DESIGNING CISTERNS FOR GREEN ROOFS IN FLORIDA

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ABSTRACT

The use of green roofs for stormwater management purposes is becoming more popular in the United States in recent years. As a result there has been several research projects aimed at determining the volume and pollution control benefits. Despite this, no design equations have been developed to properly size a cistern for irrigation and water storage purposes. While it has been speculated that green roofs also offer water quality benefits, little research has been done to quantify this claim. This work will focus on the development of design equations for the sizing of a cistern and the resulting water quality benefits of a specifically designed green roof stormwater treatment system. This system consists of an irrigated green roof with a cistern to store and recycle stormwater for irrigation. The primary water quality pollutants of concern are nutrients, such as nitrogen and phosphorus species. These pollutants have been suspected of leaching out of the green roof growing media having an adverse affect on stormwater quality. Within this paper, design equations and a Chart are presented for the sizing of a cistern, along with water quality benefit estimates for a green roof stormwater treatment system. An example problem is also presented.

INTRODUCTION

The control of stormwater in urban Florida provides opportunities for innovative storage and treatment methods. The constant growth and expansion of the urban areas is greatly increasing the amount of impervious areas in the State. This causes several problems for all who reside in the State such as flooding and poor surface water quality to name a few. There typically is not a single discharge point to use conventional end of pipe treatment practices. In addition, rainfall becomes polluted due to poor air quality and contact with impervious surfaces. Good (1993) shows that contact with corroded and deposited roof materials is a source of stormwater pollution. In addition, contact with fertilizers and pesticides can also be a source of stormwater pollution. A solution to this problem of poor water quality from urban areas is the use of green roof stormwater treatment systems for the storage and treatment of stormwater.

A green roof stormwater treatment system is a green roof with a cistern to store and reuse filtrate for irrigation. Green roof stormwater treatment systems are a highly adaptable treatment solution with the ability to utilize most roof surfaces. This technology allows for the conversion of an impervious surface to a pervious one while having the ability to treat additional impervious areas on the property such as parking lots or adjacent roofs. In addition, green roofs can utilize other wastewater streams as “make up” water for irrigation such as grey water or condensate water.

The reuse of green roof filtrate for irrigation of the green roof enhances hydrologic related factors such as evapotranspiration, the filtering abilities of the plants and media, and the water holding abilities of the plants and media, as well as greatly reduces the volume of stormwater runoff leaving the site. To achieve runoff reduction, a cistern, or equivalent storage device, needs to be used to store green roof filtrate as well as other potential irrigation sources. The only way water will leave the system is through evapotranspiration and cistern overflow when the system reaches maximum storage capacity. The only way water will enter the system is through precipitation and “makeup” water when the existing storage is insufficient to irrigate. The efficiency of the system will be determined from the total precipitation and the total overflow. Design equations and a model are developed to estimate the size of a cistern given a desired efficiency.

An approach to the problem of stormwater runoff is to try to treat the water as close to where it was contaminated as possible. This concept is called source control (Ellis 2000). Developing an undeveloped land reduces the evapotranspiration and increases the stormwater runoff for that area, thereby changing the hydrologic cycle for the watershed. The practice of using plant- and soil-based techniques for treating and holding stormwater at the source to decrease stormwater runoff and increase evapotranspiration rates is called low-impact development (LID) (Davis et al. 2003). Within this paper, introduced is a new LID treatment option - the use of a green roof stormwater treatment system. If green roofs are shown to remove pollutants from stormwater, then the green roof system will be a way to utilize the roof space, which is in many cases a source of stormwater pollution.

Green roofs have been studied in the United States for stormwater management volume and rate control properties. Hunt and Moran (2004) completed a water budget on a non-irrigated green roof and found that for “small” precipitation events, the green roof was able to retain approximately 75% of the precipitation and reduce the peak flow by as much as 90% as well as increase the time of concentration to almost four hours. The time of concentration is the amount of time it takes for stormwater runoff to occur after a precipitation event has begun (Hunt and Moran, 2004).

Green roofs water quality has not been studied as extensively. There are currently some published water quality results and of these the results are mostly not in agreement. Emilsson (2004) found that with a fertilization rate of 5 g N/(m^2, year) the nitrogen loss from the growing media was about 16%, he also noted that a high concentration pulse occurred during the first few weeks after the fertilization event. This nutrient leaching is consistent with the findings of Moran et al. (2004). The water quality analysis done by Moran et al. (2004) also suggests that nutrients are leaching out of the growing media. This is mainly in the form of TN and TP, however there was no statistical difference between the green roof and the control roof for both concentration and mass loading for TN. TP concentration however, was significantly higher than the control roof but again, there was no statistical difference for the mass loading (Moran et al., 2004). MacMillan (2004) found that the main nutrient leaching out of the green roof is phosphorous, both phosphate and total phosphorous, which is about 97% and 95%, respectively, higher than the control roof. MacMillan (2004) found that some nitrogen species were reduced when compared to a control non-green conventional roof, or ammonia/ammonium, nitrite, and nitrite/nitrate. Hardin (2006) also did water quality analysis of green roof filtrate. He found that green roofs were effective at reducing both the concentration and mass of ammonia and nitrite+nitrate by 61% and 68% for concentration respectively and 94% and 95% for mass respectively (Hardin, 2006). Using a cistern for reuse of the filtrate, Hardin (2006) also found that green roof filtrate has an increased concentration of phosphorus, but when using a formulated pollution control media, Black & Gold™, phosphorus concentrations were not statistically different from that of the control roof while the mass reduction was about 83%.

APPROACH

An irrigated green roof in central Florida was instrumented to quantify the water volume and quality of the runoff leaving the cistern. The water quantity parameters of interest are those listed in Table 1 and the water quality parameters of interest are ammonia, nitrite+nitrate, ortho-phosphorus, and total phosphorus. There were 18 experimental green roof chambers built to model the 1600 ft^2 green roof system which is located on the Student Union building at the University of Central Florida. These chambers were located about one half mile from the full size roof and used to isolate certain variables of interest. Each chamber had an area of 16 ft^2. The overall green roof design used to construct the full scale green roof was held constant in all of the chambers. This includes the use of insulation with an R (insulation efficiency) value of 19, which is installed directly onto the roof structure. The same waterproof membrane was used, which acts as both a root barrier and a waterproofing layer, and was installed over the insulation. The protection layer (which is a three-layer material with a non-woven fabric on either side of a plastic mesh) was used to protect the waterproofing membrane against being punctured or damaged and was installed directly on top of the waterproofing layer.

The drainage media used was also consistent with that used for the full size roof, not just in material type but also at the same depth of 2 inches. The drainage media, which is installed directly onto the protection layer, creates additional pore space allowing water to flow more freely to the point of discharge while maintaining a low flow rate. The same separation fabric, which is installed directly on top of the drainage media, was also used. The purpose of the separation fabric is to keep the fine particles associated with the growing media out of the drainage media and prevent clogging.

Table 1: Water Budget Parameters of Interest. Source: Hardin 2006

Parameter	Anticipated value
P' [in/GR Area]	62.51¥
I' [in/GR Area]	1 in/week or 2 in/week
ET' [in/GR Area]	0.14¤
Z' [in/GR Area]	Will vary with storm event
O' [in/GR Area]	-
Ms [in/GR Area]	-
F' [in/GR Area]	Will vary with storm event
S' [in/GR Area]	-

www.cityoforlando.net/public_works/stormwater/
¥ Based on 2004 data, Inches per year
¤ Monthly average, Inches per day

The species of plants, which also were held constant for this experiment, include; Helianthus debilis (Dune sunflower), Gaillardia pulchella or aristata (Blanket flower), Lonicera sempervirens (Coral honeysuckle), Myricanthes fragrans (Simpson's stopper), Clytostoma callistegioides (Argentine trumpet vine), Tecomeria capensis (Cape honeysuckle), and Trachelospermum jasminoides (Confederate jasmine). The plants were selected based on hardiness, drought tolerance, the aesthetically pleasing aspects of the plant and whether or not they are native to Florida. The first four plant species are Florida natives while the last three are not.

There were two different types of growing media mixes studied; an expanded clay mix and a tire crumb mix (Black & Gold™). It should be noted at this time that the experimental chambers with the tire crumb mix were notated as both T and B&G. The expanded clay mix is 85% mineral and 15% organic. The tire crumb mix is 45% mineral, 40% inorganic and 15% organic. All of the preceding percentages are percent by volume.

The 1600 ft^2 green roof located on the University of Central Florida's Student Union building consists of a 4-6 inch deep growing media made up of the expanded clay composite mix, and is irrigated twice a week totaling 1 inch of water per week. The growing media, use of plants and irrigation rates are the variables of interest for this project.

Two different irrigation rates were studied to determine the effects on water volume retention and water quality. The regular irrigation consisted of two weekly irrigation events that totaled 1.0 inch of water per week while over irrigation consisted of two weekly irrigation events that totaled 2.0 inches of water per week. Irrigation occurred whenever the precipitation for the last 24 hours was less than the volume to be irrigated.

The added benefit of the biological processes associated with the use of plants was also examined. This was determined by constructing some of the chambers with only growing media and no plants and some with both growing media and plants. The purpose of this aspect of the experiment is to qualify which set-up (plants or no plants, regular irrigation vs. over-irrigation, etc.) will most efficiently improve the quality and reduce the quantity of stormwater runoff.

The previously mentioned experiment was used for the development of a model, CSTORM, to size the cistern component of the system and predict the expected water quantity and quality efficiency of the green roof stormwater treatment systems. The results from the experimental chambers were used to identify the variables of interest and check the accuracy of the model for the comparable central Florida climatic data.

CSTORM MODEL DEVELOPMENT

Mass Balance

Modern green roofs have been used for three decades or more in Europe. Despite this longevity there have been little or no equations developed for the design of cisterns intended to store green roof runoff for irrigation. There have been models developed to predict the runoff from a green roof using historical precipitation and evapotranspiration data. Hoffman (2006) and Miller (2000 & 2006) have both developed models for the purpose of green roof stormwater retention, but did not include the addition of a cistern to store and reuse stormwater for green roof irrigation. Both Hoffman (2006) and Miller (2000 & 2006) have identified the important factors that determine green roof efficiency without a cistern. These factors are soil moisture, soil water holding capacity, plant water holding capacity, precipitation, evapotranspiration, temperature, and humidity to name a few. While Miller (2000 & 2006) discusses the different approaches used to develop a green roof model he uses a modified groundwater modeling program for the development of the model. The models proposed by Hoffman (2006) and Miller (2000 & 2006) are a representation of the actual findings from several working green roofs. However, the mass balance across the green roof boundary may not be preserved. Further, by using groundwater modeling variables that are not easy to measure or describe with equations likely introduces more uncertainty relative to a mass balance model. The development of a mass balance approach to preserve a hydrologic balance resulted.

Similar to the design of a reuse pond, a mass balance approach can be used for the design of a green roof stormwater treatment system. To design a green roof stormwater treatment system, the inputs and outputs for a mass balance must be preserved (see Figure 1). The main system inputs and outputs are precipitation, evapotranspiration, makeup water, and overflow.

The main factors that influence the cistern water level are the filtrate from the green roof, the irrigation rate, the rate at which makeup water is added, and the overflow rate. The overflow rate will be a function of the maximum cistern storage volume and the rate at which makeup water is added will be a function of available storage water and irrigation rate. The irrigation rate is not to exceed 1.5 inches per week in the summer months, 1 inch per week in the spring and fall and 0.5 inches for the winter months. It should be noted that irrigation will not occur if, in the twenty four hours previous to the irrigation event, the precipitation volume is greater than or equal to the irrigation volume. From this it can be seen that filtrate from the green roof is the only variable that is not known.

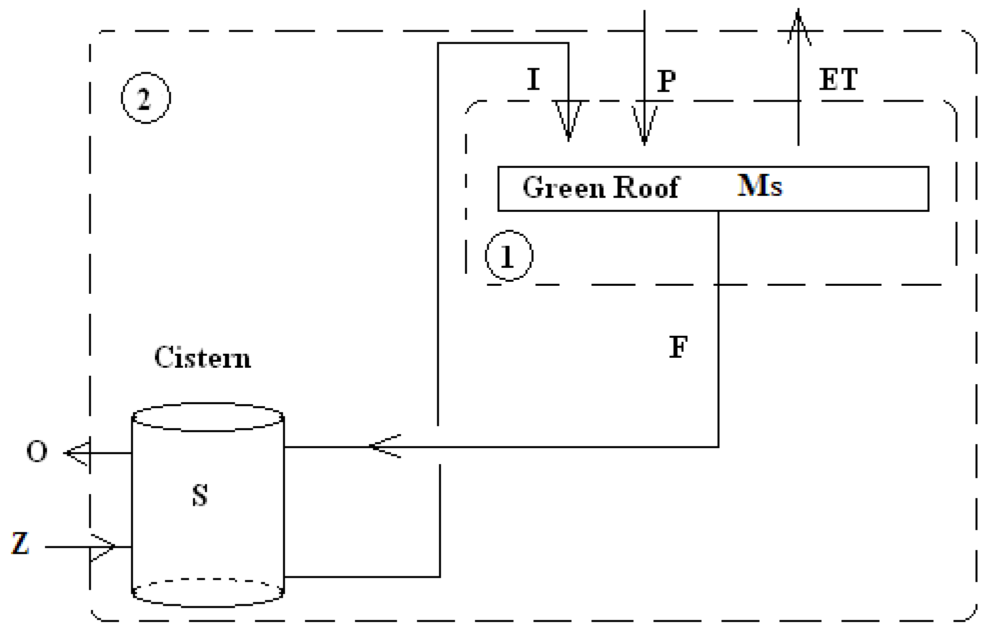

Figure 1: Green Roof Stormwater Treatment System Boundaries. Source: Hardin 2006

The variables of Figure 1 are as follows:
M_S = Media storage [in/ft^2 of green roof]
P' = Precipitation [in/ ft^2 of green roof*time]
I' = Irrigation [in/ ft^2 of green roof*time]
ET' = Evapotranspiration [in/ ft^2 of green roof*time]
F' = Filtrate [in/ ft^2 of green roof*time]
S = Cistern storage [in/ ft^2 of green roof]
Z' = Makeup Water [in/ ft^2 of green roof*time]
O' = Overflow [in/ ft^2 of green roof*time]

Isolating the green roof stormwater treatment system into mass balances as shown in Figure 1 is necessary in order to determine the filtrate, or the filtrate coefficient. Using the system boundaries for system one in Figure 1, an expression for the filtrate factor as it varies with soil conditions, precipitation, evapotranspiration, and irrigation amount can be derived.

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

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

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

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

$$\Delta Ms = P' + I' - ET' - F' \quad \textbf{(2)}$$

where the prime nomenclature is indicative of volume. Solving for the filtrate gives:

$$F' = P' + I' - ET' - \Delta Ms \quad \textbf{(3)}$$

But:

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

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

$$f = \frac{P' + I' - ET' - \Delta Ms}{P' + I'} \quad \textbf{(4)}$$

It can be seen from equation 4 that the filtrate will vary depending on the soil conditions and therefore with time. Since green roofs need to be irrigated more frequently when first installed to ensure the health of the plants (FLL, 2002) the assumption that the initial soil storage is equal to the soil saturation is made. All other variables needed to solve this equation are known with the exception of the final soil storage and the filtrate coefficient.

To solve for the filtrate coefficient additional mass balance equations are developed. First, precipitation and irrigation contribute to the soil storage up until the point of saturation. For this equation, assume that media saturation is at a volume of 20% of the growing media depth. Also, assume that any precipitation and irrigation past the point of saturation will contribute to the filtrate volume, or the filtrate equals input for any additional water past the saturation point of the soil. Therefore, for saturated conditions the equation that describes the final soil storage term, M_{S2}, is as follows:

$$M_{S2} = M_{Ssat} - ET' \quad \textbf{(5)}$$

That is, whenever filtrate occurs, equation 5 is used to determine the soil storage at the end of the time step. If filtrate does not occur, or the soil does not get saturated, then the soil storage at the end of the time step can be found from the following equation:

$$M_{S2} = M_{S1} + P' + I' - ET' \tag{6}$$

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

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

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

Next, using the second system boundaries in Figure 1, an equation is developed to describe the overall system. The equation for this system is as follows:

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

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

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

This equation further simplifies to:

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

Rearranging gives:

$$S_1 + (M_{S1} - M_{S2}) + Z' + P' - O' - ET' = S_2 \tag{8}$$

Finally, an equation needs to be developed for the cistern. This can be done by combining equations 7 and 8 to give:

$$S_1 + f(P' + I') - I' + Z' - O' = S_2 \tag{9}$$

This equation describes how the water level in the cistern fluctuates over time.

Using the equations previously developed, equations 4, 5, 6, and 9, a green roof model is formulated. The model developed is called the continuous stormwater treatment outflow reduction model, or CSTORM. The equation developed to solve for the filtrate coefficient, equation 4, needs to be solved simultaneously with equation 9 using the entire record of daily precipitation data and monthly average evapotranspiration data for a one day time step. The purpose of using the entire precipitation record is to reduce the introduction of error into the model due to the variability of yearly precipitation for any given area. The equations that describe the soil storage potential, equations 5 and 6, are to be used as stipulations that depend on the current conditions of the system.

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

With the CSTORM model, a green roof and cistern system can be designed to achieve a desired stormwater retention efficiency. The efficiency expressed as a percentage is defined as the volume of stormwater retained divided by the volume of precipitation.

$$Efficiency = [1-(\frac{O'}{P'})]*100 \qquad \textbf{(10)}$$

Using the above equations the CSTORM model was developed. This model can produce design curves which can be used for quantification of stormwater efficiency.

CSTORM Model Output

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

Design curves developed using the above equations can be produced for effective cistern sizing given a desired retention. Presented in Table 2 is a summary of efficiencies for different cistern storage volumes and locations in the state of Florida. From Table 2 it can be determined that the main factors that affect the efficiency of the system are precipitation, evapotranspiration, and cistern storage volume. Lower precipitation and higher evapotranspiration produces a higher efficiency green roof stormwater treatment system, while the converse yields a lower efficiency for the system. Also from Table 2, it is noted that for an irrigated green roof the roof runoff without a cistern can be reduced by about 33% - 51%. If the no cistern option is used, there are more pollutants (nutrients) from the green roof than from the control roof and an additional stormwater management technique will need to be used to help meet TMDL standards. Another way to increase the efficiency of the system is to irrigate additional areas, such as ground level landscaping.

The results of the CSTORM model shown below in Table 2 show that an expected efficiency of 87% can be achieved for the Orlando area when storing five inches over the green roof area. Hardin 2006 showed from experimental data that the actual efficiency is about 83%. These results show that the CSTORM model can be used to accurately predict, plus or minus 4%, the green roof system performance.

Table 2: Summary of yearly hydrologic efficiencies for different cistern storage volumes and locations in Florida

Location	Cistern Storage Volume [in/square feet of GR area]					
	0	1	2	3	4	5
Belle Glade	50	72	80	84	87	89
Boca Raton	42	61	69	73	77	79
Brooksville	45	66	74	78	81	83
Daytona Beach	42	66	74	79	82	85
Ft. Myers	44	65	72	76	79	81
Gainesville	42	67	76	80	83	86
Homestead	44	64	71	75	77	79
Jacksonville	40	65	73	77	80	82
Key West	51	72	80	85	88	9
Lakeland	42	67	75	8	83	85
Miami	42	63	69	73	76	78
Niceville	33	57	65	69	71	73
Orlando	40	67	77	82	85	87
Panama City	33	57	66	70	73	76
Tallahassee	35	58	66	70	72	74
Tampa	44	69	77	82	84	86
Venice	47	70	78	83	86	88
West Palm	42	62	69	73	76	78

Source: Hardin 2006

EXAMPLE PROBLEM

For this example, design an 800 square foot green roof to be located on the new stormwater lab addition at the University of Central Florida. The roof drains via an interior drain system routed to a cistern for storage and irrigation. The desired yearly hydrologic efficiency of the system is 80%. The green roof is to be a passive roof and consist of a water proof membrane, drainage layer, 2 inches of pollution control media, 4 inches of growing media, and vegetation.

Proper design of a green roof in Florida requires irrigation to ensure plant survival. For this reason a surface drip irrigation system is to be used with the irrigation rate to vary with season. The irrigation rate is 1.5 inches per week for the summer months, 1 inch per week for the spring and fall months, and 0.5 inches per week for the winter months. Due to depth restrictions the vegetation will need to be native ground cover similar to that on the Student Union building (i.e. firewheel daisy, dune daisy, etc.). The cistern size is to be determined using the Orlando curve presented in Figure 2.

Based on an efficiency of 80% the resulting cistern should store about 2.5 inches over the green roof area or a volume of 1250 gallons. From Hardin (2006), the mass loading of a conventional roof of the same size would be 8.5 grams, 30.2 grams, 24.5 grams, and 44.4 grams for ammonia, nitrate, ortho-phosphorus, and total phosphorus respectively. The mass loading for the green roof design proposed for this problem is 0.9 grams, 2.3 grams, 5.7 grams, and 13.2 grams for ammonia, nitrate, ortho-phosphorus, and total phosphorus respectively. These results show a mass loading reduction of 89%, 92%, 77%, and 70% for ammonia, nitrate, ortho-phosphorus, and total phosphorus respectively. Using this green roof stormwater treatment system design all of the design criteria should be meet. It should be noted that if further nutrient removal is required a treatment train should be used.

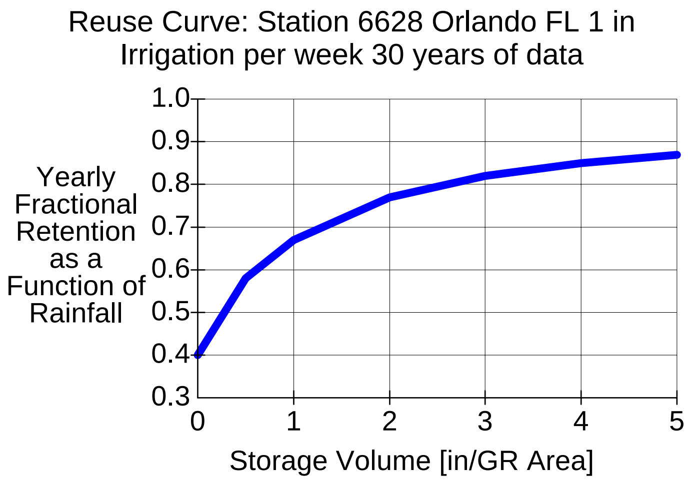

Figure 2: Orlando Green Roof Stormwater Treatment System Efficiency Curve. Source: Hardin 2006

CONCLUSIONS

Stormwater management continues to be a growing problem in urban areas because of limited space and resources. Green roof stormwater treatment systems are a solution to this problem that offers several other benefits. As presented within this paper an irrigated green roof with a cistern is an effective way to reduce the volume of stormwater runoff from rooftops. From the results of the CSTORM model it can be seen that green roof stormwater treatment systems can effectively reduce the volume of runoff by as much as 87% for the Orlando, Florida region. This efficiency is based on a cistern that stores a volume of five inches over the green roof area. It should be noted that an irrigated green roof without a cistern will only achieve a runoff reduction of about 40% for the same region. Examination of Table 2 shows that the expected efficiency is highly dependent on the geographic region. This is due to local climate conditions.

Based solely on these data, a suggested design for a green roof stormwater treatment system is to vary the irrigation rate with season, use vegetation, use the Black & Gold™ growing media, and size the cistern (filtrate storage) to achieve a desired reduction in runoff. It is also recommended to use the expanded clay growing media to ensure vibrant plant growth, and to use the pollution control media beneath the growth media for water quality benefits. From the example problem presented in this paper it can be seen that with the aforementioned design a significant reduction in stormwater runoff can be achieved. This reduction also translates into significant nutrient mass loading reductions. To achieve this pollutant reduction a cistern needs to be used to store filtrate from the roof for irrigation and the Black & Gold™ pollution control media also needs to be used to reduce phosphorus loads (Hardin, 2006).

RECOMMENTATIONS FOR FUTURE WORK

While green roofs have been used in Europe for more than 50 years they have only just recently been evaluated for stormwater management potential. Due to the lack of experience with green roofs in the United States several areas need to be further addressed. This work examined the hydrologic and water quality benefits of a specifically designed green roof stormwater treatment system and model to predict performance. Research examining the effect of different media depths on stormwater retention efficiency and evapotranspiration rates needs to be done. These results should be checked against the CSTORM model to ensure the model is accurate for different depths. The media water storage capacity should also be examined to develop more effective techniques to determine this storage capacity. This in turn will produce more accurate model predictions.

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