	62.3	21.12	41.17	90.04	26.4
September	53.8	20.45	33.35	72.94	21.4

It was suggested that the growing season for the year 2011-12 in addition to these four months would include the months April, May and October, a total of 7 months. Due to insufficient data to estimate irrigation requirements for these months at the site, it was assumed that April and May would have the same irrigation requirements as that of June while October would have the same as that of September. Figure 6 provides the irrigation requirements for the entire growing season including the additional three months. Based on these calculations, it appears that the maximum irrigation demand occurs during the month of July (60.9 mm/week).

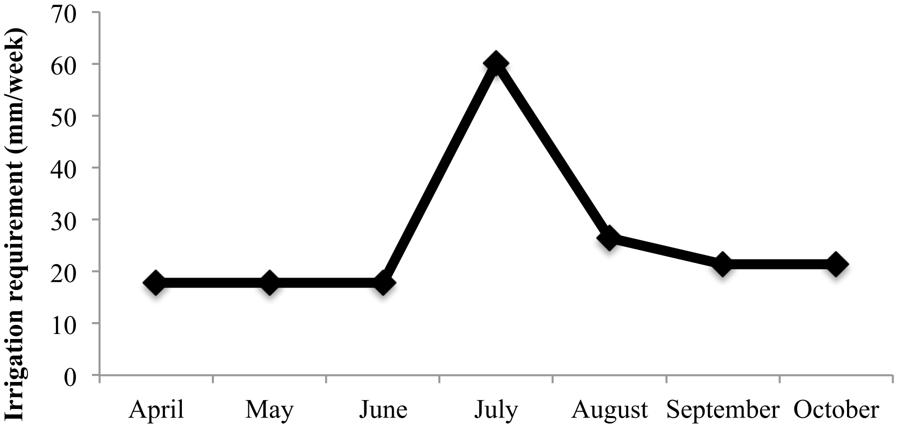


Figure 6. Irrigation requirements for the new growing season (2011-12)

2.3.2 Blaney-Criddle method

The Blaney-Criddle method was employed as an alternative method to obtain the irrigation usage based on the calculation of evapotranspiration (Blaney & Criddle, 1950). The method computes the crop consumptive water requirements using air temperature data that may be satisfied either by incident precipitation (rain fed), irrigation or a combination of the two. The Blaney-Cridle equation states that the consumptive use (U) is equal to seasonal coefficient K times a monthly consumptive use factor (F) as shown below.

$$\mathrm{U} = \mathrm{k_s} \, \mathrm{X} \, \mathrm{F} \qquad (1)$$

The monthly consumptive use factor (F) can be defined as the product of the average monthly temperature in Fahrenheit (T) and the average monthly percent of daylight hours (P). K_c is the crop factor that is defined as the ratio between the reference grass crop and the crop actually grown. The factors that define the consumptive use (U) are measured using tightly controlled conditions and is given by the following equation.

$$\mathrm{U} = \mathrm{K_c} \sum_{\mathrm{i}=0}^{4} \frac{\mathrm{T_i P_i}}{100} \qquad (2)$$

Where,

T_i – Average monthly temperature in Fahrenheit

P_i – Monthly percent of daytime hours

K_c - Crop coefficient

i – denotes the month (June, July, August or September)

Based on the weather data obtained for the city of Philadelphia the average monthly hours of daylight is displayed in Table 2 while the average monthly temperature in Fahrenheit is given in Table 3.

Table 2. Monthly % daytime hours (P) for the growing season

Months	**Monthly % daytime hours of the year**
June	10
July	10.1
August	9.4
September	8.3

Table 3. Monthly average Temperature (T) in Fahrenheit for the growing season

Month	**Monthly average Temperature (F)**	**Monthly average Temperatures (C)**
June	78	25.56
July	82	27.78
August	79	26.11
September	73	22.78

The number of growing days was assumed to be approximately 120 days based on the duration of the growing season (June-Sept.). The crop coefficient (K_c) was determined by dividing the growing season into four growing stages that includes the initial development stage (25 days), crop development stage (35 days), mid-season stage (40 days) and late season stage (20 days) that is defined for various crops in Table 4 (Natural Resources Management and Environment Department, 2008).

Table 4. Values of crop coefficient (K_c) for various crops and growth stages

Crop	Initial Stage	Crop development stage	Mid-season stage	Late season stage
Barley/Oats/Wheat	0.35	0.75	1.15	0.45
Bean, green	0.35	0.7	1.1	0.9
Bean, dry	0.35	0.7	1.1	0.3
Cabbage/Carrot	0.45	0.75	1.05	0.9
Cotton/Flax	0.45	0.75	1.15	0.75
Cucumber/Squash	0.45	0.7	0.9	0.75
Eggplant/Tomato	0.45	0.75	1.15	0.8
Grain/small	0.35	0.75	1.1	0.65
Lentil/Pulses	0.45	0.75	1.1	0.5
Lettuce/Spinach	0.45	0.6	1	0.9
Maize, sweet	0.4	0.8	1.15	1
Maize, grain	0.4	0.8	1.15	0.7
Melon	0.45	0.75	1	0.75
Millet	0.35	0.7	1.1	0.65
Onion, green	0.5	0.7	1	1
Onion, dry	0.5	0.75	1.05	0.85
Peanut/Groundnut	0.45	0.75	1.05	0.7
Pea, fresh	0.45	0.8	1.15	1.05
Pepper, fresh	0.35	0.7	1.05	0.9
Potato	0.45	0.75	1.15	0.85
Radish	0.45	0.6	0.9	0.9
Sorghum	0.35	0.75	1.1	0.65
Soybean	0.35	0.75	1.1	0.6
Sugarbeet	0.45	0.8	1.15	0.8
Sunflower	0.35	0.75	1.15	0.55
Tobacco	0.35	0.75	1.1	0.9

Though slightly varying, the number of days for each stage was assumed to be approximately a constant of 30 days resulting in each month (June-Sept) comprising an entire growing stage. Therefore, the crop coefficient for each stage was calculated (Table 5) by estimating the average for those defined for various crops in Table 4. Finally, once the parameters were defined, the consumptive use (U) by the crop was estimated for each month as shown in Table 6.

Table 5. Values of crop coefficient (K_c) for the growing season

Month (Growth Stage)	**Crop Coefficient (K_c)**
June (Initial stage)	0.41
July (Crop development stage)	0.73
August (Mid-season stage)	1.08
September (Late season stage)	0.76

Table 6. Monthly water consumption based on the Blaney-Criddle equation

Month	**Monthly (inches/month)**	**Weekly (mm/week)**
June	3.12	18.49
July	6.6256	38.00
August	7.7973	44.72
September	4.2413	25.14

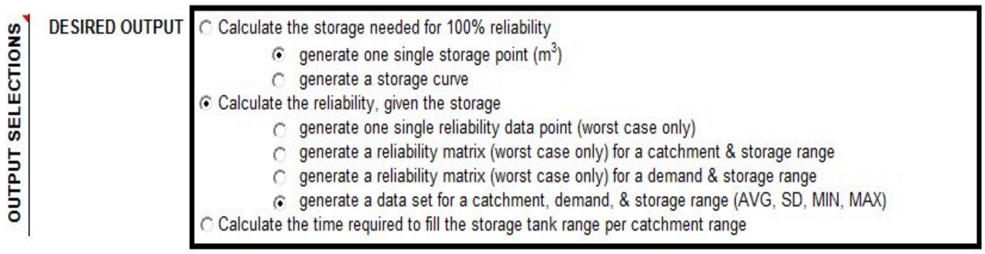
2.3.3 Estimated irrigation demand

The two methods described above give a very different picture of the distribution of irrigation demand during the entire growing season. The Blaney-Criddle method predicts lesser water requirements (irrigation and rain fed) when compared to the method using the water bills (irrigation only) that can be attributed to the various assumptions made in evaluating the parameters in the Blaney-Criddle method. The first method suggests that July has the highest irrigation requirements while the second method suggests that water requirements remain almost constant over the entire growing season. Since, the method that employs the use of water bills is based on actual data obtained at the site it is preferred over the Blaney-Criddle method. The RWH system was sized based on this irrigation requirement in order to make sure that the storage facility is able to store enough volume of water to be able to irrigate even during possible drought conditions. Therefore, the worst-case scenario was defined as the ability of the system to irrigate an estimated 60.9 mm/week (based on the irrigation requirement for July) for the entire growing season (April-Oct).

2.4 Overview of the Water budget reliability model: SARET

For the estimation of storage tank volume, the reliability contour curves between various values of storage volume and catchment area using the Storage and Reliability Estimation Tool (SARET), a model constructed using Visual Basic for use in Excel were plotted. This RWH system sizing approach has been varied in sophistication as well as accuracy.

The overall working of SARET can be sub-categorized into two stages, the first being the generation of non-parametric precipitation sequence using Markov chain transition probabilities derived from the 25 year daily precipitation values of Philadelphia from 1964 to 1988. The second stage consists of using these multiple realizations of local precipitation outcomes to develop system reliability curves based on user-defined catchment areas, demand, tank volumes and first flush criteria. The model allows the user to select the output desired such as calculating the storage needed for 100% reliability, calculating the reliability for a specific value of storage and finally to calculate the time required to fill the storage tank range per catchment range as shown in Figure 7. For the purpose of designing the storage facility the reliability for a given catchment area, demand, and storage volume range was calculated. Therefore, using this feature, a reliability curve is generated plotting the percentage reliability for various storage values vs. catchment values.

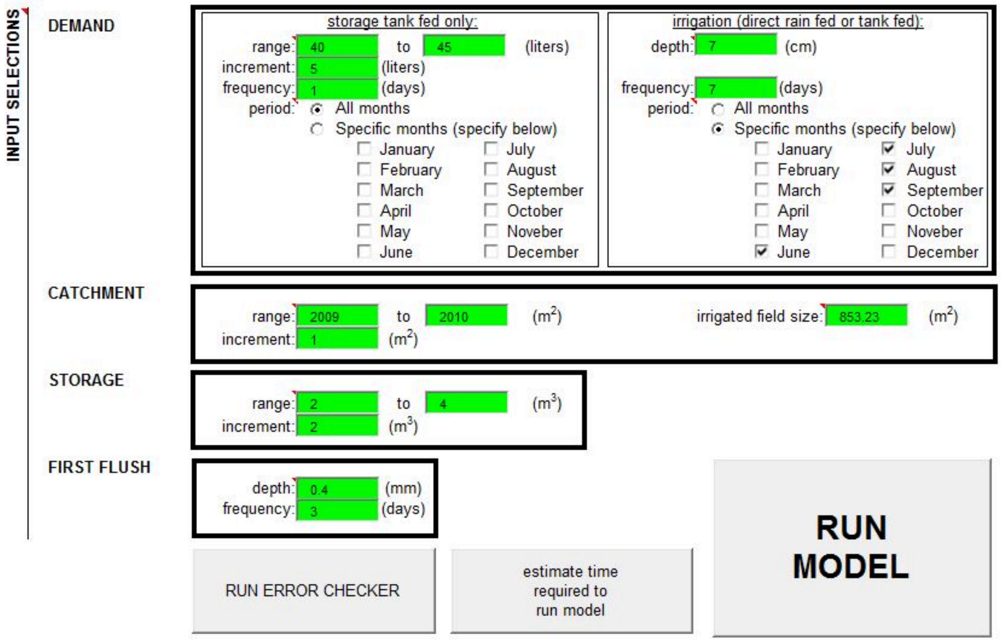


DESIRED OUTPUT
- ○ Calculate the storage needed for 100% reliability
  - ● generate one single storage point (m^3)
  - ○ generate a storage curve
- ● Calculate the reliability, given the storage
  - ○ generate one single reliability data point (worst case only)
  - ○ generate a reliability matrix (worst case only) for a catchment & storage range
  - ○ generate a reliability matrix (worst case only) for a demand & storage range
  - ● generate a data set for a catchment, demand, & storage range (AVG, SD, MIN, MAX)
- ○ Calculate the time required to fill the storage tank range per catchment range

Figure 7. Output Selections for the Storage and Reliability Estimation Tool (SARET)

The next step was to enter the input values for the model, which includes the irrigation demand as estimated in the previous section. The system was to be designed based on the “worst-case scenario” that basically assumes that the entire growing season would require an irrigation amount of 60.9 mm/week. The storage facility was sized based on this constraint in order to maximize reliability of the RWH system and also since SARET prohibits the variation of irrigation demand. This suggests that the system may be oversized and was done so to make sure that the system might be able to store sufficient runoff volume in order to be able to work during extreme drought conditions and to also incorporate the flexibility to add more residential roofs to the RWH system in the future.

An important input parameter defined was the first flush depth. According to the values recommended by the Texas Water Development Board (2005), a first flush value in the range 0.4-0.8 mm of rain for three consecutive dry days was used in the model. Figure 8 shows the SARET model that displays the input selections the user is required to enter following which the input parameters of the model are defined.



DEMAND

storage tank fed only:
range: 40 to 45 (liters)
increment: 5 (liters)
frequency: 1 (days)
period: ● All months
○ Specific months (specify below)
☐ January ☐ February ☐ March ☐ April ☐ May ☐ June
☐ July ☐ August ☐ September ☐ October ☐ Noveber ☐ December

irrigation (direct rain fed or tank fed):
depth: 7 (cm)
frequency: 7 (days)
period: ○ All months
● Specific months (specify below)
☐ January ☐ February ☐ March ☐ April ☐ May ☑ June
☑ July ☑ August ☑ September ☐ October ☐ Noveber ☐ December

CATCHMENT

range: 2009 to 2010 (m^2)
increment: 1 (m^2)
irrigated field size: 853.23 (m^2)

STORAGE

range: 2 to 4 (m^3)
increment: 2 (m^3)

FIRST FLUSH

depth: 0.4 (mm)
frequency: 3 (days)

Figure 8. Input Selections for the Storage and Reliability Estimation Tool (SARET)

Input parameters as defined in SARET are as follows:

- Irrigation (direct fed or rain fed) demand values were estimated as per the water bills provided. But we use the SARET model to generate the worst-case scenario contours assuming 60.9 mm/week is irrigated for all the months from April to October. An irrigation area of 853 square meters was used based on the new growing area.
- Catchment Area: Using Google Earth (Google, 2010) the roof area was estimated to be 85 square meter and since the total area of the twelve roofs was 1020 square meters, the catchment area was varied between 85 square meters and 1020 square meters (12 roofs) with an increment of 85 square meters that assumes each building had an equal roof area.
- Storage Volume: The storage volume was ranged between 1 cubic meter and 10 cubic meters (264 gallons to 2641 gallons).

- First flush: The first flush values were set to the recommended value of 0.4 mm of rain after 3 consecutive dry days.

Once the model was run for the specified input values, a reliability curve for the worst-case scenario was obtained as shown below in Figure 9. The Y-axis represents the volume of the storage facility in cubic meters while the X-axis represents the catchment area in square meters. The reliability can be seen to range from 74.5% to 76%. Thus, it can be inferred from the graph that the reliability seems to be high even when the catchment area is low in the case of high storage volume. This suggests that by having a high storage volume one can offset the problems of having a low catchment area and vice versa.

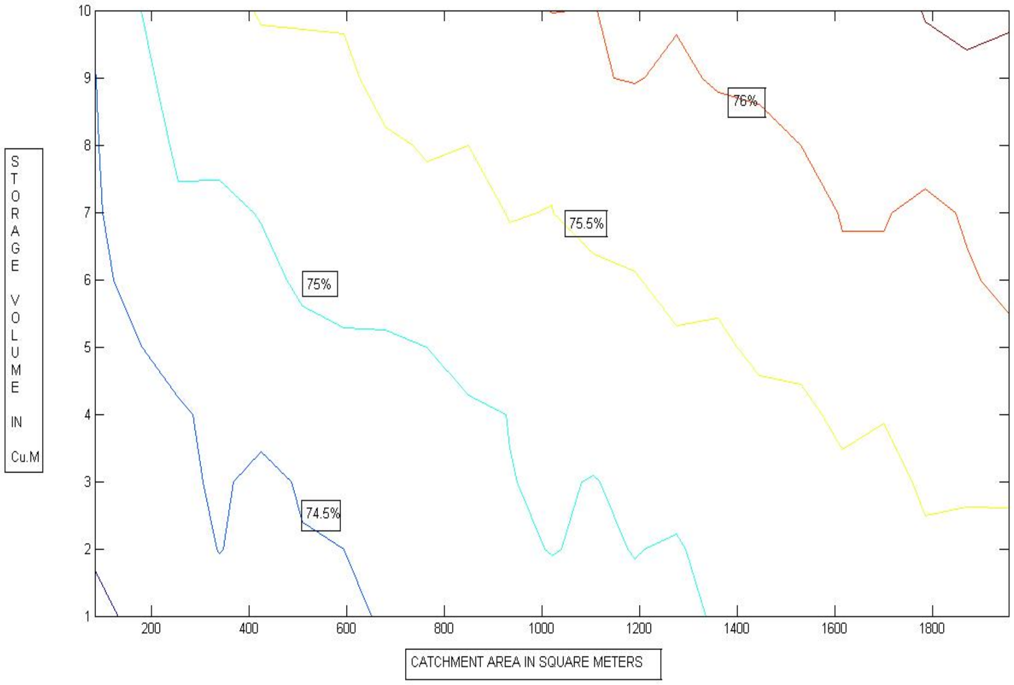


Figure 9. Reliability chart obtained from SARET for the worst case scenario

Therefore, the storage volume was chosen based on the reliability for a specific catchment. During preliminary cost analysis, it was noted that it was more cost efficient to add one cubic feet of storage than to add additional roofs. In accordance to this analysis, 10 residential roofs (approx. 850 square meter) at the site and a storage tank of approximately 2600 gallons (about 10 cubic meters) were selected for the construction of the system.

2.5 Bioretention facility Design

For small drainage areas (less than 20,000 square meters), it is suggested that a filtering system can be applied in order to improve the quality of stormwater runoff before storage and reuse (Schueler, 1996). These filtering systems direct stormwater through various natural and engineered media such as sand, soil, gravel or compost in order to filter out pollutants and improve quality. Since stormwater runoff from residential rooftops are better in terms of WQ when compared to those from other types of drainage areas such as roads, simple filtering systems are sufficient in these systems (Grottker, 1987).

In general, filtering systems consists of four basic design components (Schueler, 1996):

- Inflow Regulation: The inflow regulator is used to divert runoff from a impervious surface into the treatment facility Most inflow regulators divert a specific water quality volume into the filter while allowing the larger volumes to flow to continue flow through the conveyance channel.
- Pretreatment: Pretreatment is a requirement for any treatment facility to trap course sediments before they reach the filter bed. Without pretreatment, the treatment system will quickly clog thus losing its pollutant removal capability.
- Filter Bed and Filter Media: The filtering system utilizes sand, peat, gravel, grass, soil or compost as a media to filter out pollutants while the filter bed is defined by three key properties: surface area, depth and profile.

- Outflow Mechanism: The final component is the outflow mechanism that defines a method to collect the filtered runoff while the uncollected runoff drains into groundwater.

Treatment facilities have been categorized into five broad group of filtering systems that include sand filters, open vegetated channels, bioretention areas, filter trips and submerged gravel filters (Schueler, 1996).

Although each filtering system has its own advantage, it was concluded that a bioretention facility (Figure 10) with benefits such as low land consumption and ease of maintenance would be constructed. The homeowner of the house situated 5333 Wyalusing Avenue which is located within the residential block consented to provide their backyard with a dimension of 16.5 feet by 13 feet (5 m by 3.96 m) for construction of the bioretention facility.

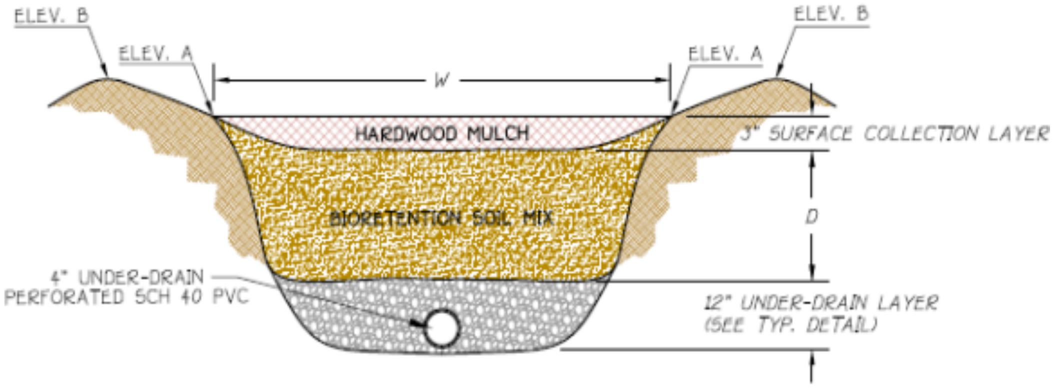


Figure 10. A Cross section of a Bioretention facility (Bioretention facility) *Not to Scale

The bioretention facility was designed based on the “Design of Stormwater Filtering Systems” manual (Schueler, 1996) and included the following assumptions:

- Volumetric coefficient for urban runoff (R_v) was assumed to be 0.95.

- The depth for Water Quality (WQ) was assumed to be 25.4 mm (1 inch).
- The bioretention facility was designed for a sub-catchment area (A_s) of 850 - 1020 square meters (10-12 Roofs)
- The maximum level of ponding (H_{max}) that may be allowed in the bioretention facility was assumed to be approx. 1 foot (0.305 m).
- The retention time (t_f) of the bioretention facility is assumed to be approx. 24 hours (1day).
- The coefficient of permeability for the topsoil mix (k) is assumed to be approx. 1ft/day (0.305m/day). This was based on coefficient of permeability for Loamy and Sandy soils which are 0.157 m/day and 0.61 m/day respectively.
- The planting soil depth (d_f) that is the sum of the mulch and the topsoil layer was assumed to be about 2 feet (0.61 m).
- The bioretention facility will be situated at a minimum of 7.5 feet (2.286 m) away from the house as a precaution to prevent possible flooding of the basement.

Once these assumptions were made, the surface area of the bioretention facility was estimated using the following formula:

$$\mathrm{Af} = \mathrm{WQV\ x}\ \frac{\mathbf{df}}{\mathbf{k\ (Havg + df)x(tf)}} \tag{8}$$

Where,

A_f - Surface area of the bioretention facility planting bed (ft^2)

WQV – Water Quality Treatment Volume (ft^3),

Where,

$$\mathrm{WQV} = [\ \mathrm{WQ\ x}\ \frac{\mathrm{Rv}}{12''/1\mathrm{ft}}\ ]\ \mathrm{x\ Area\ of\ Subcatchment(As)} \tag{9}$$

d_f - Planting soil bed depth (ft)

k - Coefficient of permeability for planting soil bed (ft/day)

H_{avg} - Average height of water above the bioretention facility bed (ft)

Where,

$$H_{avg} = \frac{1}{2} \times (H_{max}) \tag{10}$$

t_f - Retention time

With reference to the design manual, the bioretention facility was designed to have the following layers (from top to bottom):

- Shallow Ponding Layer: The ponding layer provides surface storage for a percentage of the WQV and also allows for particulate settling during the detention period allowing finer particles to settle on the surface of the mulch layer.
- Surface Mulch Layer: The mulch layer provides an environment for plant growth by minimizing evaporation at the surface (maintaining moisture) and allow the decomposition of organic matter. The surface layer also acts as a filer for finer particles and maintains an environment for the microbial community to help breakdown urban runoff pollutants.
- Planting Material: The planting material takes up nutrients and pollutants, and available water through evapotranspiration. Also, the use of native plant material provides a cover for wildlife and creates a microenvironment within the urban landscape thus aesthetically pleasing.
- Top Soil Layer: The topsoil layer, which comprises the planting soil bed, provides the region of storage of water and nutrients for the planting material above. The voids in the soil also provide additional storage for the WQV while the soil particles can absorb various pollutants through ion exchange.

- Gravel Layer: This layer is utilized to collect the treated runoff and helps keep the soil from being saturated. The under drain thus consists of a gravel layer with a 4” perforated pipe system.

Based on the previously mentioned equations, the WQV was determined to be 95 cubic feet (2.7 cubic meters) while the surface area of the bioretention facility was determined to be 76 square feet (7 square meters), with the following specifications:

- Allowed ponding: 0.305 m
- The sum of the depths of the mulch layer and the top soil layer: 0.61 m
- The pipe from the downspouts enters the bioretention facility at a depth of approx. 0.311 m hence the bioretention facility will be 0.311 m below the existing grade (0.311 m).
- A gravel layer of approximately 0.305 with the entire Bioretention facility consist of a 2% gradient to make sure that runoff could be gravity-fed into the storage facility.

2.6 Summary

In this chapter, the procedures used to design the volume of storage facility as well as the area of the bioretention facility were described. The storage facility specifications were calculated based on the Storage and Reliability Estimation Tool (SARET) that uses a non-parametric rainfall simulation model to generate storage vs. catchment relationships. To better understand the non-parametric simulation model incorporated in SARET, the model results for the month of January during the period 1964-1988 were compared to that generated using a customized non-parametric model constructed in MATLAB and using an external HMM tool. These results suggest that synthesized precipitation sequences generated using a non-parametric model are able to mimic the seasonality of the historic record for the same period. Two methods were employed to estimate the irrigation demand based on which a worst-case scenario was defined to size the storage facility of the RWH system in order to improve system reliability. SARET was then used to size the storage facility based on which it was decided to use a storage facility of about 10 cubic meters (approximately 2600 gallons) that would be connected to ten residential rooftops situated within the residential block. Once the storage facility specifications were calculated, the next step involved estimating bioretention facility specifications based on the "Design of Stormwater Filtering Systems" manual (Schueler, 1996). It was concluded that the area of the bioretention facility would be approximately 7 square meters with a Water Quality Volume (WQV) of 2.7 cubic meters.

CHAPTER 3: FINAL SPECIFICATIONS OF THE RWH SYSTEM

Once the volume of the storage facility was calculated based on the SARET model and the area of the bioretention facility was estimated based on a design manual, the next step was to realize the whole RWH system by developing system specifications to guide construction. The construction process was constrained by the construction budget ($9000 USD) and other practical considerations.

The system was broadly categorized into having the following components:

- Bioretention facility (rain garden)
- Storage facility
- Pond liner for the storage facility as well as the bioretention facility
- Overflow trench to prevent the bioretention facility from flooding
- Interceptor trench connecting the downspouts from the roofs to the bioretention facility
- Pump connecting the storage facility to the irrigation facility
- Irrigation facility

The placement of each of these components at the residential block was based on minimizing the runoff travel time and obtaining clearance from various homeowners. Based on which, the location of each of these components including the pipe layout is shown in Figure 11. Yellow indicates the location of the storage facility while green indicates the location of the bioretention facility. Based on the requirements for various aspects of the system pipes, elbows, soil mix and other components were chosen to minimize cost by researching various products and alternatives available in the market.

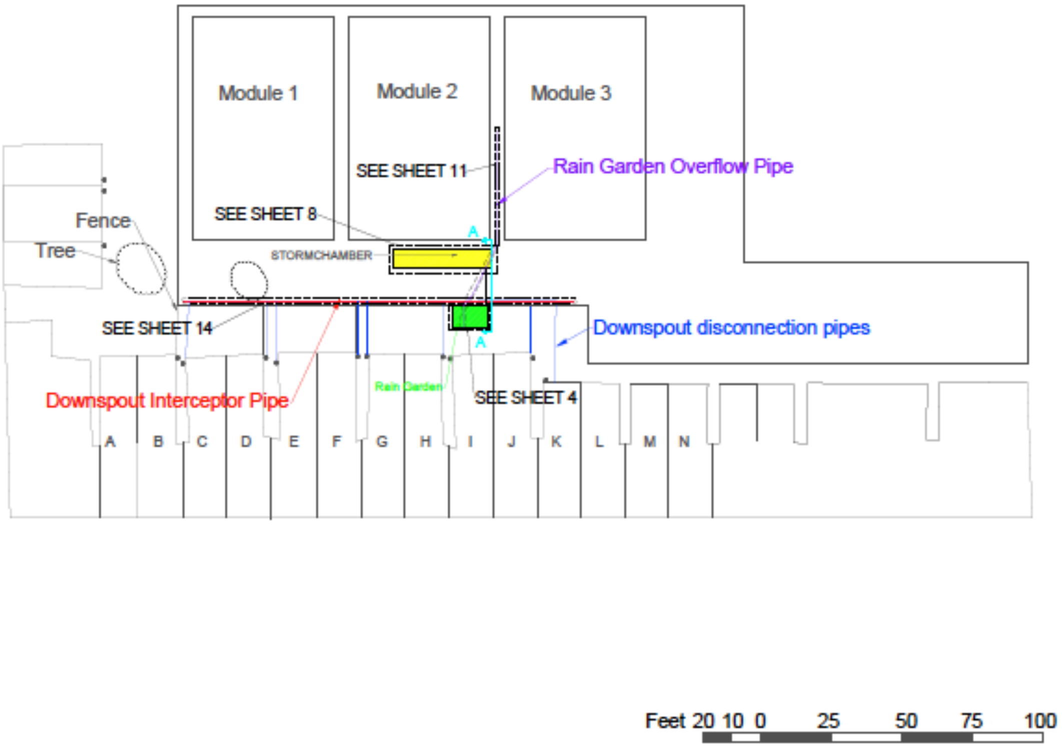


Figure 11. Pipe and component location layout

3.1 Bioretention facility

Based on the calculations performed using the design manual (Chapter 2), the required area was estimated to be 76 square feet (approximately 7 square meters). The site chosen at 5333 Wyalusing Avenue (Nicole’s Home) to house the bioretention facility had a total potential available space of 16.5 feet by 13 feet (5 m by 3.96 m). As mentioned previously, an important constraint was that the bioretention facility be situated at least 7.5 feet (2.286 m) away from the building structure to prevent possible flooding. To be conservative, the bioretention facility was actually sited 9 feet from the. To satisfy the minimum bioretention facility area requirements a12 feet by 7.5 foot (3.66 m by 2.286 m) space was selected for bioretention facility construction (a total area of 90 square feet) shown in Figure 12.

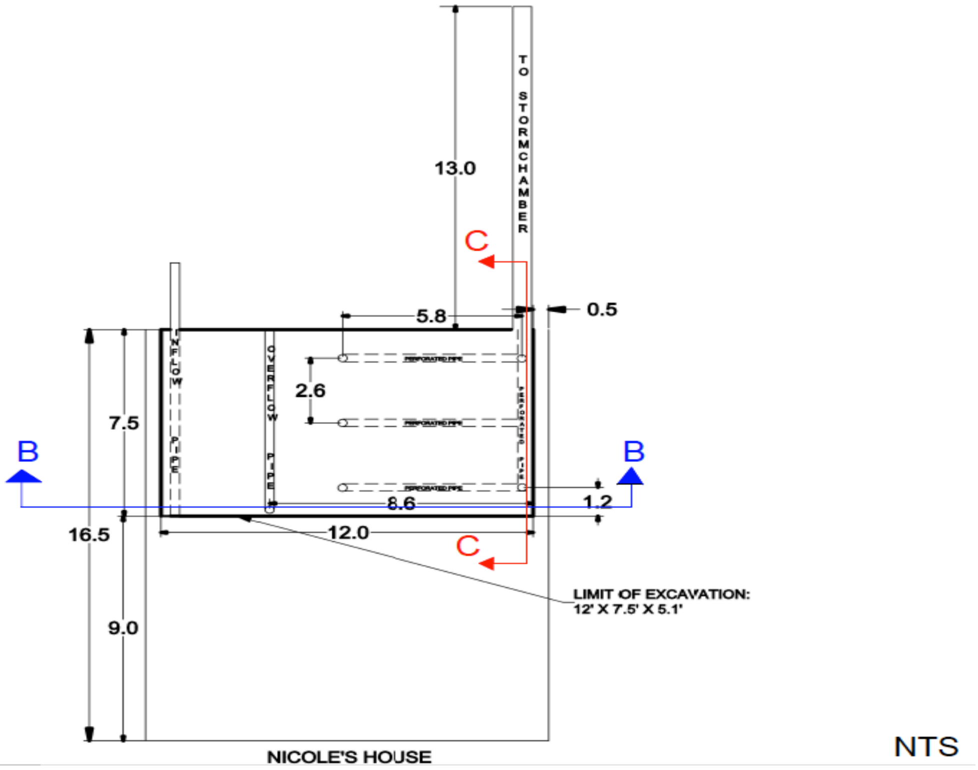


Figure 12. Bioretention facility pipe location -plan view (Not to Scale)

The depth of the bioretention facility was also estimated based on the calculations performed in Chapter 2 (Figure 13).

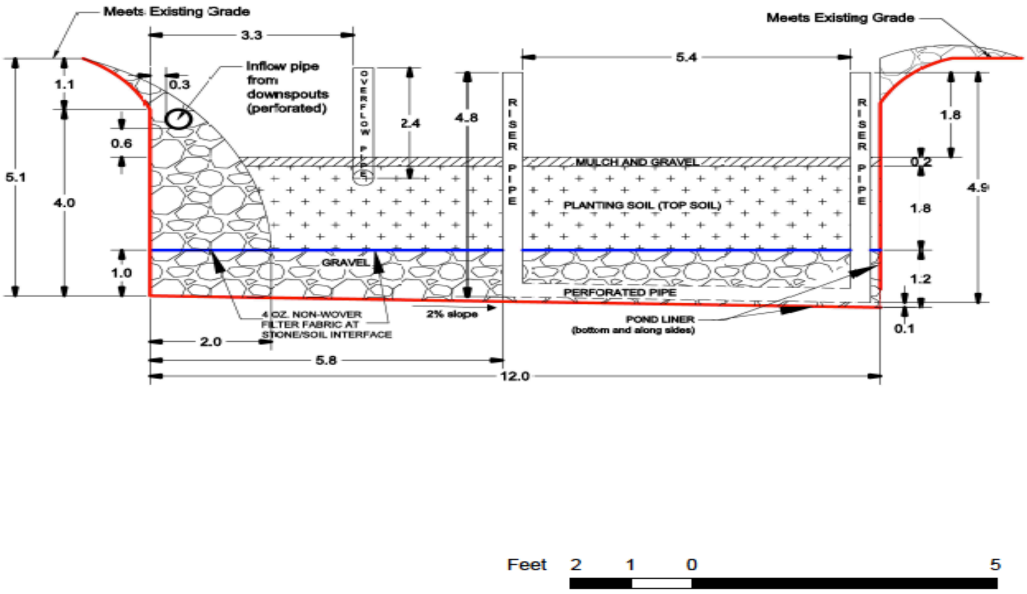


Figure 13. Section BB of the bioretention facility

The inflow pipe is a perforated pipe that runs across the bioretention facility that in turn is connected to the downspouts that collect roof runoff. Riser pipes were installed in order to make sure that if the bioretention facility inundates, it would drain faster through the riser pipes that directly feed into the storage facility. As a precaution an overflow pipe is also placed to drain water away from the site and towards the growing areas in the event that the bioretention facility becomes saturated. This overflow pipe discharges water far away from the bioretention facility (Figure 14). The bioretention facility also acts as a first-flush diverter thus it gives the chance for the system to get rid of small contaminants before capture by the storage facility.

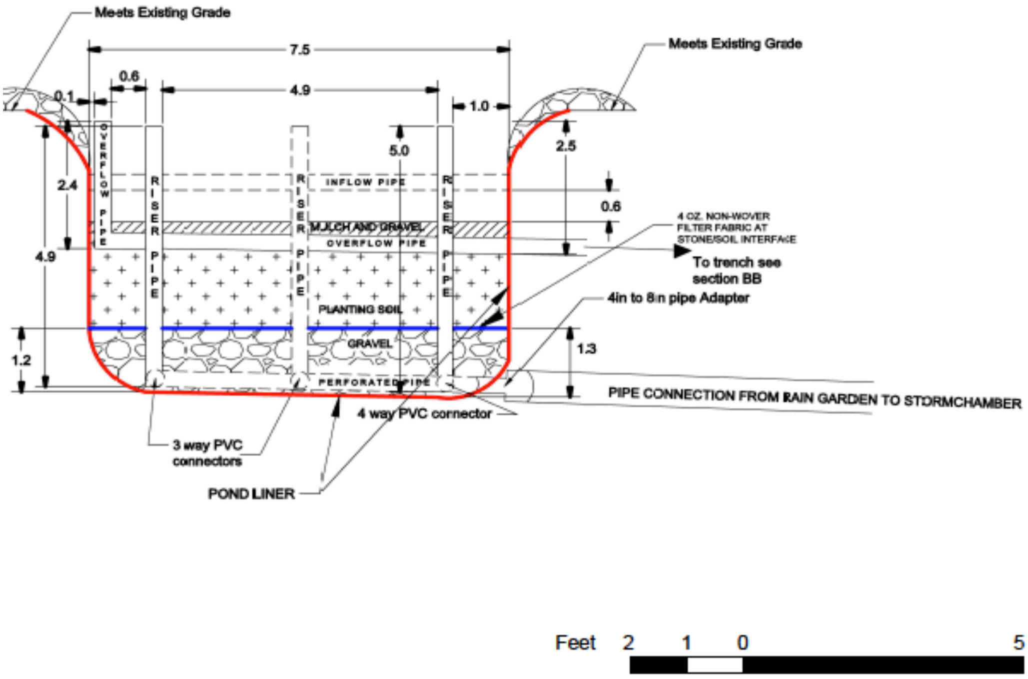


Figure 14. Section CC of the bioretention facility

3.2 Storage facility

The storage tank is expected to be the most expensive component of an RWH system (Texas Water Development Board, 2005) and thus proper sizing and selection of the type of storage vessel is important to minimize costs.

There are two general classes of potential storage vessels that can be considered for use in RWH systems: surface storage and underground storage, each having their respective advantages and disadvantages. Surface storage facilities are the more popular of the two primarily due to the ease of installation and maintenance when compared to underground storage facilities that require excavation and accompanying due to which it is relatively more expensive for small storage requirements when compared to surface storage facilities. Water extraction can be executed via gravity in the case of surface storage facilities while pumps are an integral part of the system in the case of underground storage facilities. Although surface storage facilities seem to be a better option, unlike underground storage facilities they are obtrusive since they require space for installation and hence in cases where large storage is required underground storage facilities are a better option

Based on the "Texas Manual of Rainwater Harvesting" (Texas Water Development Board, 2005) and "A Handbook on Rainwater Harvesting in the Caribbean" (The Caribbean Environmental Health Institute, 2009), the following constraints were considered while selecting the type of storage facility as well locating it at the site:

- Storage tanks must be covered in order to discourage mosquito breeding and contamination
- Tanks should be located as close to the supply and demand points (in this case as close to the residential roofs as well as the irrigation site) to minimize distance water conveys.
- Storage tanks must be protected from direct sunlight to minimize the adverse effects of sunlight on plastic containers and also to prevent algae growth accompanying exposure to sunlight.
- Underground storage tanks should be located a minimum of 50 feet (approximately 15 meters) from animal stables and above ground application of wastewater treatment.

Based on the constraints on the site and the space available it was proposed to build an underground storage facility for the RWH system. After extensive research, StormChamber® a product developed by Hydrologic Solutions to provide solutions for stormwater management was chosen as a suitable alternative as a storage facility. Based on the specifications provided by the company, each StormChamber® has a capacity of about 2.18 cubic meters while the same with a crushed stone surround has a capacity in the range of 3.49 to 4.8 cubic meters (Hyrologic Solutions, 2011). The configuration of the StormChamber$^{\circledR}$ provided by the company is shown in Figure 29 of Appendix D. The StormChamber$^{\circledR}$ consist of 3 parts, a start chamber, a middle chamber and an end chamber, each of which having their own configuration as shown in Figure 29 of Appendix D.

Based on the design volume of 10 cubic meters estimated for the storage facility (Chapter 2), initially three StormChamber$^{\circledR}$ were planned to be installed but UTC later requested the addition of another StormChamber$^{\circledR}$ in accordance with the availability of more funds and also to be able to capture and store a larger runoff volume with the future addition of residential roofs to the system. Based on the above storage specifications (Figure 15) it was decided that the system would consists a total four StormChamber$^{\circledR}$ with one each of start and end chamber while two middle chambers.

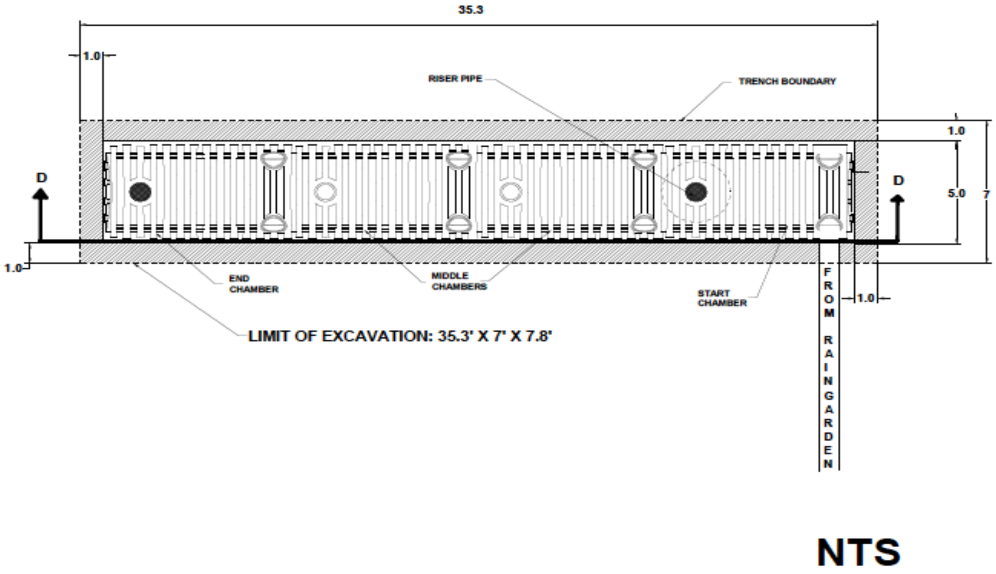


Figure 15. StormChamber$^{\circledR}$ plan view (Not to Scale)

Based on the “STORMCHAMBER^{TM} Design Manual” (Hydrologic Solutions, 2009), the specifications of the StormChamber$^{®}$ trench was planned and designed as shown in Figure 16. It was made sure that the connecting pipes between the bioretention facility and the StormChamber$^{®}$ consisted of at least 2% slope in accordance of the design requirement of a gravity fed RWH system.

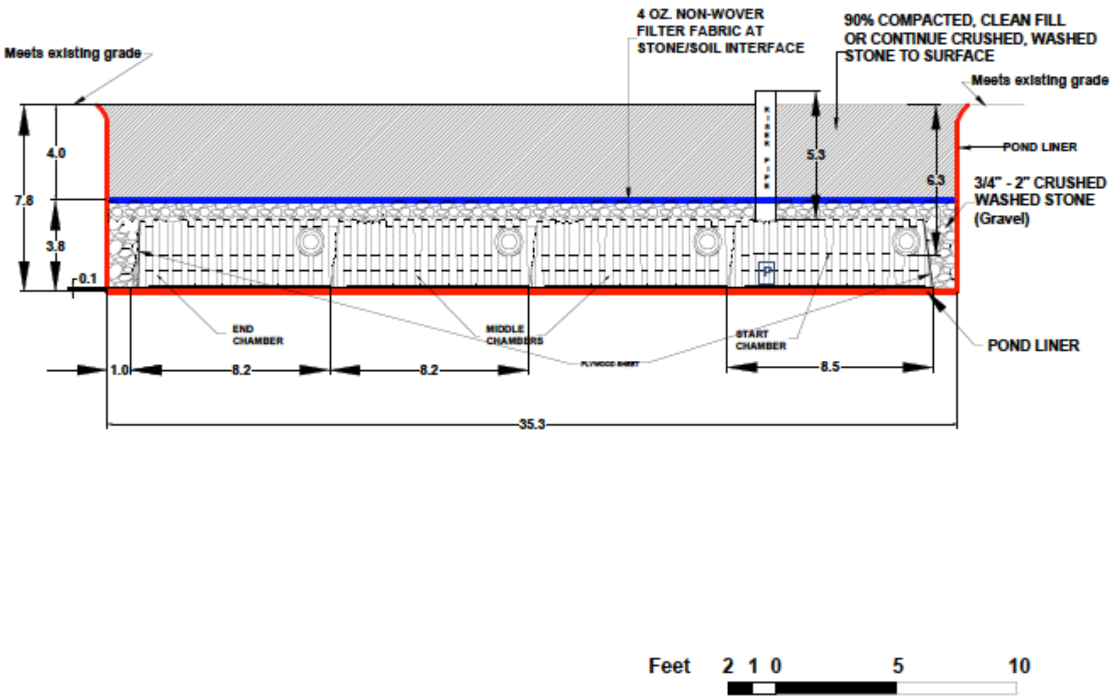


Figure 16. Section DD of the storage facility (StormChamber$^{®}$)

3.3 Pond liner

In order to minimize the loss of water due to infiltration from the bioretention facility and the storage facility a pond liner was employed to encapsulate each one of them. Hence, once the bioretention facility and storage facility specifications were defined, the pond liner specifications were defined as shown in Figure 17 and 18 respectively.

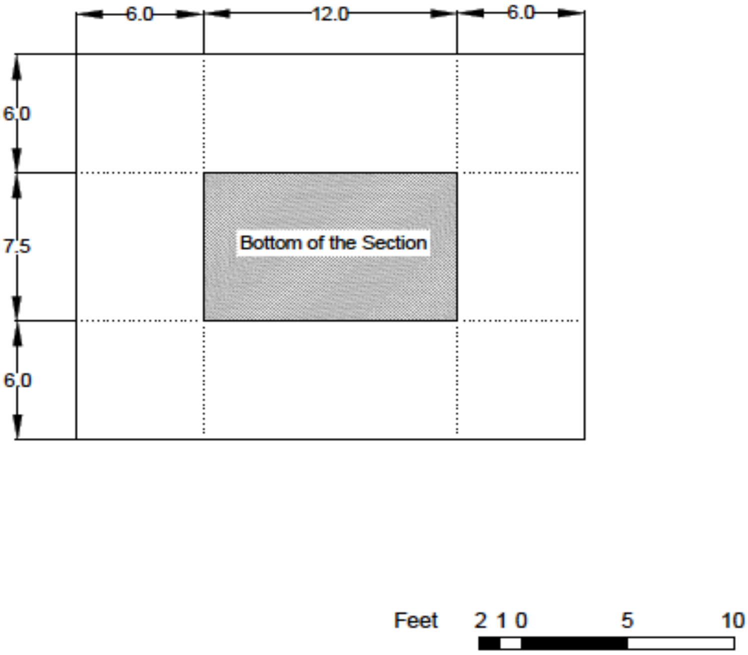


Figure 17. Pond Liner Specifications for the Bioretention facility

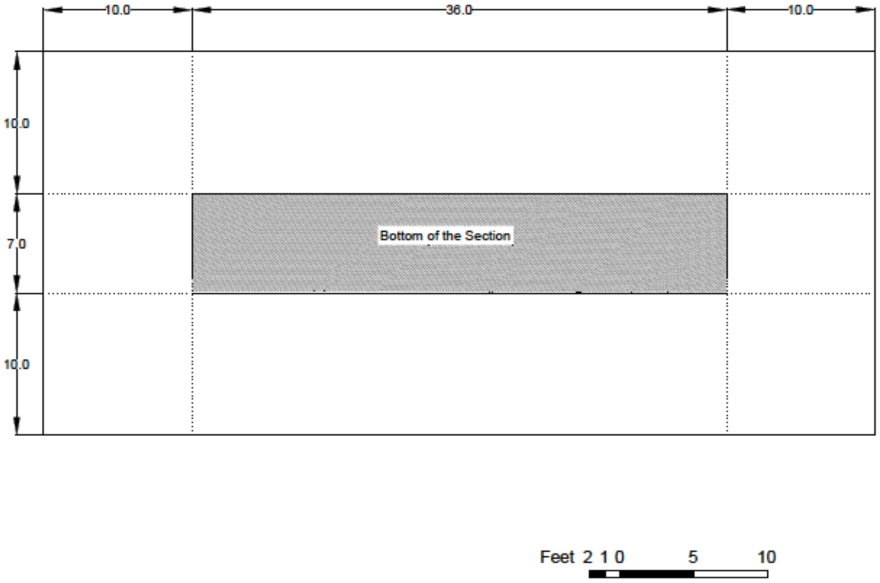


Figure 18. Pond Liner Specifications for the storage facility (StormChamber$^{®}$)

To make sure all dimensions on field were the same relative to the plans, it was made sure an existing grade was chosen for this purpose to minimize construction errors. Once the storage facility and the bioretention facility were constructed, the two were connected as shown in Figure 19.

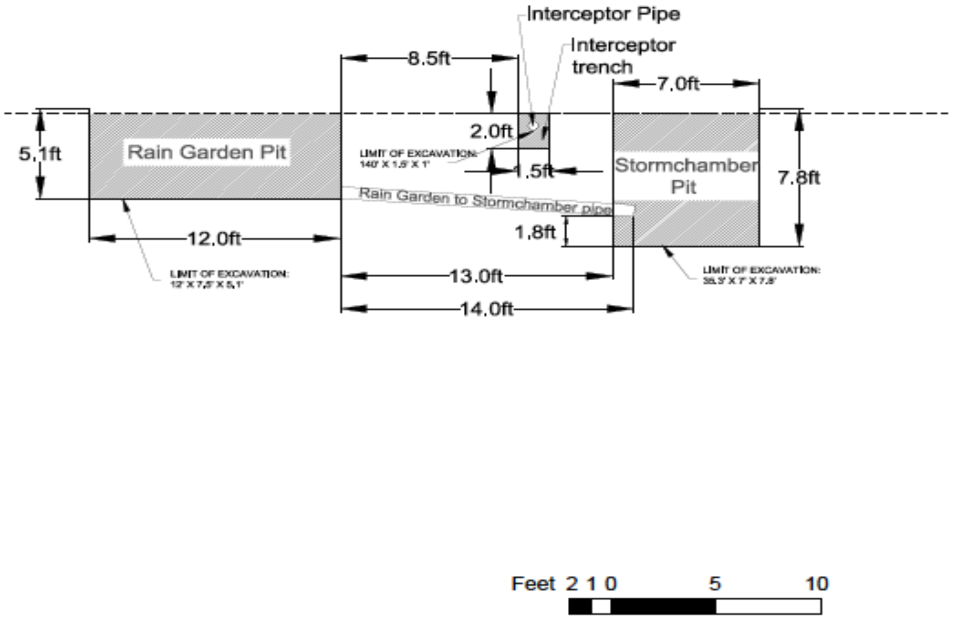


Figure 19. Pipe connection layout between the rain garden (bioretention facility) and the storage facility (StormChamber®)

In order to connect the RWH system to the irrigation facility a pump was installed to pump water out of the storage facility. Although initially it was planned to install a submersible pump at the bottom of the storage facility (Figure 16) it was later preferred to instead install a non-submersible pump as per the requests made by UTC. The pump was selected based on the pressure required to irrigate the entire irrigation facility. While analyzing various options, ECOTRONIC 130 (Appendix E) a non-submersible pump was chosen and installed (Leader Pumps, 2011) at the location of the storage facility.

A complete list of various components with their specifications is provided in Table 8 of Appendix F. Although, the RWH system was designed to include ten residential rooftops only seven residential rooftops a total of 595 square meters of roof area were connected due to residential homeowner issues faced during construction.

3.4 Irrigation system

The irrigation system was installed prior to the design of the RWH system using a drip irrigation appurtenance. The system is divided into three modules with each module consisting of approximately 13 beds. The dimensions of the farm are shown in Figures 30 and 31 of Appendix G. Each bed consists of 2 drip irrigation lines each containing an approximate of 50 drip irrigation holes. The drip irrigation line has a flow range of 3.78×10^{-5} to 5.68×10^{-5} cubic meters per second. More detailed technical specifications of the drip irrigation lines are provided in Appendix H.

3.5 Summary

In this chapter, the construction plans for the entire RWH system were laid out to initiate the final construction of the system. Various requirements for the implementation of the design at the site were laid out such as the components and specific design constraints as observed on site based on which the location of these components were also finalized as shown in Figure 11. Furthermore, the bioretention facility specifications were laid out as shown in Figure 12 through 14 while the storage facility specifications are laid out in Figure 15 and 16. The specifications of the pond liner were also finalized as shown in Figure 17 and 18. Once the system was constructed, a non-submersible pump was used to connect the storage facility to the already existing irrigation facility.

CHAPTER 4: ASSESSMENT OF PERFORMANCE OF THE SYSTEM

To ensure RWH systems achieve the rainwater management goal, it must be able to secure sufficient quantity of rainwater and also control the WQ. The goal of the performance assessment was to verify the quantitative performance of the RWH system. Though water quality performance was beyond the scope of this thesis, it has been recommended for future work. In the past, system performance have been analyzed by estimating the Operational Parameters (OPs) of the system that consists of rainwater use efficiency (RUE), water saving efficiency (WSE) and cycle number (CN) (Mun & Han, 2011).

To assess the performance of the rainwater harvesting system monitoring techniques were used. The depth of water in the StormChamber® was recorded continuously using a pressure transducer WL16U water level logger (Global Water, 2011) placed within the storage facility (specification sheet of the apparatus as shown in Appendix I). To obtain rainfall from the site a rain gauge RG 200 (Global Water, 2011) was installed at the site that was located approximately ten meters away from the storage facility.

The original goal of the performance assessment was to observe the variation in the depth of water within the storage facility for the entire growing season (April – October) following which the data would be analyzed and compared to the precipitation data and irrigation events observed to finally estimate the system performance. Based on this an analysis would be carried out in order to estimate whether the system is successful in satisfying the irrigation requirements of the agricultural facility. However, these goals could not be realized due to unanticipated circumstances. These included regular pump failure resulting in an inability to irrigate periodically and a shortened period for which data was obtained (approximately 2 months).

The remainder of the performance assessment is based on performing an analysis to understand the storage capacity of the StormChamber® by observing depth data obtained and understanding its relationship to observed precipitation data. However, further work is recommended to thoroughly complete the performance assessment of the system.

4.1 Manual depth readings vs. Transducer depth readings

Before getting into the core section of the analysis, the first step was to verify the working of the pressure transducer. Figure 20 shows the location of the pressure transducer and the measuring tape with reference to the pump location. The pressure transducer cord sits right at the bottom of the storage facility while the measuring tape beeps when the sensor end of the tape is in contact with the water surface.

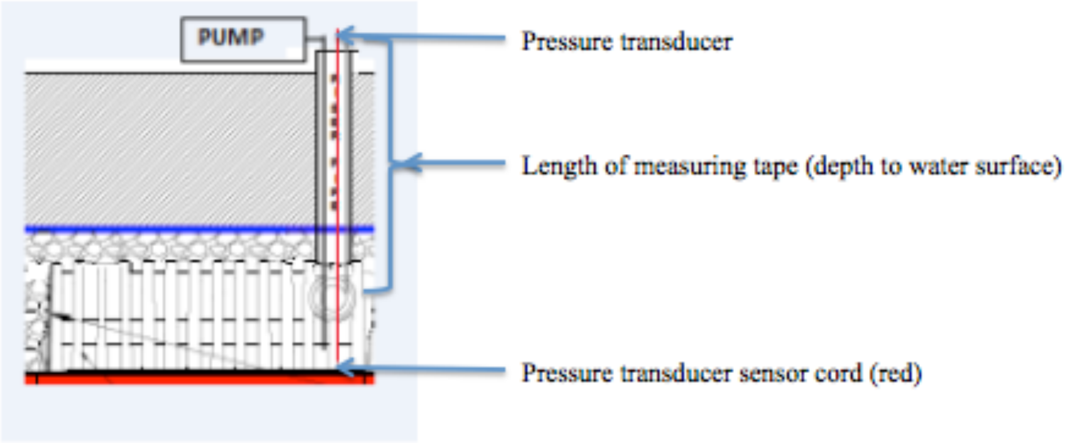


Figure 20. Location of the pressure transducer and the measuring tape

To verify the pressure transducer readings, the water was pumped out of the storage facility while the depth of water in the storage facility was measured periodically using both the pressure transducer and the measuring tape. Figure 21 provides the relationship between the measured depth (via measuring tape) and the pressure transducer reading. As expected a linear relationship was obtained ensuring that the pressure transducer is working as desired.

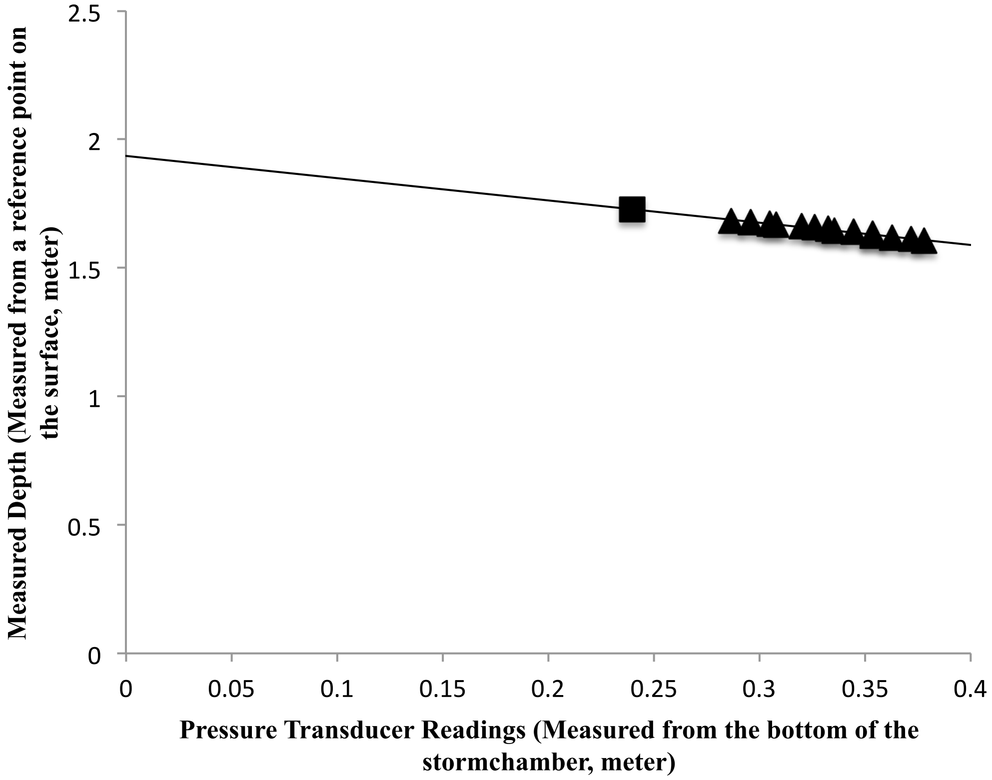


Figure 21. Measured depth (measuring tape) vs. Pressure Transducer depth

Although a linear relationship was obtained at higher depths, extrapolating this might be incorrect since the side walls of the excavation are not perfectly vertical which can be observed in the geometry of the storage facility as shown in Figure 29 of Appendix D and the storage facility drawings (Figure 15 and 16) in Chapter 3.

4.2 Stage – Storage relationship

One the working of the pressure transducer was verified; the following step was to define a stage-storage relationship for the facility estimated by pumping out water at a known rate and simultaneously recording the change in depth within the storage facility. The water was pumped out of the system at a constant rate into a container with known volume and the depth was periodically checked using the measuring tape and the pressure transducer. The pump operation is such that there must be a minimum depth of water available, below which the pump would stop pumping out water automatically. At this minimum depth, it was assumed that the volume of water in the StormChamber® is zero due to the inability to pump water out. Once this minimum depth was determined, the volume at each interval was calculated based on the known amount of water pumped out and therefore the total volume of water pumped out was also estimated. Once the stage-storage relationship was defined (Figure 22), a parametric equation was obtained that could be used to relate the changes in depth in the facility to changes in stored volume of water.

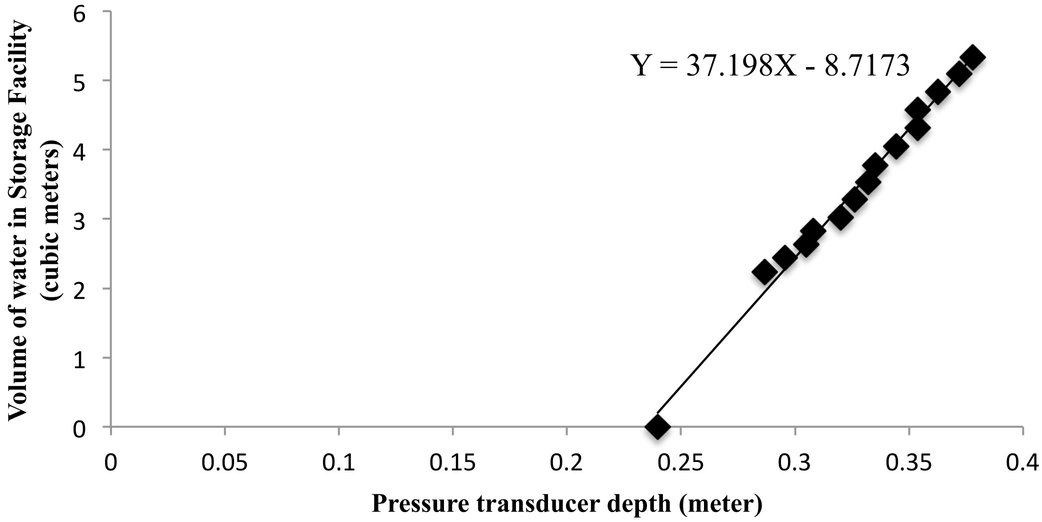


Figure 22. Stage-storage relationship of the storage facility

Based on the graph (Figure 22), the parametric equation relating the depth and the volume of the storage facility was determined to be:

$$Y = 37.198X - 8.7173$$

Where,

Y – Volume of water in the storage facility in cubic meters

X – Depth of water in the storage facility (meters)

This stage-storage relationship would thus be helpful in estimating the volume of water stored within the storage facility at any depth.

4.3 Observations

The next step was to obtain pressure transducer readings for various precipitation events as well as dry periods. Due to time constraints and other constraints on site such as malfunctioning of the pump, only data for the period 13th June 2012 to 15th August 2012 was obtained. The precipitation data obtained from the rain gage as well as the depth readings obtained from the pressure transducer are shown in Figure 23.

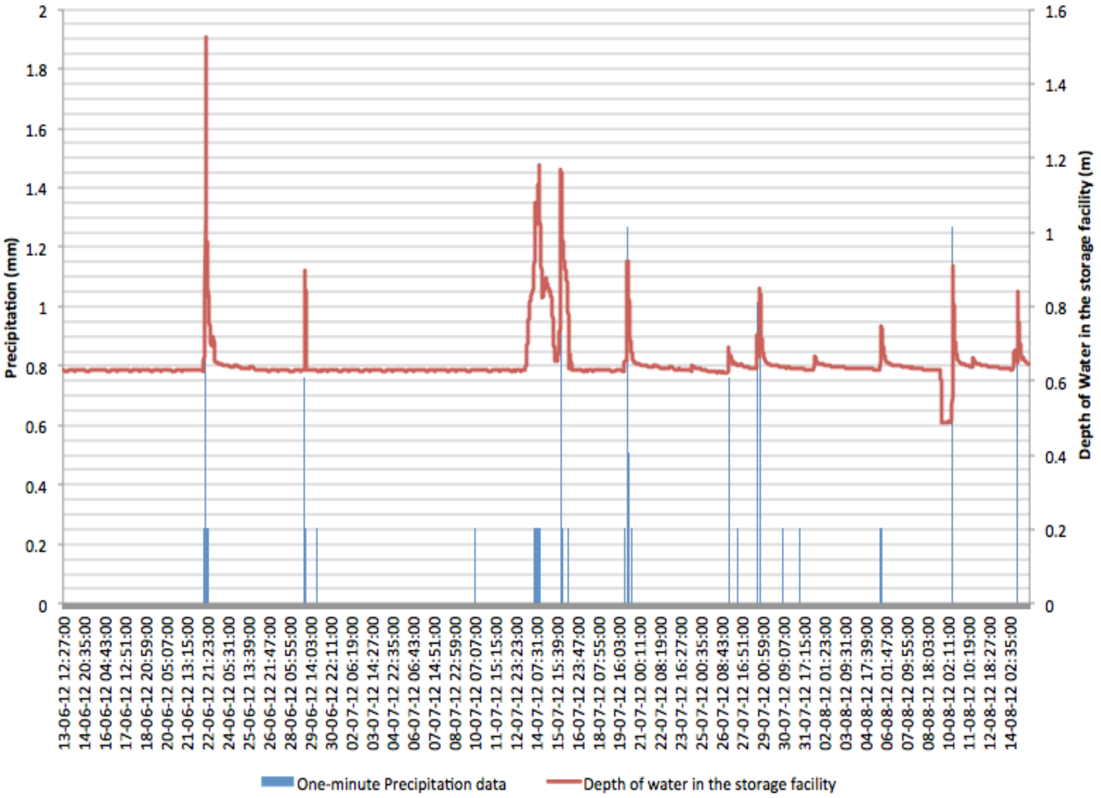


Figure 23. Depth of water in the storage facility and Precipitation data obtained at the site.

It was observed that the storage facility could hold only a certain volume of water above which the water would drain out the overflow pipe through the bioretention facility. The peaks that are visible in the above figure also validate the claim that their might exist a discharge of water possibly via the rain garden overflow pipe above a certain depth, though further analysis must be performed in order to be more conclusive.

The maximum depth of water that can be stored based on the observations was estimated to be approximately 0.626 meters. Based on the relationship obtained between the storage volume and the depth in the storage facility, it was calculated that the maximum volume that can be held within the StormChamber® to be approximately 14.568 cubic meters. This means that each StormChamber® could hold an approximate maximum volume of 3.642 cubic meters of water which is in the range of 3.49 to 4.8 cubic meters that Hydrologic Solutions claim that each StormChamber® can store when the storage facility is surrounded by crushed stone (Hyrologic Solutions, 2011). The box and whisker plot in Figure 24 depicts the range of depths recorded by the pressure transducer in the storage facility.

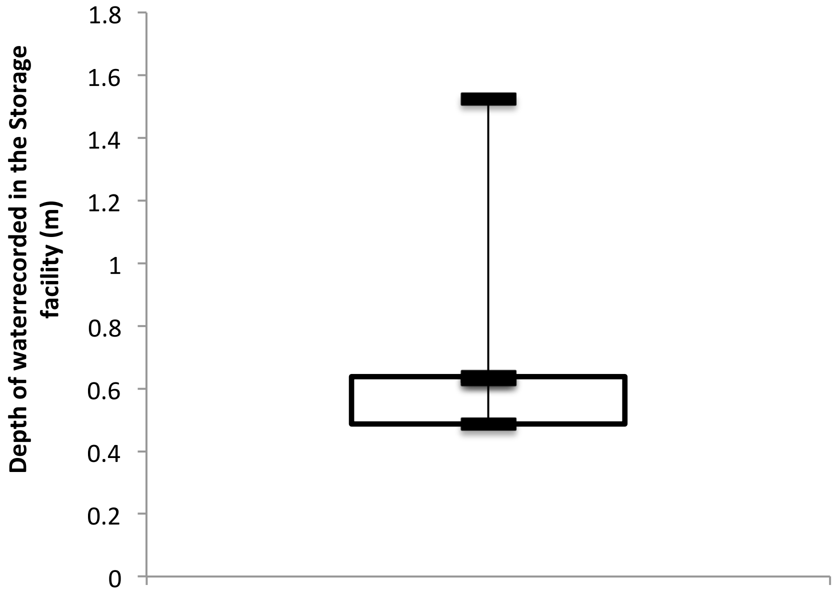


Figure 24. Range of depths recorded (13th June 2012 – 15th August 2012) by the pressure transducer in the storage facility

During this entire period, only once was the pump used to irrigate the growing area (malfunctioning of the pump was the major concern) that took place on 9th August 2012 for a period of half an hour.

4.4 Analysis

While looking at the pressure transducer data for the same period, it was observed that there was a drop in volume from 13.75 cubic meters at 16:12 hrs to 9.39 cubic meters at 16:48 hrs on 9th August 2012. A total volume of 3.96 cubic meters pumped out from the storage facility during this time interval. To better understand the efficiency with which runoff from the seven roofs connected to the system is collected by the storage facility, the runoff flowing into the system during the following precipitation event was observed. Based on the precipitation event observed on 10th August 2012 as shown in Figure 25, a total of 5.29 cubic meters of runoff was estimated to have flown into the RWH system based on the area of 7 roofs at the site.

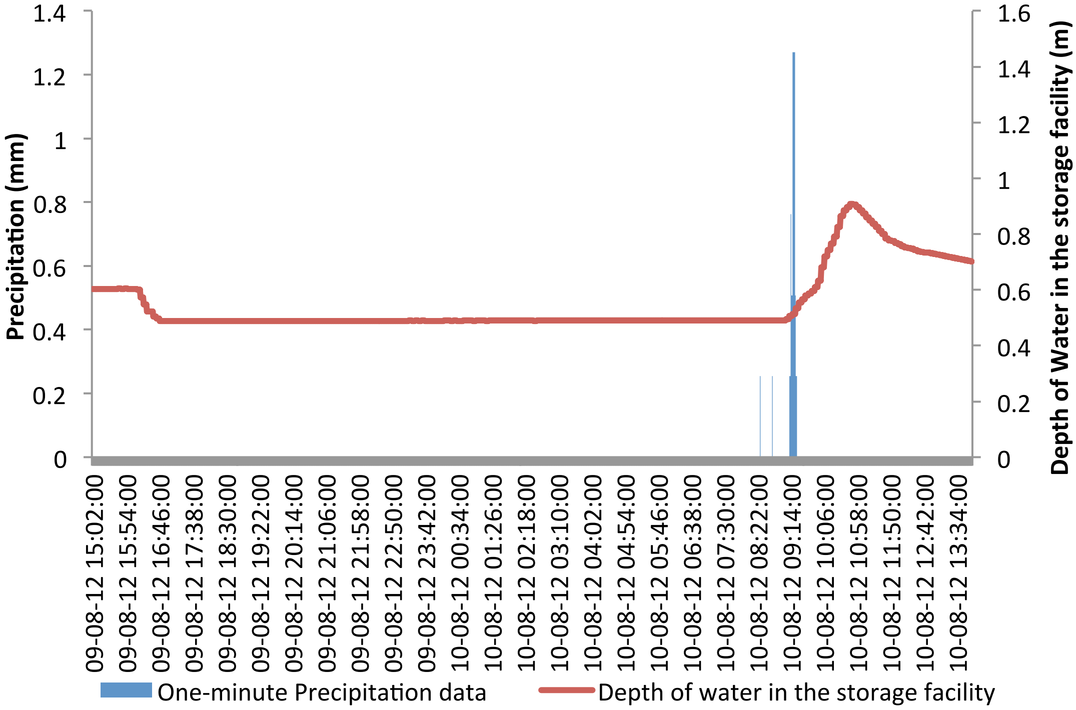


Figure 25. Pressure transducer readings and precipitation data for 9th August 2012 and 10th August 2012

By observing the pressure transducer depth data, after fluctuations in readings the volume in the storage facility was estimated to be 14.47 cubic meters, an estimated increase in volume of 5.08 cubic meters.

To better understand the relationship between the storage depth and incident precipitation, a hypothesis test was conducted to test whether a correlation between changes in depth and precipitation exists. Change in depth was defined as the difference in depth of the storage facility over a single time step (1 minute). The correlation coefficient was then determined to be 0.0168 although miniscule still suggests that there exists a correlation between changes in storage depth and precipitation while the p-value was determined to be 4.21e-7. The hypothesis test thus suggests that based on this preliminary analysis, it can be concluded that although weak there exists a positive correlation between the two variables that is statistically significant.

The two charts in Figure 24 and 25 iterate the fact that the storage facility is able to capture stormwater runoff nevertheless for the facility to function as a stormwater management facility, the system must be able to supply water for irrigation or other non-potable purpose. In either case, it can be concluded that stormwater management goals are being met since there is a reduction in stormwater runoff that would otherwise flow into the combined sewer system.

4.5 Summary

In this chapter, a preliminary analysis on the performance of the system based on the pressure transducer and precipitation data collected between 13th June 2012 and 15th August 2012 was presented. The analysis suggests that the system is responsive to various precipitation events and because of limited use of the pump, the observed depth in the storage facility was at maximum capacity for most of the observation period. A linear relationship was also obtained between the storage capacity of the StormChamber® and the pressure transducer depth data. Based on a single pumping event that took place on 9th August 2012 and the precipitation event following that and by hypothesis testing it was determined that there exists a correlation between depth and precipitation data that is significant, thus rejecting the hypothesis that their does not exist a relationship between the two. These findings although not completely conclusive suggests that the runoff obtained from the residential roofs is collected and stored by the RWH system. It is thus recommended that a larger data set of observations spanning the entire growing season would be helpful in order to determine whether the system is able to efficiently capture residential runoff.

CHAPTER 5: ANALYZING SIMILAR SITES IN PHILADELPHIA USING GIS

The final step in the analysis was to develop a map that displays various residential blocks across the City of Philadelphia where a similar RWH system, built to manage stormwater and provide supplemental irrigation needs to an urban agriculture facility can be replicated. For this purpose, planimetric data (spatial data that describes only the horizontal position of features) downloaded from PASDA (Pennsylvania Spatial Data Access, 2011) was obtained and imported into ArcGIS 10.1 (ESRI, 2009). The planimetric data contains features such as (AIMS, 2009):

- Building Outlines
- Topographic data
- Edge of Pavement
- Fences
- Trees

The analysis was limited to the municipal boundary of the city (Figure 26). Within this boundary, only areas classified as building outline, individual blocks, grass and shrubs, trees and other vacant spaces were considered. Using GIS, a sequence of queries were performed to obtain prospective sites where a similar RWH system as constructed at 53rd and Wyalusing Avenue can be replicated. A separate set of queries were also performed to obtain prospective sites where a stand alone storage facility could be connected to residential roofs in order to replicate the same system but without the bioretention facility and the irrigation facility. The entire analysis was divided into a GIS analysis followed by analyzing two residential blocks to validate the results obtained.

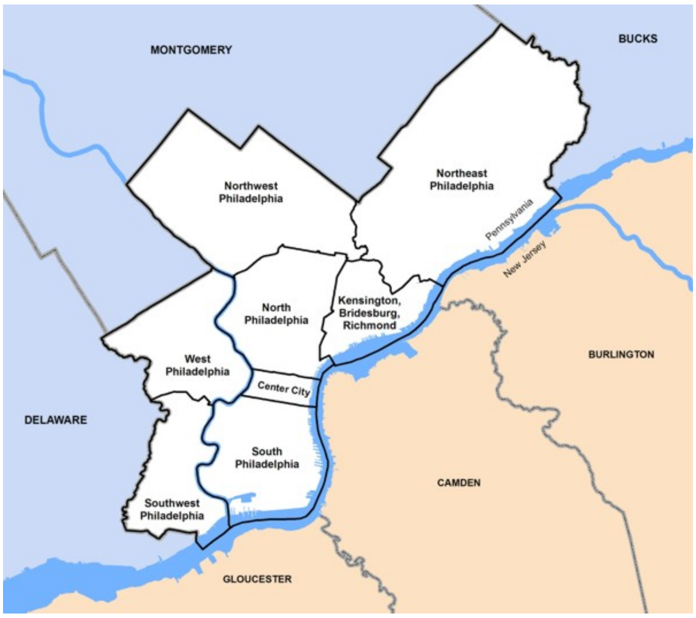


Figure 26. Municipal boundary of the City of Philadelphia

5.1 Constraints

Based on the Rainwater Harvesting (RWH) system designed at 53rd and Wyalusing, we develop the following constraints to determine which sites across the city of Philadelphia will be suitable to use the same design to construct the RWH system including the ability to accommodate a farm of the same size as at 53rd & Wyalusing:

- Only land parcels that are residential areas shall be considered in the analysis.
- Only green spaces within residential blocks shall be taken into consideration as available space while for replicating the RWH system. The area consisting of tree canopy and paved surface (excluding roof area) shall be assumed to be unavailable for the construction of the RWH system.
- Only residential blocks with a minimum conjoined roof area of 1020 square meter would be considered as a prospective site for the replication of the

RWH system. This value was based on the total area of 12 residential roofs that were used to design the RWH system at 53rd and Wyalusing Avenue.

- A minimum area of 42 sq. m of green space is required for the storage facility while an area of 853 sq. m of green space is required to replicate the entire RWH system. These values were based on the area occupied by the storage facility and the RWH system at the site at 53rd and Wyalusing Avenue.

5.2 GIS Analysis

In order to analyze the spatial data, the buildings were extracted from the planimetric data and then intersected with the tax parcels that were also obtained from the data. By obtaining various properties such as land use, these sites were analyzed to obtain sites across Philadelphia where a RWH system may have a significant impact on the reduction of runoff as well as provide economic benefits. The following steps give a more detailed outlook on how the analysis was performed using the ArcGIS 10.1 software (ESRI, 2009):

- The first step was to segregate the type of area (city block) such as residential, commercial or industrial and extract only residential blocks. Figure 32 in Appendix J shows the residential areas across the city that includes various residential blocks as defined in the planimetric data. Based on this, the total residential area across the city was estimated to be approximately 31 square miles (i.e. about 80.3 square kilometers).
- The next step was to determine which residential blocks contain at least 1020 square meters of roof area and thus only such residential blocks were taken into consideration. Figure 33 in Appendix J shows the residential blocks across the city that contains at least 1020 square meters of conjoined

residential roof area. Based on this analysis, the total residential area with this minimum required residential roof area across the city of Philadelphia was estimated to be approximately 4.3 square miles (i.e. about 11 square kilometers)

- The next step was to extract the layer that displays vacant green spaces within the city limits that includes both grass/shrubs as well as tree canopy. Figure 34 in Appendix J shows the vacant green spaces for the City of Philadelphia, based on which the total vacant green space area was estimated to be approximately 60 square miles (about 155.4 square kilometers).
- Since tree canopies do not in fact represent vacant green spaces, they were omitted and only green spaces that represent grass and shrubs were taken into consideration. Figure 35 in Appendix J shows the green spaces that excludes tree canopy based on which the area of green space was estimated to be approximately 33.3 square miles (about 86 square kilometers).
- The next step was to take into consideration only those green spaces that are located within residential blocks and omit if otherwise. Figure 36 in Appendix J shows the green spaces that excludes tree canopy within residential area in the City of Philadelphia, based on which it was estimated this area was to be approximately 11.84 square miles (about 30.7 square kilometers).
- The penultimate step involved plotting a map that displays residential blocks (containing at least 1020 square meters of conjoined roof area) that contain at least 42 square meter or 452 square feet (required for storage facility) of green space as shown in Figure 37 in Appendix J.
- The final step in the GIS analysis was to plot a map that displays residential blocks (containing at least 1020 square meter conjoined of roof area) that

contain at least 853 square meter (required for the growing area of same size as Polselli, the storage facility as well as the Bioretention facility) of green space as shown in Figure 38 in Appendix J, based on which the total green space available for replication the entire

5.3 Results and Validation

Based on the GIS analysis it was concluded that the total green space at residential areas available for replicating the RWH system without the irrigation facility was estimated to be 0.482 square miles (about 1.25 square kilometers) with a total of 933 different sites (each site representing a different residential block). While the total green space at residential blocks where the entire design could be exactly replicated was estimated to be 0.257 square miles (about 0.66 square kilometers) with a total of 86 different sites (each site representing a different residential block).

The final step of the analysis was to perform a validation process by looking at two specific sites where the GIS analysis suggested a RWH system could be replicated. The first site was located at 2200 Benjamin Franklin Parkway, Philadelphia that consists of approximately 4 residential buildings within the residential block (Figure 27).

Figure 27. Map of the residential site located at 3300 Benjamin Franklin Parkway, Philadelphia

Each residential building at the site has an approximate roof area of 1175 square meters while the total green space within the residential block was approximately estimated to be at least a minimum of 2500 square meters (excluding tree canopy).

The second site located at 44th and Haverford (Figure 28), Philadelphia consist of a minimum conjoined roof area of 2325 square meters while the total green space within the residential block was estimated to be a minimum of 4000 square meters (excluding tree canopy).

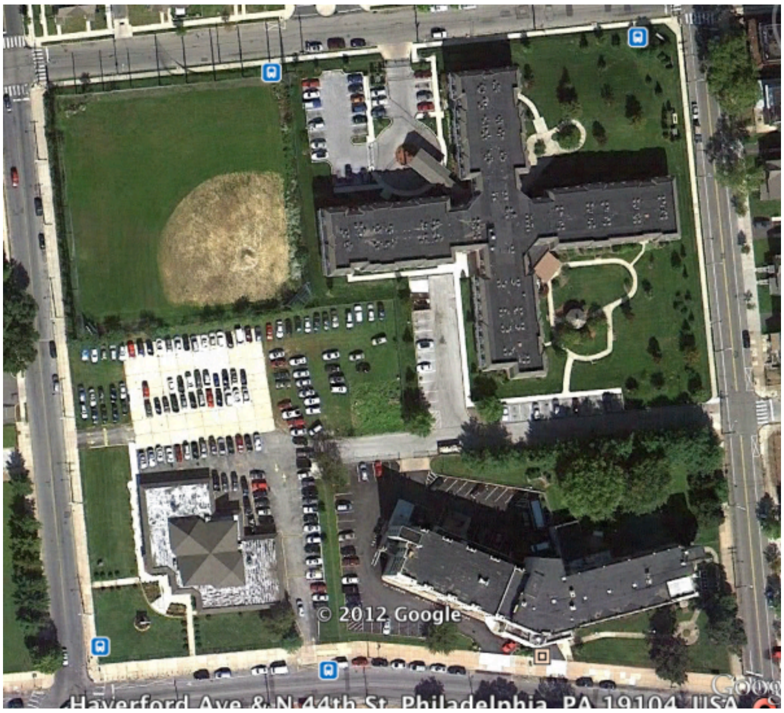


Figure 28. Satellite image of the residential block located 44th and Haverford, Philadelphia

Therefore, by studying these two sites it was concluded that GIS analysis could be efficiently implemented to obtain a rough estimate of areas where an RWH system such as the one at 53rd and Wyalusing Avenue can be replicated.

5.4 Summary

Using ArcGIS 10.1 a comprehensive GIS analysis was performed in order to analyze other residential blocks within the City of Philadelphia where a similar RWH system can be constructed. The analysis was performed using planimetric data obtained from PASDA. Based on the analysis performed, it was estimated that stand alone storage facility with the same specification as those at 53rd and Wyalusing Avenue could be constructed at 933 residential blocks within the city while the entire system could be replicated at an estimated 86 residential blocks within the city. Though the analysis does not take into account various other constraints such as soil quality at these locations, a preliminary validation process was conducted suggesting that GIS analysis can be efficiently used to estimate areas where an RWH system such as the one installed at 53rd and Wyalusing Avenue can be replicated without specific individual site analysis.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

The RWH system for the urban agricultural facility situated at 53rd and Wyalusing Avenue was successfully designed and constructed using a non-parametric stochastic process implemented through SARET (Basinger, Montalto, & Lall, 2010). The following chapter summarizes results from sections of this thesis including a summary of the analytical methods used to design the RWH system, a summary of the design vs. constructed RWH system, a summary of the assessment of the system, a summary of the scale up study followed finally by overall conclusions and few recommendations made for future work.

6.1 Summary of analytical design methods

The RWH system at 53rd and Wyalusing Avenue was designed using a non-parametric rainfall simulation method incorporated in SARET that utilizes 25-year historical daily precipitation data (1964-1988). The working of the model in SARET was later verified by developing a customized non-parametric model using the HMM tool and a MATLAB program. Five 25-year precipitation sequences for the month of January was created and compared to January precipitation sequence synthesized using SARET for the same period. It was evident while comparing the box and whisker plot for the five precipitation sequences with those obtained from SARET and the historical precipitation record that non-parametric rainfall simulation models are able to encapsulate statistical properties of the input historical data.

6.2 Designed RWH system vs. Constructed RWH system

In order to estimate the irrigation requirements two methods were employed, the Blaney-Criddle method and the use of water bills. Though similar, the results obtained using the water bills seem to be more reliable since they were estimated by the use of actual data on the site. Once the irrigation requirements for the entire growing season was determined, it was concluded to design the RWH system based on a worst case scenario of irrigating 60.9 mm/week throughout the entire new growing season in order to maximize the reliability of the system during periods of droughts. Finally, the storage vs. catchment area reliability curves was developed using historical daily precipitation data and other site constraints such as range of catchment area, storage range, irrigation usage and first flush based on which it was concluded that for a catchment area of 850 square meters (10 residential roofs), the volume of the storage facility would be 10 cubic meters.

The specifications of the RWH facility were finalized by designing the bioretention facility (rain garden) employed to improve the water quality of the runoff before storage based on the "Design of Stormwater Filtering Systems" manual (Schueler, 1996) that was to be situated at the backyard of residential building with a dimension of 5 m by 3.96 m (16.5 feet by 13 feet). The area of the bioretention facility was designed to be 7 square meters with a WQV of 2.7 cubic meters.

Based on various constraints encountered at the site, construction plans for various sections of the RWH system were laid out. The locations of each of these were based on the availability of space, minimize the runoff travel time as well as other site constraints such as landowner consent. StormChamber® developed by Hydrological Solutions normally used for temporary detention was implemented in the RWH system as a storage facility with the use of a pond liner to minimize initial investment.

Although only three StormChamber® was to be used as a storage facility, an extra chamber was added in order to incorporate the flexibility of connecting further roofs to the system. The bioretention facility had the following specifications of 3.65 m by

2.3 m (12 feet by 7.5 feet) satisfying the designed area requirement of 7 square meters. The depth of the facility was designed based on those suggested by the "Design of Stormwater Filtering Systems" manual to allow a retention time of 24 hours. Although the system was to be connected to ten residential roofs, due to unexpected homeowner issues seven residential roofs were connected to the system instead but with the hope of connecting more roofs in the future.

6.3 Summary of performance testing

In order to assess the performance of the system, depth readings from the storage facility and precipitation data were obtained at the site. The stage-storage relationship was obtained based on which a parametric equation was defined relating the depth and storage volume for the storage facility. This equation could be used to estimate the volume of water available based on the measured depth in the storage facility. A single pumping event was observed to have taken place during the entire two-month period for which data was collected, this lack of use of the system for the purpose of irrigation was attributed to the malfunctioning of the pump. It was observed that during this single pumping event 3.96 cubic meters of water was pumped out while the following precipitation event resulted in an increase in storage by 5.08 cubic meters. Finally, a statistical test was performed to estimate whether there actually exists a correlation between incident precipitation and change in storage depth. Based on the test, a correlation coefficient of 0.0168 with a p-value lesser than 0.05 was estimated suggesting that although the linear correlation may be weak, it is significant. Based on this preliminary assessment, it was concluded that the system satisfies the goal of a stormwater management system but the system efficiency could not be commented upon due to the lack of pumping events and the period of observation.

6.4 Summary of the scale up study (GIS analysis)

Using planimetric data, GIS analysis was employed to perform a sequence of queries to obtain prospective sites where a similar RWH system as constructed at 53rd and Wyalusing Avenue could be replicated. For the analysis, only residential areas and green spaces excluding tree canopy within the municipal boundary of Philadelphia were considered as available space for replicating the system. To replicate the entire RWH system it was required that the residential block have at least 1020 square meters of conjoined roof area and at least 853 square meters of green space. Based on which, it was estimated that the entire RWH system could be replicated at 86 residential blocks within the municipal boundary of Philadelphia. The results were then validated by individually analyzing two residential blocks that were claimed by the GIS analysis to be conducive for the replication of the RWH system.

6.5 Overall Conclusions

The non-parametric rainfall simulation method incorporated in SARET was successfully used to design the RWH system at the urban agricultural facility. Reiterating previous findings (Basinger, Montalto, & Lall, 2010), a comprehensive analysis can be performed using SARET to obtain storage vs. catchment area reliability curves using historic daily precipitation data, based on which volume of the storage facility and the catchment area are estimated that would comprise the core design of the RWH system. The bioretention facility was utilized as a cost effective option to improve the WQ of stormwater runoff collected from residential roof areas while StormChamber® developed by Hydrological Solutions was implemented as an cost effective alternative to a conventional storage facility. The RWH system was constructed to make sure available space was efficiently used and the distance between the catchment area and storage facility was minimized. The performance of the system was analyzed based on a preliminary assessment using depth obtained from the storage facility for two months. A statistical test was also performed to establish a linear correlation between storage depth and incident precipitation that although weak was statistically significant.

Finally a GIS analysis was performed to obtain an estimated 86 residential sites across the municipal boundary of Philadelphia where the RWH system could be replicated. The result was then validated by individually analyzing two residential blocks by obtaining residential roof area and area of green space (without canopy) at the respective sites.

6.6 Recommendations and future work

Based on this projects and the following analysis, few recommendations were made pertaining to future work at the site as well as recommendations to improve the RWH system:

- Though SARET can be used in order to efficiently size the RWH system, irrigation requirements for agricultural facilities must be more rigorously calculated. Due to inability to obtain sufficient data at the site, various assumptions were made in order to estimate irrigation requirements. This plays an important role since irrigation defines the demand aspect of the RWH system.
- In the future, RWH systems such as the one constructed that involve the consent of various homeowners, a written consent must be obtained in order to ensure that problems aren’t encountered that restricts the realization of the system.
- To better understand the efficiency with which the bioretention facility is employed as a treatment facility, data pertaining to the WQ of the runoff must be obtained prior and after treatment.

- Problems regarding the working of the pump such as over heating were encountered at the site within the first few months. This setback proposed operations and delayed the use of the system. Therefore, the pump might play a critical role in order to conclude whether the system is a success. Hence, RWH systems that employ underground storage facilities for the purpose of irrigation must make sure that the pump is efficiently used to minimize wear and tear and the pump installed can irrigate the entire facility without over burdening operations.
- With better use of the pump and regular use of the RWH system for the purpose of irrigation as required, data can be obtained to better analyze various operational parameters of the system and better understand the working of the system.
- Comprehensive data must be obtained at the site and extensive analysis must be performed to understand the reason behind the instantaneous discharge of water from the storage facility after a certain depth is reached. Analysis must be conducted with larger data sets in order to contemplate the reason behind this. For this purpose, it is proposed that flow data from the overflow pipe in the bioretention facility must be obtained.
- Though a similar RWH system could be replicated based on the GIS analysis performed, other constraints such as soil composition may affect the system stability at different sites and hence before implementation, the site and its background must be fully understood.

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Appendix A: Abbreviations

Table 7. A summary of abbreviations used throughout the text

Abbreviation	Description
NPS	Non-Point Source
LID	Low Impact Development
BMP	Best Management Practices
CSO	Combined Sewer Overflow
WPCP	Water Pollution Control Plant
RWH	Rain Water Harvesting
SARET	Storage and Reliability Estimation Tool
HMM	Hidden Markov Model
MATLAB	MATrix LABoratory
GIS	Geographical Information System
R_y	Volumetric Coefficient for Urban Runoff
WQ	Water Quality
A_s	Sub-catchment Area
H_{max}	Maximum level of ponding
t_f	Retention time
k	Coefficient of permeability for the top soil mix
d_f	planting soil depth
W	Number of wet days
D	Number of dry days

Table 7 (continued). A summary of abbreviations used throughout the text

Abbreviation	**Description**
WW	Number of wet days following a wet day
WD	Number of dry days following a wet day
DD	Number of dry days following a dry day
DW	Number of wet days following a dry day
$P_i(W)$	Probability of a wet day for a day "i"
$P_i(WW)$	Probability that day "i" will be wet, given day "i-1" was wet
$P_i(WD)$	Probability that day "i" will be dry, given day "i-1" was wet
$P_i(DD)$	Probability that day "i" will be dry, given day "i-1" was dry
$P_i(DW)$	Probability that day "i" will be wet, given day "i-1" was dry
NTS	Not to Scale

Appendix B: Description of the Non-parametric rainfall simulation (SARET)

The following text gives a brief description of the non-parametric method employed in SARET (Basinger, Montalto, & Lall, 2010). Once the historic observations are provided as an input, a separate array is created for each day of the year for the each observation that consists of daily precipitation year amounts for the 15 days preceding the target day and 14 days following the target year. In this case of a 25 year precipitation record, each day of each year consists of 750 daily precipitation amounts in this “moving window”, the 15 days preceding the target day 1 of year 1 are the last for 15 days of year 32 and the 14 days following the target day 365 of year 32 are the first 14 days of year 1. Once such an array is developed, SARET calculates the probability of a wet day that (Eq. 1), the probability of a wet day following a wet day (Eq. 2), the probability of a dry day following a wet day (Eq. 3), the probability of a dry day following a dry day (Eq. 4) and the probability of a wet day following a dry day (Eq. 5) for each of the 365 days in a year. Therefore, each day “i” has its own unique set of first order Markov chain probabilities, incorporating seasonality directly into the rainfall generation algorithm.

$$\mathrm{Pi(W)} = \frac{\mathrm{W}}{\mathrm{W+D}}$$

$$\mathrm{Pi(WW)} = \frac{\mathrm{W}}{\mathrm{W+D}}$$

$$\mathrm{Pi(WD)} = 1 - \mathrm{P(WW)}$$

$$\mathrm{Pi(DD)} = \frac{\mathrm{DD}}{\mathrm{DD+DW}}$$

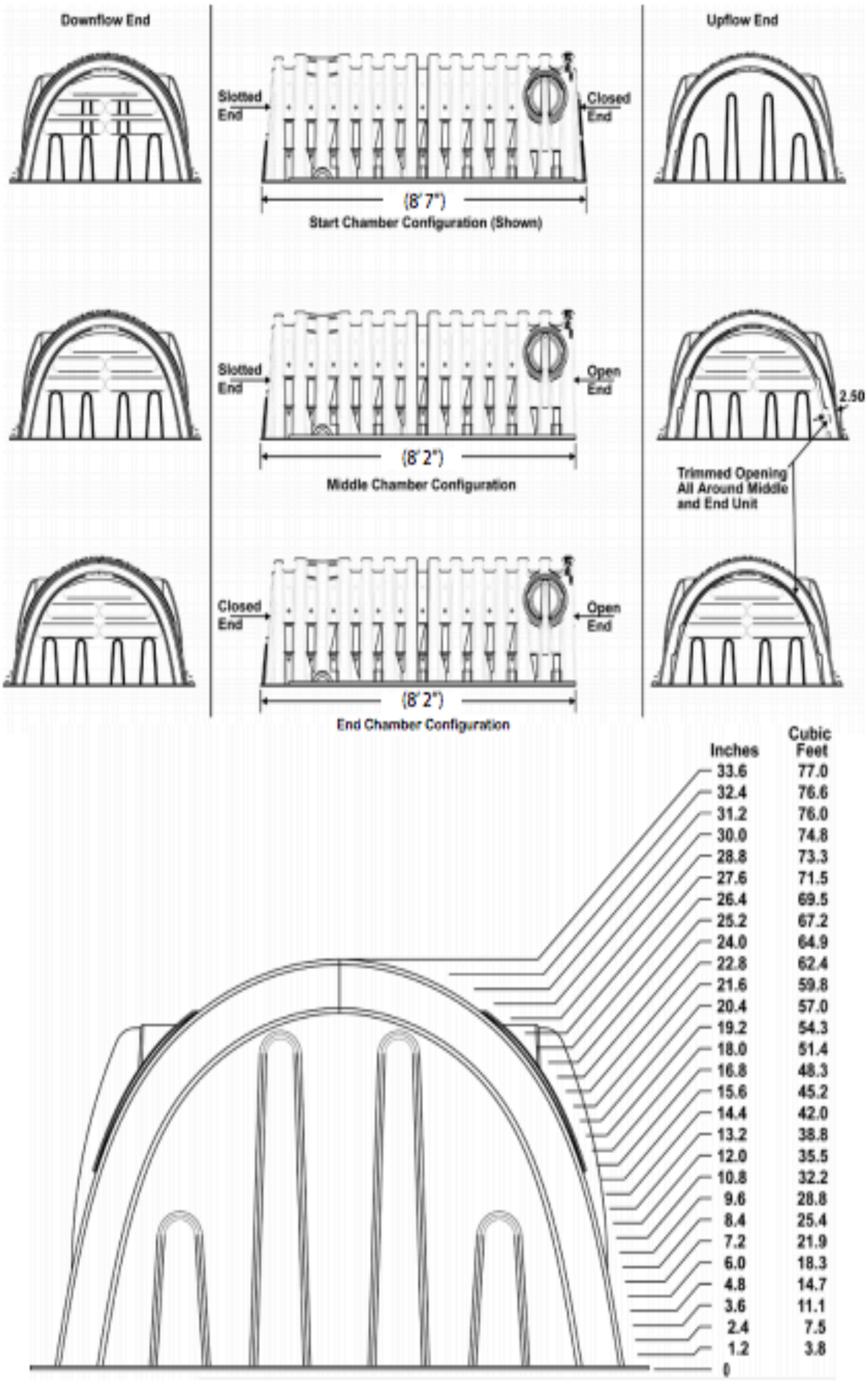
$$\mathrm{Pi(DW)} = 1 - \mathrm{P(DD)}$$

Once the five probabilities are calculated using the equations shown above, SARET generates a synthetic series of daily wet and dry flags (a synthetic 32 year record), in which the flag of the first day in each scenario is determined solely based on P(W), while subsequent days looks at the “wet” or “dry” flag assigned to previous days using the appropriate probability. For example, if day 1 was assigned a “dry” flag, then day 2 would utilize P(DD) from the day 2 array, but if day 1 was assigned a “wet” flag, then day 2 would utilize P(WW) from the same day 2 array, hence the Markov relationship to prior values adds memory to the model thus improving the robustness of the model (Basinger, Montalto, & Lall, 2010).

Appendix C: Customized non-parametric rainfall simulation model (MATLAB)

```
% The purpose of this program is to mimic the capability of an HMM tool
% and thus create ten simulations (8 years x 31 days) for each station.
% for this model we assume that a dry day would have 0 mm precipitation
load Philadelphiastate2valuespostcompjan.txt
Trans(1,1)=0.4964728124873;
Trans(1,2)=0.5035271875127;
Trans(2,1)=0.7437956038655;
Trans(2,2)=0.2562043961345; % Define the Transition Probability Matrix
emis=[1/2,1/2; 1/2,1/2];  % Define the Emission Matrix though according to this
program, might not have any implication on the resulting sequencing matrix
[seq,states]=hmmgenerate(775,Trans,emis); % use the hmmgenerate tool to generate
% the states
states=states'; % Transpose the States matrix to implement in Bootstrap
% Bootstrap is then performed for each station to obtain ten simulation for each
for j=1:1:10
for i=1:1:775
if states(i,1)==1
    s1(i,j)=0;
else
  [bootstat,bootsam]=bootstrp(100,@mean,Philadelphiastate2valuespostcompjan);
  s1(i,j)=Philadelphiastate2valuespostcompjan(bootsam(1,1),1);
end
end end
```

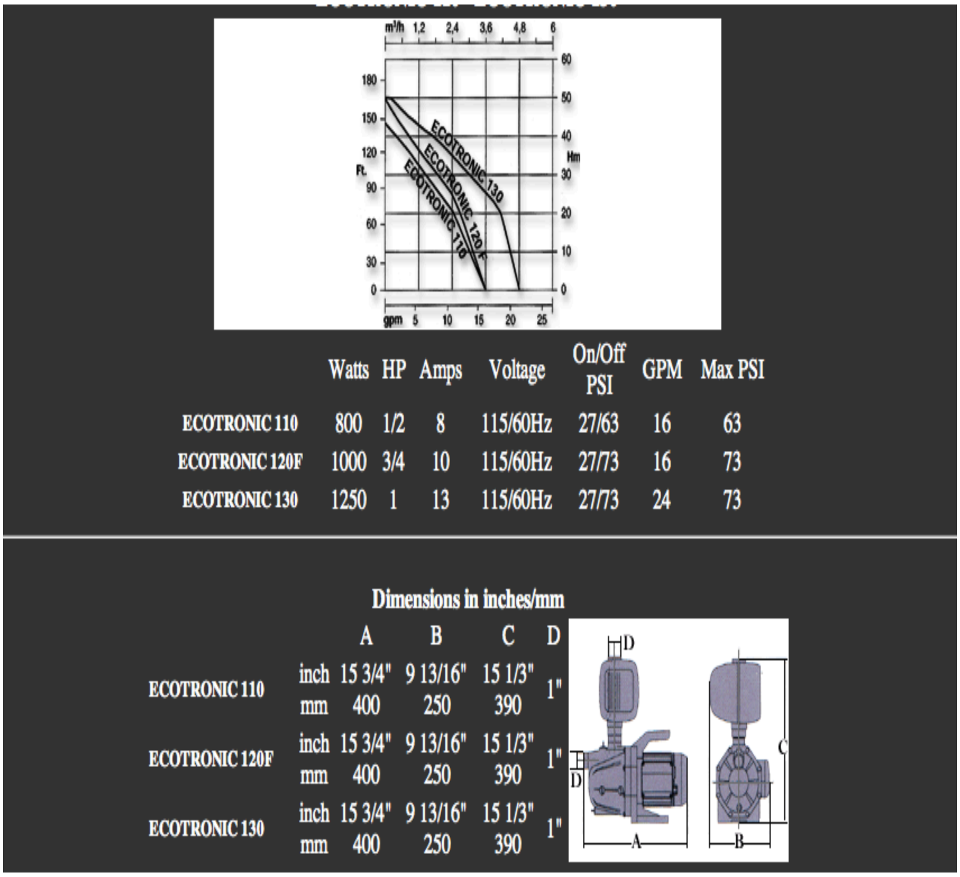
Appendix D: StormChamber® chamber configurations



Inches	Cubic Feet
33.6	77.0
32.4	76.6
31.2	76.0
30.0	74.8
28.8	73.3
27.6	71.5
26.4	69.5
25.2	67.2
24.0	64.9
22.8	62.4
21.6	59.8
20.4	57.0
19.2	54.3
18.0	51.4
16.8	48.3
15.6	45.2
14.4	42.0
13.2	38.8
12.0	35.5
10.8	32.2
9.6	28.8
8.4	25.4
7.2	21.9
6.0	18.3
4.8	14.7
3.6	11.1
2.4	7.5
1.2	3.8
0	

Figure 29. Start chamber, middle chamber and end chamber configurations of the StormChamber® as provided by HydroLogic Solutions

Appendix E: Pump Specifications



	Watts	HP	Amps	Voltage	On/Off PSI	GPM	Max PSI
ECOTRONIC 110	800	1/2	8	115/60Hz	27/63	16	63
ECOTRONIC 120F	1000	3/4	10	115/60Hz	27/73	16	73
ECOTRONIC 130	1250	1	13	115/60Hz	27/73	24	73

Dimensions in inches/mm

		A	B	C	D
ECOTRONIC 110	inch	15 3/4"	9 13/16"	15 1/3"	1"
	mm	400	250	390	
ECOTRONIC 120F	inch	15 3/4"	9 13/16"	15 1/3"	1"
	mm	400	250	390	
ECOTRONIC 130	inch	15 3/4"	9 13/16"	15 1/3"	1"
	mm	400	250	390	

Appendix F: RWH System component list

Table 8. Rainwater Harvesting system component list at the site

Component	Specifications	No. of Units (Quantity)
Stormchamber (Storage Facility)	approx. 920 to 1265 Gallons/unit (3.49 to 4.8 cubic meters)	4
Heavy Duty Netting for Storage facility	1 piece Heavy duty netting for the Storage facility	1
Pond Liner (for Storage facility)	Will need 56' by 26' Firestone 45 mil EPDM Pond Liner	1
Pond Liner (for bioretention facility)	Will need 24' by 20' of Firestone 45 mil EPDM Pond Liner	1
Top Soil mix (for bioretention facility)	Top Soil Mix	6 Cubic Yards
Gravel (for Storage facility)	-	60 Cubic yards (assume all that is used is Gravel) out of which 45 cubic yards can be substituted for other uniform stone
Gravel (for bioretention facility)	-	5 Cubic yards
PVC pipe 1 (for Storage facility manhole)	Sch 40 10inch x 8ft Rigid PVC pipe	4
PVC pipe 3 (for	Sch 40 8inch x 6ft Rigid	3

Table 8 (continued). Rainwater Harvesting system component list at the site

Component	Specifications	No. of Units (Quantity)
Bioretention facility connection to Storage facility)	PVC pipe	-
PVC pipe 3 (Riser pipe for Bioretention facility)	Sch 40 4inch x 6ft Rigid PVC pipe	11
8in to 4in pipe Adapters for Raingarden	P102-582 8" x 4" reducing couple DVW	1
Elbows (Raingarden riser pipe and overflow pipe)	406-040 90 degree 4 inch elbow	4
Elbow (for overflow pipe from Raingarden)	417-040 45 degree 4 inch elbow	3
4 way and 3way PVC pipe connectors for Bioretention facility	426-040 4 inch 4 way	3
PVC caps (for bioretention facility clean out pipes)	447-040 4inch cap sch 40	5
PVC pipe couplers (Bioretention facility to Stormchamber)	429-080 8inch couple	1
PVC pipe couplers (4")	429-040 4inch couple	5
French Drain (for bioretention facility and for overflow pipe)	Genova Products 40051-WEST 4" dia (10 feet) SDR35 Perf Pipe	8
PVC caps (for Manhole)	10in fabricated Flat Cap	4
4-oz non-woven Filter fabric	Mirafi® 140 NC 4 oz. 12.5’ x 360’	1 (will be used for Stormchamber and Bioretention facility)

Appendix G: Irrigation facility at 53rd and Wyalusing Avenue, Philadelphia

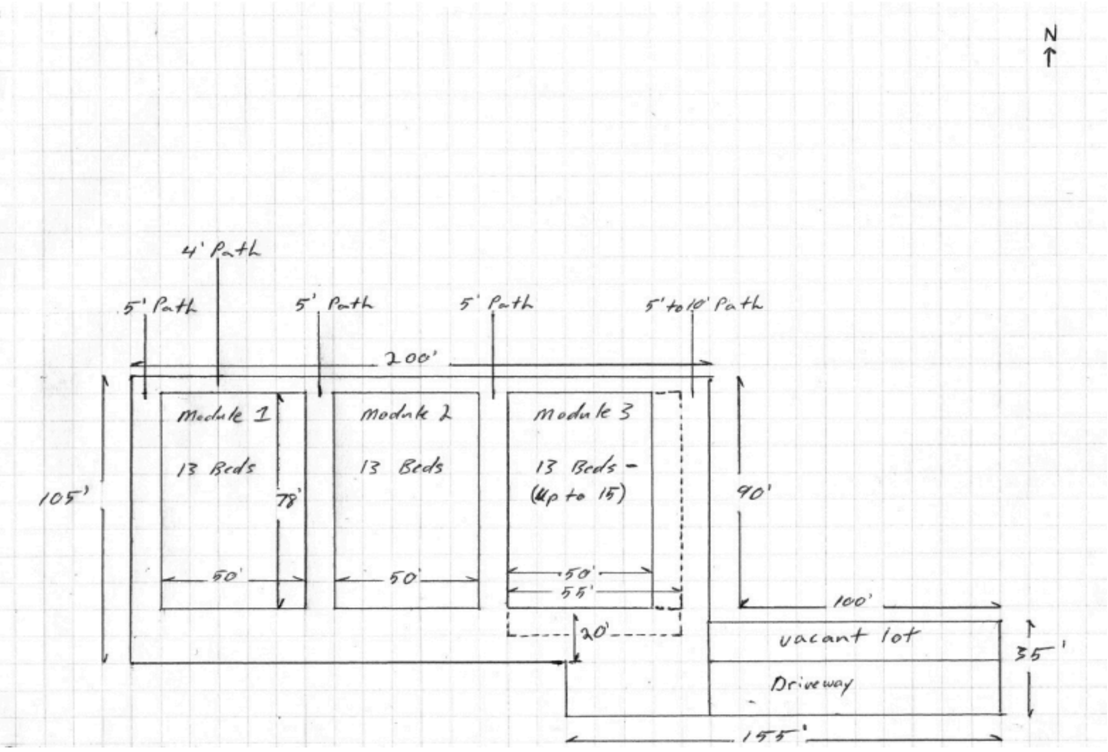


Figure 30. Layout of the Irrigation facility (all dimensions in feet)

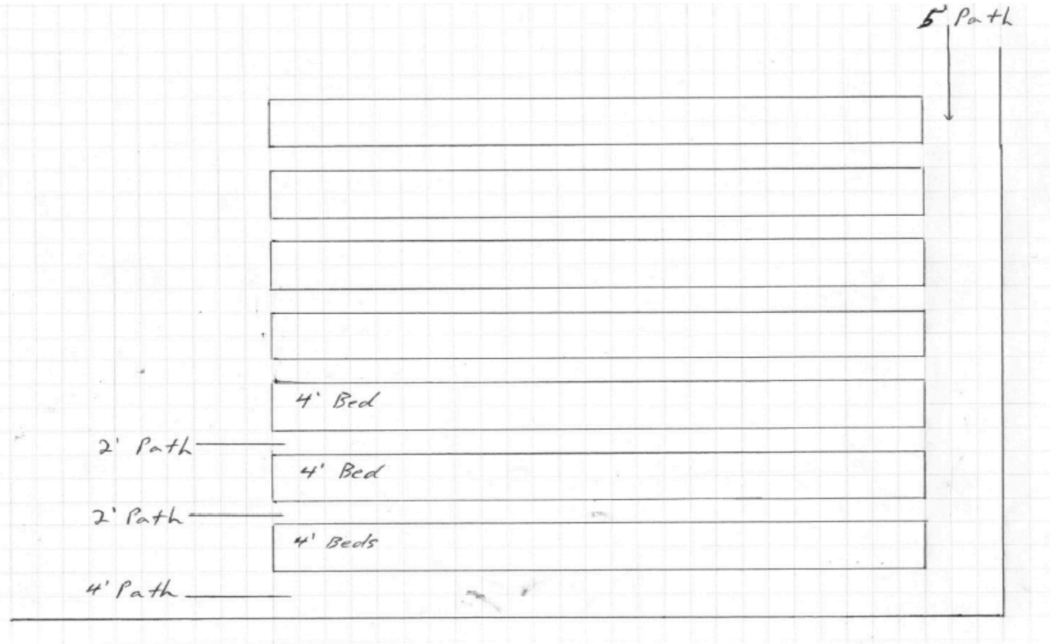
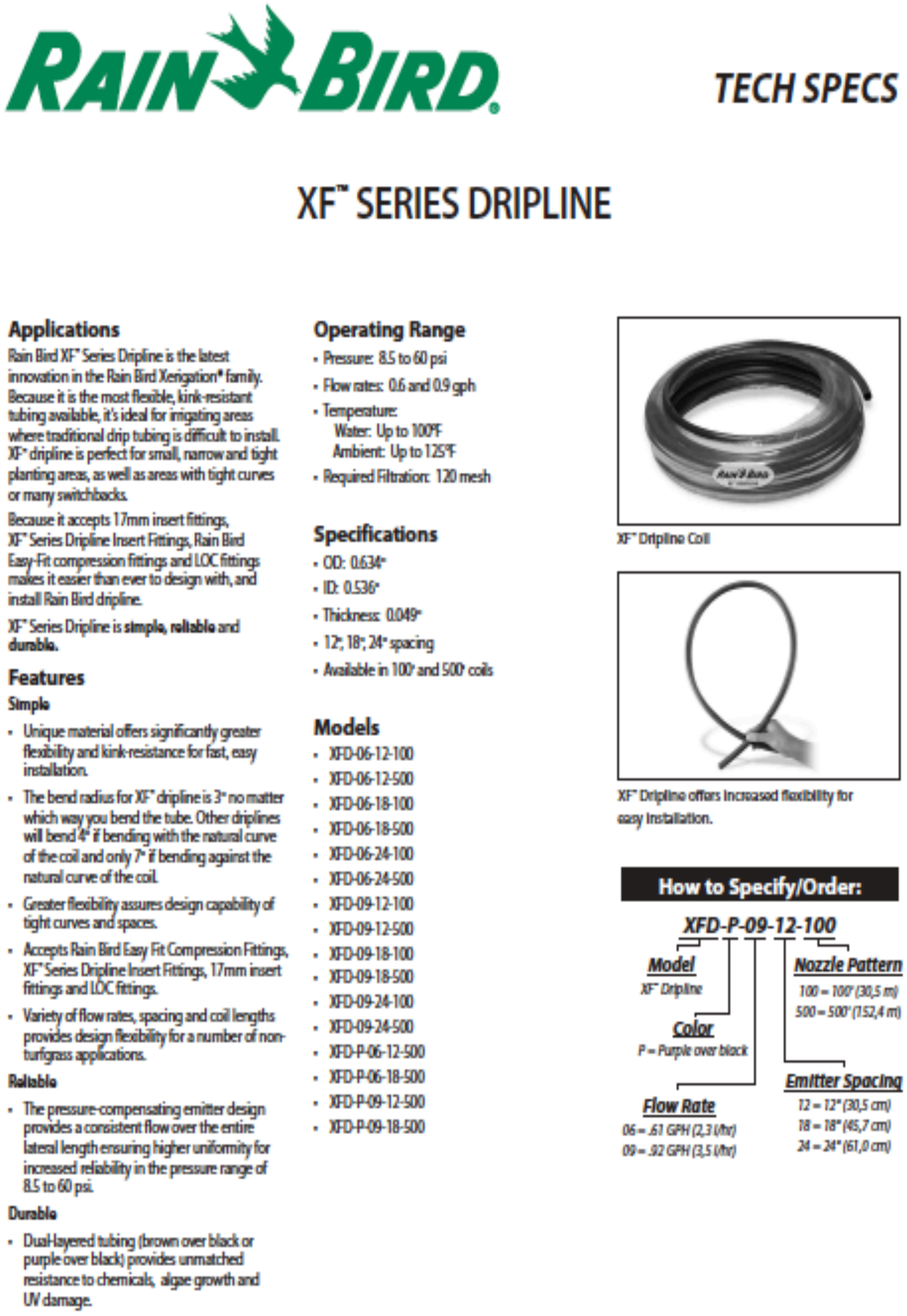


Figure 31. Layout of growing beds at Module 1 (all dimensions in feet)

Appendix H: Irrigation facility at 53rd and Wyalusing Avenue, Philadelphia



RAIN BIRD

TECH SPECS

XF™ SERIES DRIPLINE

Applications

Rain Bird XF™ Series Dripline is the latest innovation in the Rain Bird Xerigation® family. Because it is the most flexible, kink-resistant tubing available, it's ideal for irrigating areas where traditional drip tubing is difficult to install. XF™ dripline is perfect for small, narrow and tight planting areas, as well as areas with tight curves or many switchbacks.

Because it accepts 17mm insert fittings, XF™ Series Dripline Insert Fittings, Rain Bird Easy-Fit compression fittings and LOC fittings makes it easier than ever to design with, and install Rain Bird dripline.

XF™ Series Dripline is **simple, reliable** and **durable.**

Features

Simple

- Unique material offers significantly greater flexibility and kink-resistance for fast, easy installation.
- The bend radius for XF™ dripline is 3" no matter which way you bend the tube. Other driplines will bend 4" if bending with the natural curve of the coil and only 7" if bending against the natural curve of the coil.
- Greater flexibility assures design capability of tight curves and spaces.
- Accepts Rain Bird Easy Fit Compression Fittings, XF™ Series Dripline Insert Fittings, 17mm insert fittings and LOC fittings.
- Variety of flow rates, spacing and coil lengths provides design flexibility for a number of non-turfgrass applications.

Reliable

- The pressure-compensating emitter design provides a consistent flow over the entire lateral length ensuring higher uniformity for increased reliability in the pressure range of 8.5 to 60 psi.

Durable

- Dual-layered tubing (brown over black or purple over black) provides unmatched resistance to chemicals, algae growth and UV damage.

Operating Range

- Pressure: 8.5 to 60 psi
- Flow rates: 0.6 and 0.9 gph
- Temperature:
  Water: Up to 100°F
  Ambient: Up to 125°F
- Required Filtration: 120 mesh

Specifications

- OD: 0.634"
- ID: 0.536"
- Thickness: 0.049"
- 12", 18", 24" spacing
- Available in 100' and 500' coils

Models

- XFD-06-12-100
- XFD-06-12-500
- XFD-06-18-100
- XFD-06-18-500
- XFD-06-24-100
- XFD-06-24-500
- XFD-09-12-100
- XFD-09-12-500
- XFD-09-18-100
- XFD-09-18-500
- XFD-09-24-100
- XFD-09-24-500
- XFD-P-06-12-500
- XFD-P-06-18-500
- XFD-P-09-12-500
- XFD-P-09-18-500

XF™ Dripline Coil

XF™ Dripline offers increased flexibility for easy installation.

How to Specify/Order:

XFD-P-09-12-100

Model
XF™ Dripline

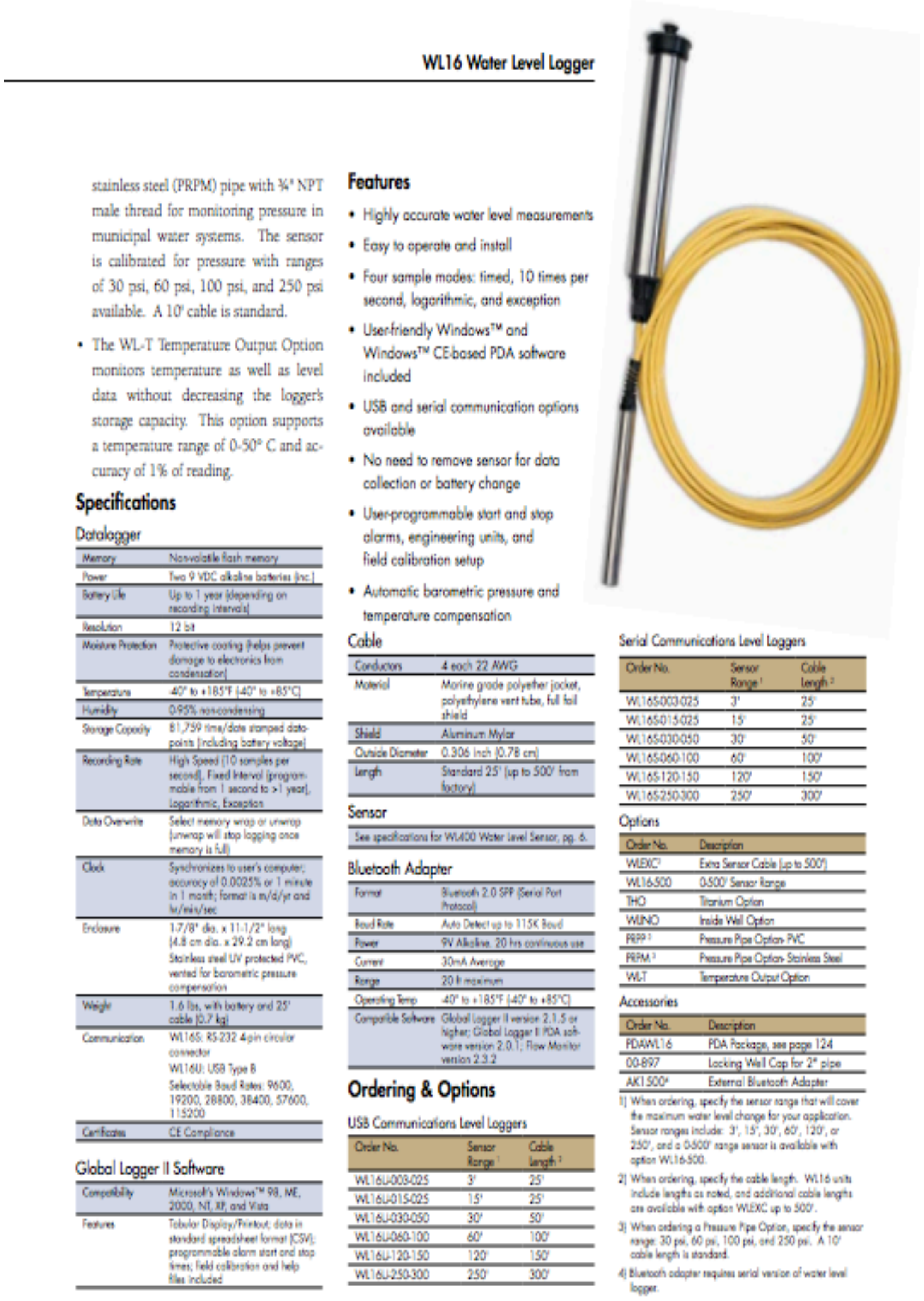
Color
P = Purple over black

Flow Rate
06 = .61 GPH (2,3 l/hr)
09 = .92 GPH (3,5 l/hr)

Nozzle Pattern
100 = 100' (30,5 m)
500 = 500' (152,4 m)

Emitter Spacing
12 = 12" (30,5 cm)
18 = 18" (45,7 cm)
24 = 24" (61,0 cm)

Appendix I: WL16U water level logger specifications sheet



WL16 Water Level Logger

stainless steel (PRPM) pipe with ¾" NPT male thread for monitoring pressure in municipal water systems. The sensor is calibrated for pressure with ranges of 30 psi, 60 psi, 100 psi, and 250 psi available. A 10' cable is standard.

- The WL-T Temperature Output Option monitors temperature as well as level data without decreasing the logger's storage capacity. This option supports a temperature range of 0-50° C and accuracy of 1% of reading.

Specifications

Datalogger

Memory	Non-volatile flash memory
Power	Two 9 VDC alkaline batteries (inc.)
Battery Life	Up to 1 year (depending on recording intervals)
Resolution	12 bit
Moisture Protection	Protective coating (helps prevent damage to electronics from condensation)
Temperature	-40° to +185°F (-40° to +85°C)
Humidity	0-95% non-condensing
Storage Capacity	81,759 time/date stamped data-points (including battery voltage)
Recording Rate	High Speed (10 samples per second), Fixed Interval (programmable from 1 second to >1 year), Logarithmic, Exception
Data Overwrite	Select memory wrap or unwrap (unwrap will stop logging once memory is full)
Clock	Synchronizes to user's computer; accuracy of 0.0025% or 1 minute in 1 month; format is m/d/yr and hr/min/sec
Enclosure	1-7/8" dia. x 11-1/2" long (4.8 cm dia. x 29.2 cm long) Stainless steel UV protected PVC, vented for barometric pressure compensation
Weight	1.6 lbs, with battery and 25' cable (0.7 kg)
Communication	WL16S: RS-232 4-pin circular connector WL16U: USB Type B Selectable Baud Rates: 9600, 19200, 28800, 38400, 57600, 115200
Certificates	CE Compliance

Global Logger II Software

Compatibility	Microsoft's Windows™ 98, ME, 2000, NT, XP, and Vista
Features	Tabular Display/Printout; data in standard spreadsheet format (CSV); programmable alarm start and stop times; field calibration and help files included

Features

- Highly accurate water level measurements
- Easy to operate and install
- Four sample modes: timed, 10 times per second, logarithmic, and exception
- User-friendly Windows™ and Windows™ CE-based PDA software included
- USB and serial communication options available
- No need to remove sensor for data collection or battery change
- User-programmable start and stop alarms, engineering units, and field calibration setup
- Automatic barometric pressure and temperature compensation

Cable

Conductors	4 each 22 AWG
Material	Marine grade polyether jacket, polyethylene vent tube, full foil shield
Shield	Aluminum Mylar
Outside Diameter	0.306 Inch (0.78 cm)
Length	Standard 25' (up to 500' from factory)

Sensor

See specifications for WL400 Water Level Sensor, pg. 6.

Bluetooth Adapter

Format	Bluetooth 2.0 SPP (Serial Port Protocol)
Baud Rate	Auto Detect up to 115K Baud
Power	9V Alkaline. 20 hrs continuous use
Current	30mA Average
Range	20 ft maximum
Operating Temp	-40° to +185°F (-40° to +85°C)
Compatible Software	Global Logger II version 2.1.5 or higher; Global Logger II PDA software version 2.0.1; Flow Monitor version 2.3.2

Ordering & Options

USB Communications Level Loggers

Order No.	Sensor Range[1]	Cable Length[2]
WL16U-003-025	3'	25'
WL16U-015-025	15'	25'
WL16U-030-050	30'	50'
WL16U-060-100	60'	100'
WL16U-120-150	120'	150'
WL16U-250-300	250'	300'

Serial Communications Level Loggers

Order No.	Sensor Range[1]	Cable Length[2]
WL16S-003-025	3'	25'
WL16S-015-025	15'	25'
WL16S-030-050	30'	50'
WL16S-060-100	60'	100'
WL16S-120-150	120'	150'
WL16S-250-300	250'	300'

Options

Order No.	Description
WLEXC[2]	Extra Sensor Cable (up to 500')
WL16-500	0-500' Sensor Range
THO	Titanium Option
WLINO	Inside Well Option
PRPP[3]	Pressure Pipe Option- PVC
PRPM[3]	Pressure Pipe Option- Stainless Steel
WL-T	Temperature Output Option

Accessories

Order No.	Description
PDAWL16	PDA Package, see page 124
00-897	Locking Well Cap for 2" pipe
AK1500[4]	External Bluetooth Adapter

1) When ordering, specify the sensor range that will cover the maximum water level change for your application. Sensor ranges include: 3', 15', 30', 60', 120', or 250', and a 0-500' range sensor is available with option WL16-500.

2) When ordering, specify the cable length. WL16 units include lengths as noted, and additional cable lengths are available with option WLEXC up to 500'.

3) When ordering a Pressure Pipe Option, specify the sensor range: 30 psi, 60 psi, 100 psi, and 250 psi. A 10' cable length is standard.

4) Bluetooth adapter requires serial version of water level logger.

Appendix J: GIS Analysis using ArcGIS 10.1

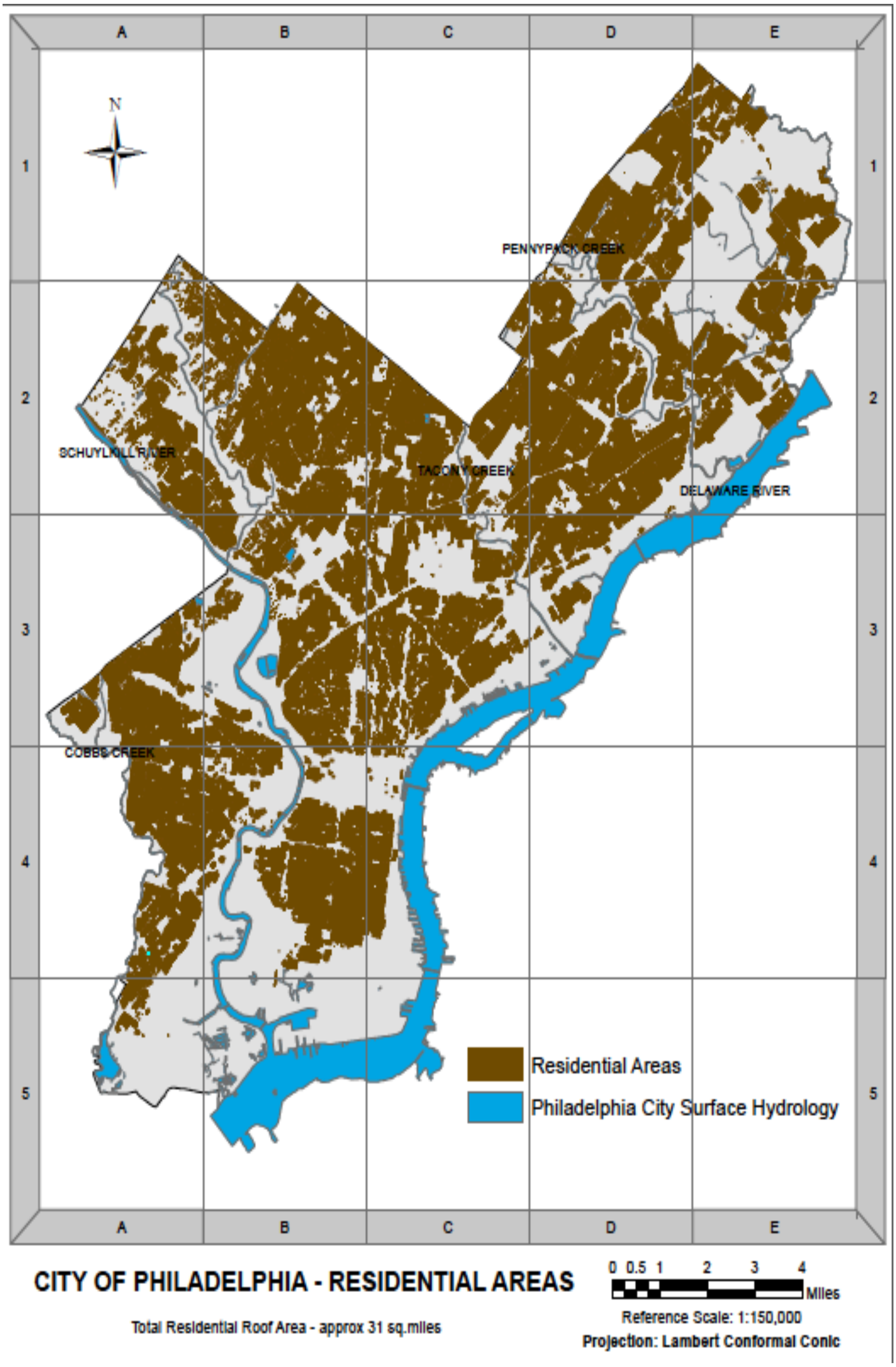


Figure 32. Map showing various residential areas across the city of Philadelphia

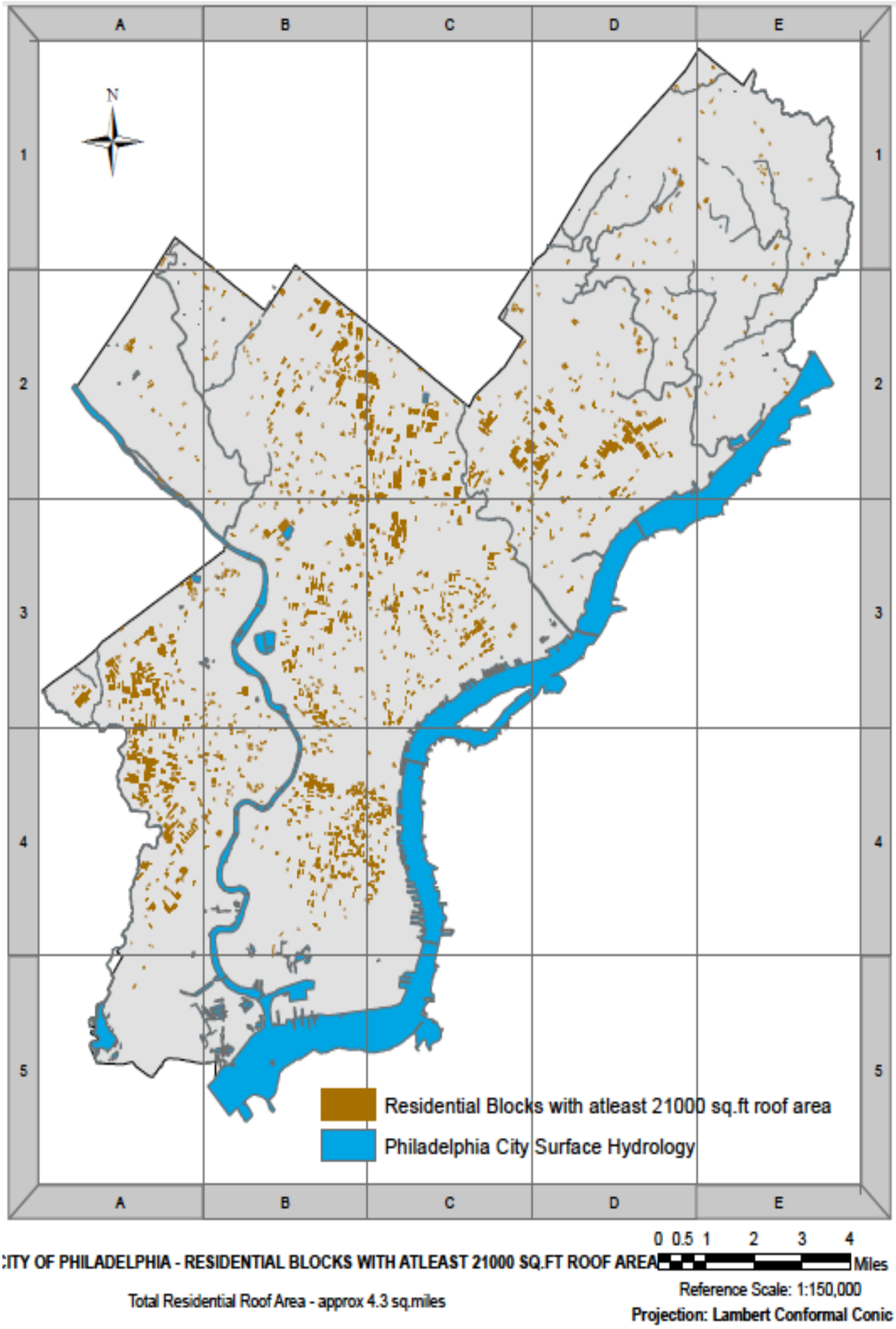


Figure 33. Map showing Residential blocks that contain at least 1950 square meters of roof area for the City of Philadelphia

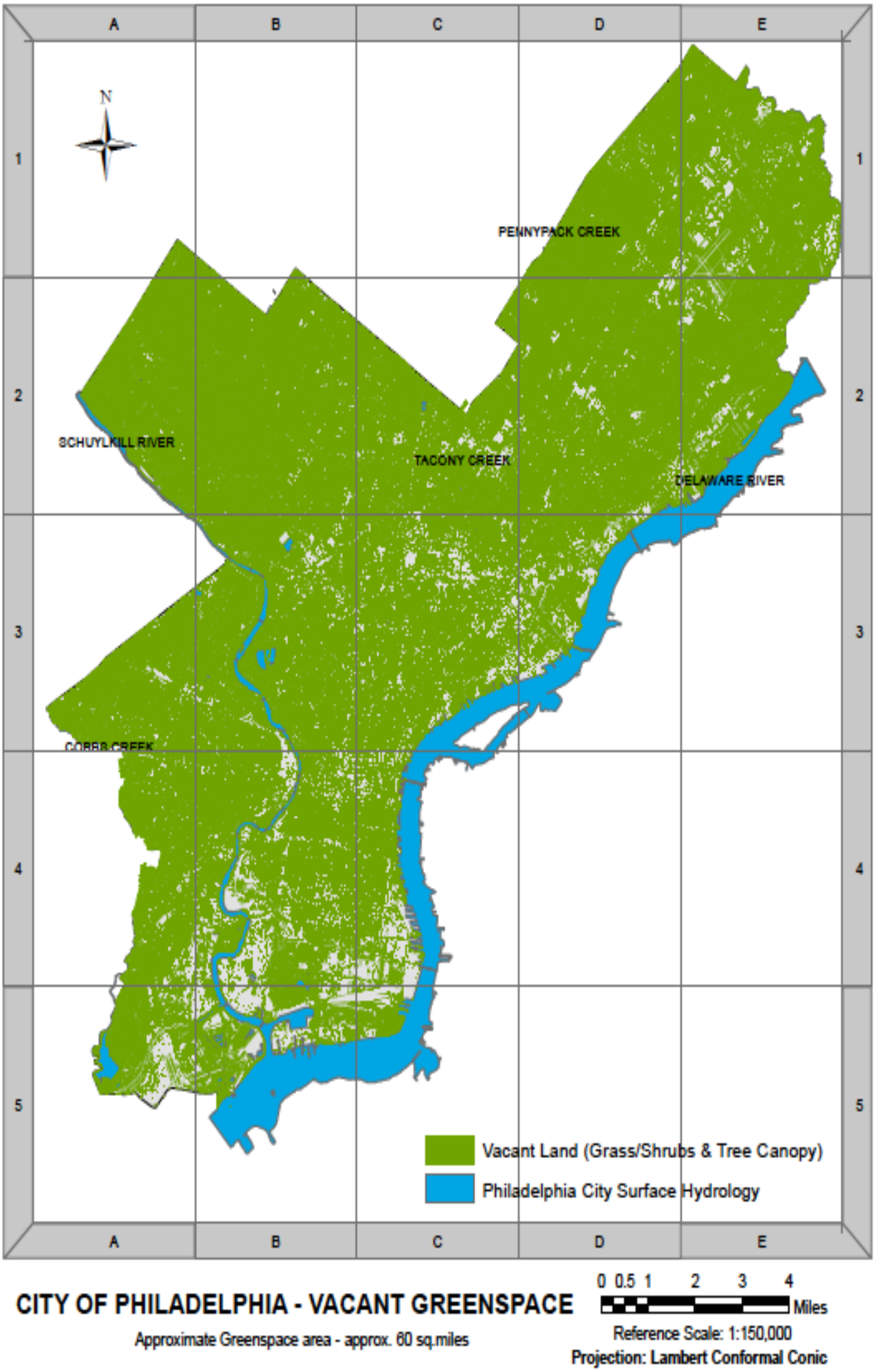


Figure 34. Map showing green spaces (Grass/Shrubs & Tree Canopy) for the City of Philadelphia

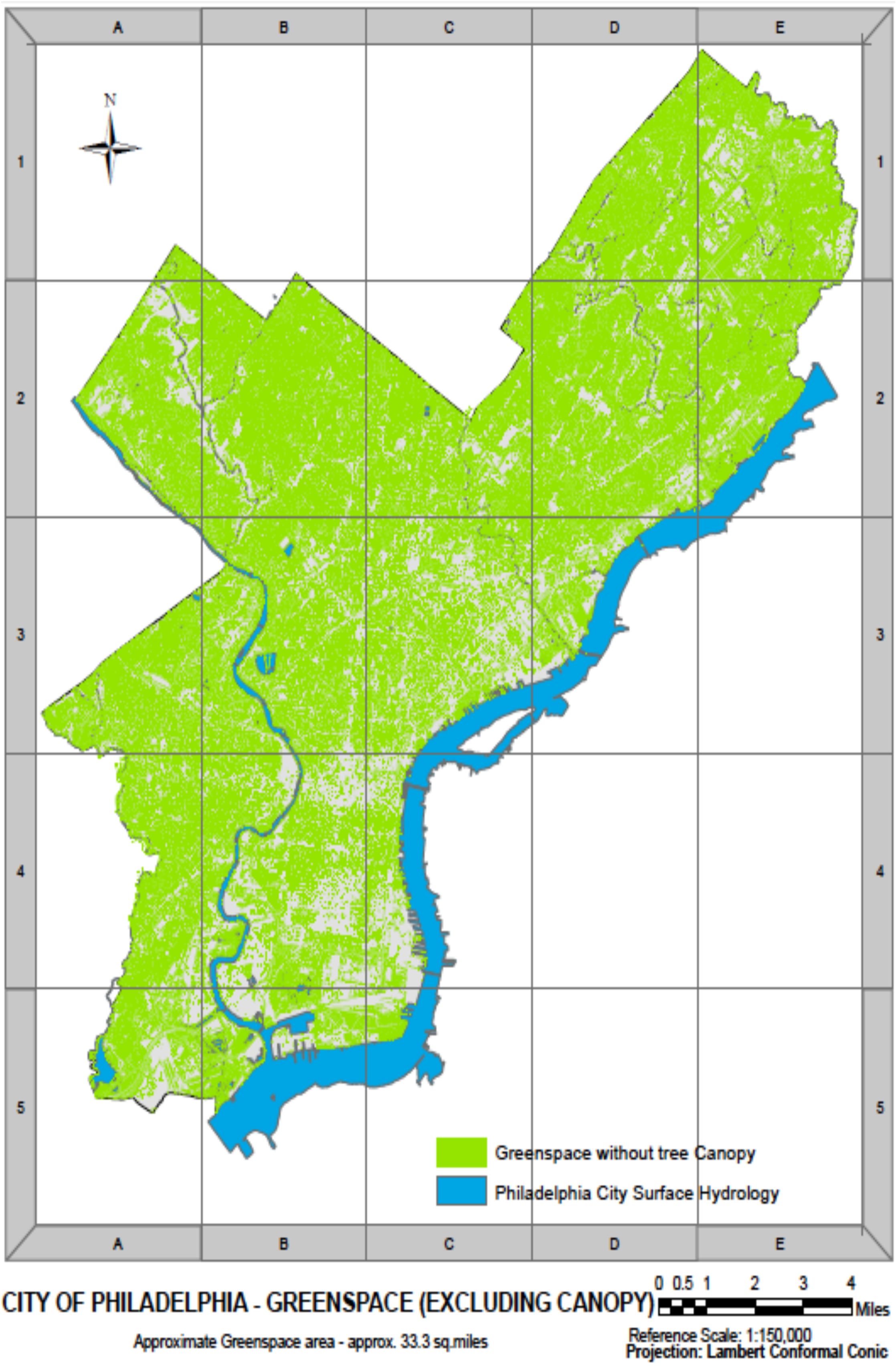


Figure 35. Map showing green spaces (Grass/Shrubs) without Tree Canopy for the City of Philadelphia

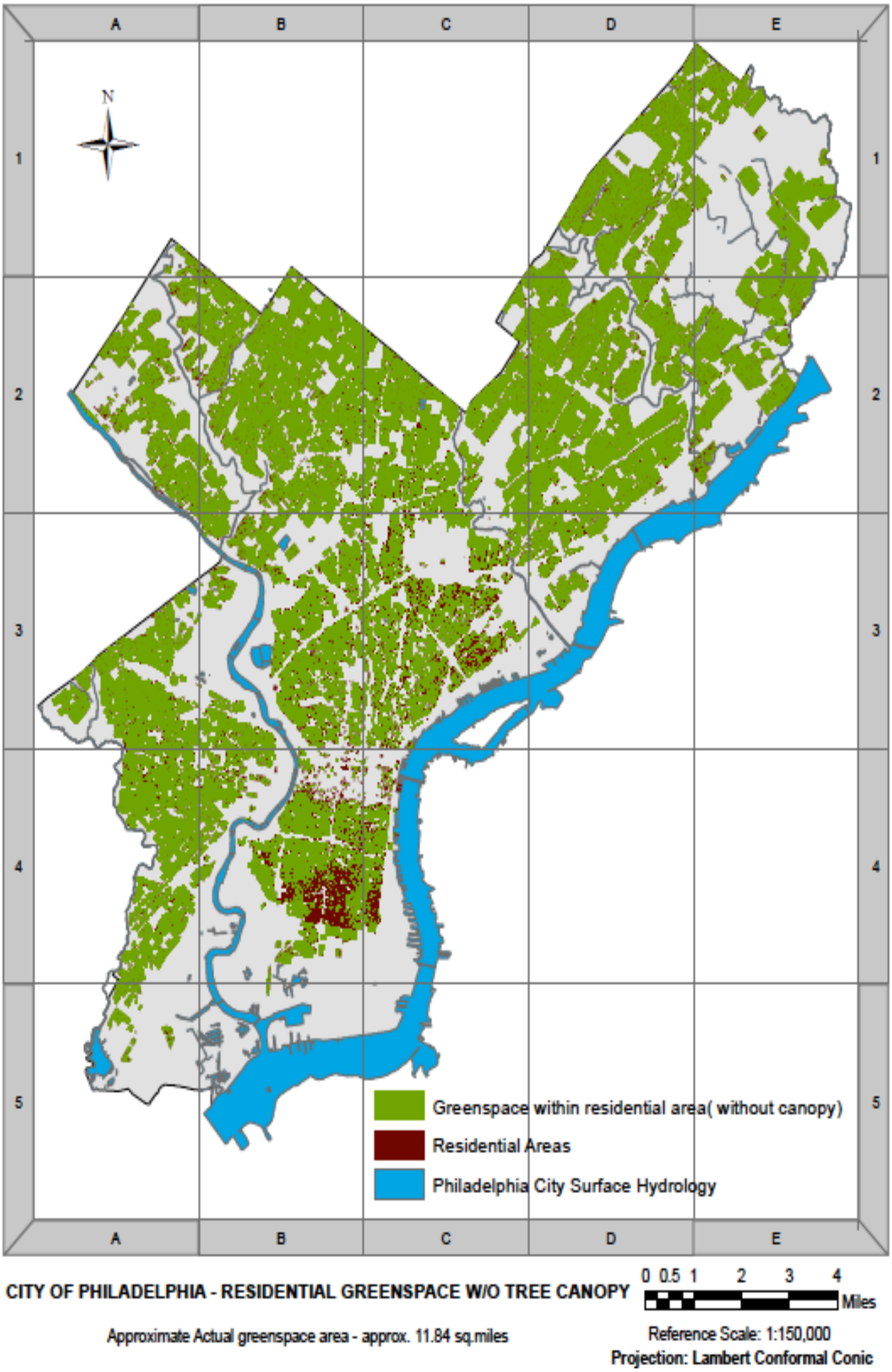


Figure 36. Map showing green spaces (Grass/Shrubs) without Tree Canopy within residential areas for the City of Philadelphia

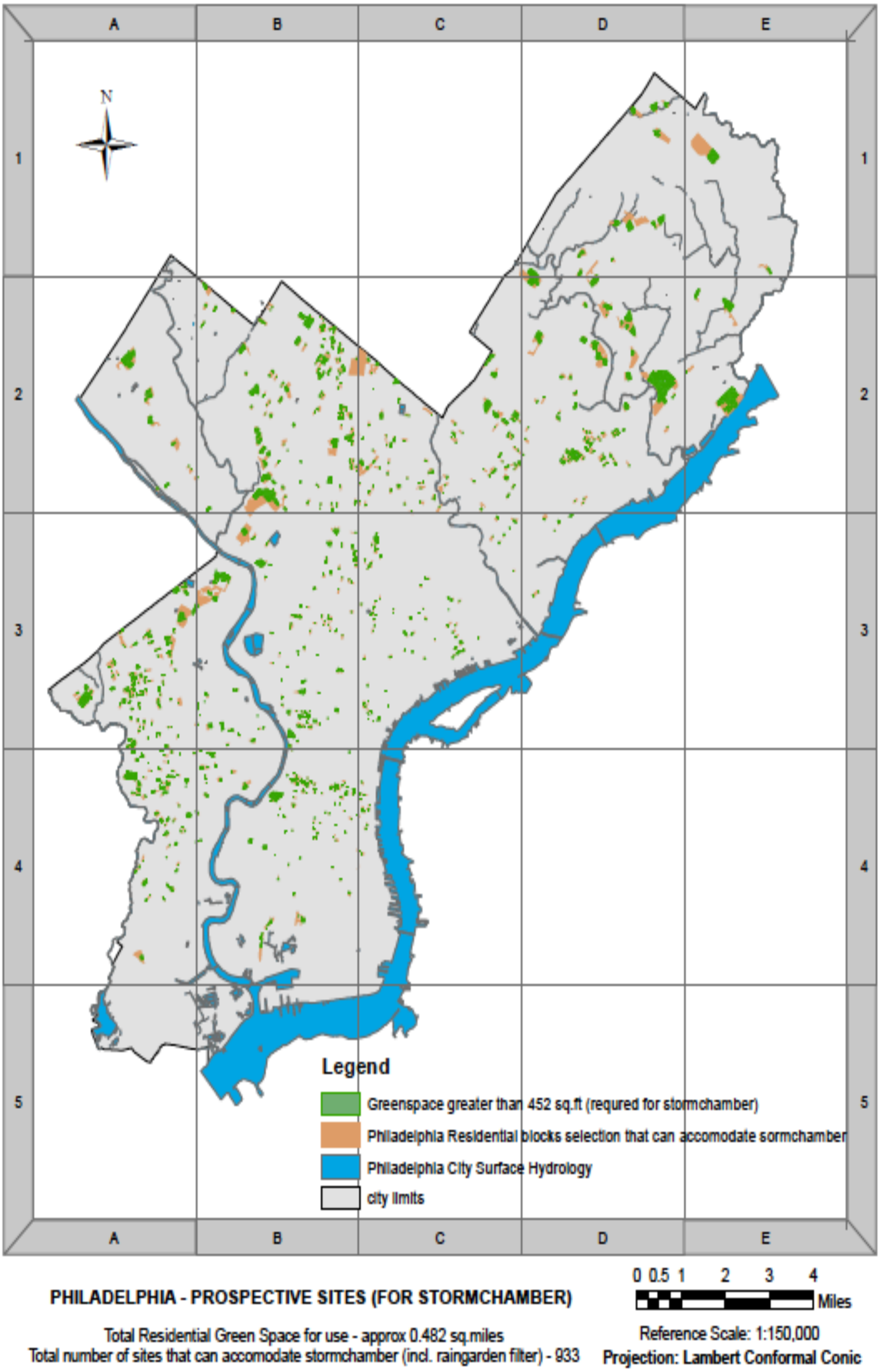


Figure 37. Map showing prospective sites for the construction of a Stormchamber with exact specifications as that at Polselli within residential areas of at least 1950 square meters of residential roof area for the City of Philadelphia

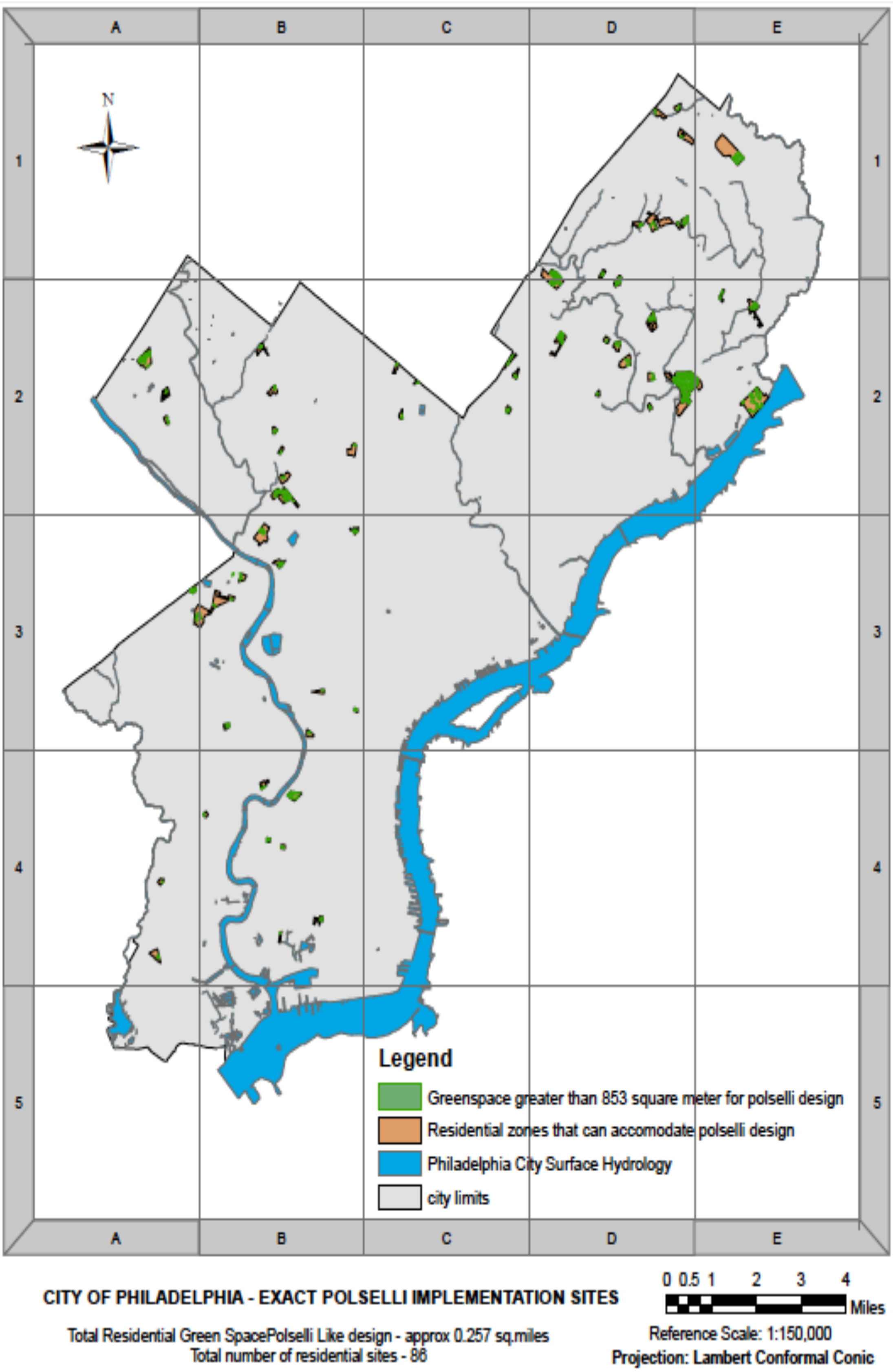


Figure 38. Map showing prospective sites to replicate the entire design at Polselli within residential areas of at least 1950 square meters of residential roof area for the City of Philadelphia