Green Roof Stormwater Performance in Puerto Rico: An Overview of the Effect in Greening The Old San Juan Area

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Abstract *— The lack of information about green roof stormwater discharge in subtropical scenarios make it difficult for engineer to use this technique for storm water mitigation in Puerto Rico. It has been proven by physical data collection and mathematical modeling that green roof can attenuate 75% of the roof peak discharge and can reduce 20% to 35% of the annual discharge volume. This paper also present the correct Curve Number values for green roof in Puerto Rico.*
In addition to presenting experimental values, an evaluation was carryout of the effect cause by greening 100% of the Old Town of San Juan. The total roof area for the analysis was around 70 acres an only 4" of growing media depth was considered. Result showed a stormwater discharge reduction of 25% and a average peak reduction of 8cfs of the Old Town Discharge.

Key Terms *— Curve Number, Green Roofs hydrology, Greening Old San Juan or Stormwater.*

INTRODUCTION

Green roof are becoming a popular technique in island of Puerto Rico. In the past decade over 150,000 square feet of green roof have been installed in the San Juan area alone, the capital city of the Puerto Rico. In 2012 one of San Juan oldest historical landmark "El Cuartel de Ballaja", was greened with a 25,000 sq.ft extensive green roof.

The island of Puerto Rico is located between latitude18°00' and 18°30', and longitude 66°00' and 68°00'. According to Holdrige, Puerto Rico is located within the Sub-Tropical region, and comprises of six different life zone [1]. The zones are characterized for there precipitation, temperature and Evapotranspiration. The city of San Juan is located in the north part of the island, it's ecological zone is defined as subtropical Moist Forest, which manages approximately 55.7 inches of rain annually. Annual temperature for San Juan could range from 70 to 90 °F [2].

Green roofs have a long history of use Germany, the first recommendation for creating a landscaped over a flat roof was given in 1867 "Natural Roofs made of volcanic cement" by the master mason from Berlin, Carl Rabitz [3].

Green Roof are best describe as "Vegetation cover over a building roof", nevertheless green roofs can be installed at street level when building seat below grown, like for example Millennium park in the city of Chicago. Another good example is the "Bellas Artes Plaza" which is constructed over the Minilla tunnel, both can be described as intensive roofs.

Green Roof are divided in to three different categories: Extensive, Semi-intensive or Hybrid and Intensive. Their difference relay in the amount of maintenance required and soil depth which can vary from 3 to 6 inches for extensive and over 7 inches for intensive. Growing Media depth will restrict the type of vegetation. The construction of a green roof is comprised of several layers; waterproofing, protective mat, drainage, filter fabric, growing media and plant. see Figure 1.

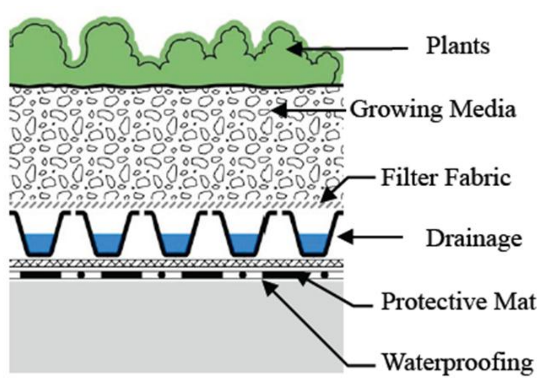

Figure 1
Green Cross Section Detail

Benefits of green roof have been widely studied in Germany and United States. About 14% of flat roof in Germany are covered with vegetation [4]. Green roof have the ability to reduce surface temperature from roof tops, one of the contributors in the heat island effect, see Figure 2. While cooling of those roofs at night contribute to global warming. It's estimated that 24% of energy consume in Puerto Rico is related to space cooling [5].

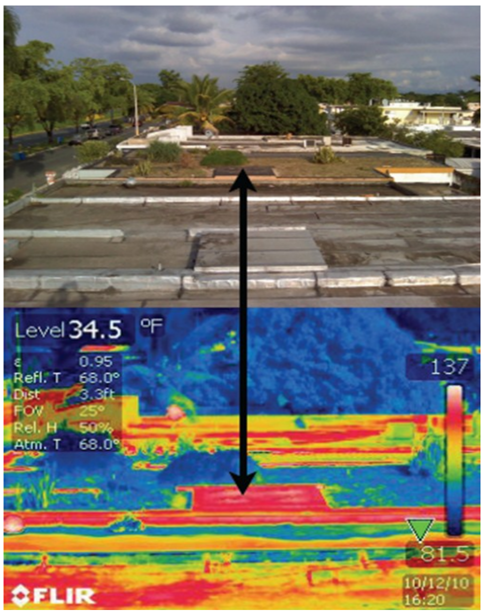

Figure 2
Thermal Image of a Green Roof in Toa Baja, PR

In addition, green roof can also provide shelter for natural habitat. The reduction of green spaces in the cities have caused the migration or loss of some species. The term brown roof or biodiversity roof has been developed for those green roofs that are designed for self colonization of local vegetation, they are sometimes seeded to increase their biodiversity potential in the short. The roofs are colonized by spiders and insects which provide a feeding site for insectivorous birds.

Another well known benefit, is the ability of Green roof to reduce stormwater. In Berlin, Germany, the average green roof absorbs 75% of the rainfall. And delay discharge around 25% [6]. While in Rio de Janeiro the annual retention is around 65% [7]. Green roofs provide an opportunity to delay and attenuate stormwater discharge at the source. There are many hydrological mechanisms operating within the green roof. For example; interception of rainfall by the plants, infiltration, storage, Evapotranspiration, overland discharge and below grade discharge . Figure 3 provides an schematic drawing of the hydrology within a green roof.

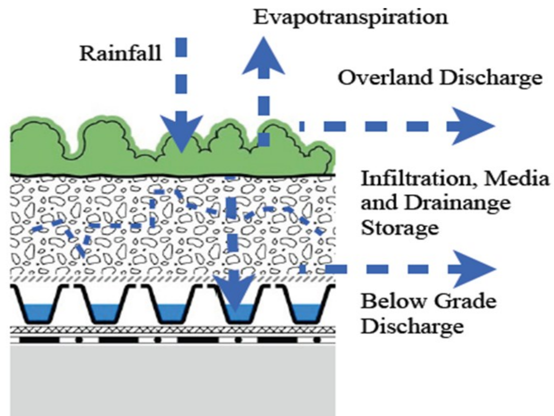

Figure 3
Hydrology of a Green Roof

Many cities in United States and Europe are looking in to this alternative to alleviate overload of combined sewer system. This has happened mainly because cities are using old systems that weren't built to handle todays population or impermeable areas. For that matter cities are looking into new ways to attend this issue.

In United State the Environmental Protection Agency (EPA) promotes the use of sustainable system for managing storm water discharge. Locally and Internationally green roof are describes as a best management practice (BMP), Low Impact Development tool (LID) and Water Sensitive Urban Design (WSUD) [8].

Could green roof have the same mitigation effect sub-tropical scenario? Would a higher precipitation and recurrence affect the storm water reduction benefit? Would water loss be too high for plant stability?

Project Description

The lack of information related to storm water benefit in a sub-tropical scenario provided the opportunity to evaluate and generate information needed to run a hydrological model. The project was dived in to two parts; data collection and quantification of the effect in a urban scenario, in this case Old San Juan, see Figure 4.

Figure 4
Area of Interest

A 143sq.ft test plot was established in Dorado, see Figure 5. The experimental site is located 20 minutes for the project, climatic condition can be described as equal or similar.

Figure 5
Experimental Location

A ZinCo's FD-25 system was installed as the underlayment material. Rooflite local lightweight blend was used as growing media. The total experimental depth was around 4 inches. Figure 6 provides a photography of the experimental site. Test plot had an average depth of four inches, typical installation depth for green roof in United States. The base for this small site was to establish the necessary data needed to quantify the effect.

The second part of this project was aimed in quantifying the hydrological impact from a 100% greening of the Old San Juan. Model was carry out using the data generated from the test plot and laboratory. A total of 6 species (Tulbahia violacea, Sedum rupestre, Rosemmarinus officinali, Lemon-lime sedum, Bulbine frutencens, Portulacaria afra and Delosperma coperii) of plant where used to cover the entire plot area. Plant where planted in sizes ranging from plugs to 4" pot.

Figure 6
Test Plot for Physical Analysis (Total Plant Material was not Yet Planted in the Picture)

The project area is 97.44 acres, approximately 72% or 70 acres are dedicated to rooftops. Despite the benefits of slope roof most of the island roofs are flat with a minimum slope of 2%, as established by building code. Figure 7 provide a representation of the pre-installation and post-installation condition of the rooftops in the project.

Figure 7
Overview of Pre and Post Condition (Ballaja Green Roof Installation)

METHODOLOGY

One of the difficulties of this project was to gathered all coefficients needed to create a real hydrograph comparison. Once the experimental site was constructed, sensor for data collection were placed. Table 1 provides the list of all used equipment.

Table 1
Experimental Roof Equipment

Identification	Company	Description
S-LIB-M003	Hoboware	Solar Radiation Sensor
S-RGA-M002	Hoboware	Rain Gage Smart Sensor
EC-5	Hoboware	Soil Moisture Smart Sensor
S-TMB-M017	Hoboware	12-Bit Temp Smart Sensor
S-WDA-M003	Hoboware	Wind Direction Smart Sensor
S-WSA-M003	Hoboware	Wind Speed Smart Sensor
Dx-10	Flowline	Level Logger

The irrigation system installed had the capability of producing a constant rainfall event of 7.5 inch per hour. Several artificial and natural rainfall events were evaluated with the equipment. A 3' by 1.5' weir box was constructed and installed at the exit point of the green roof for discharge measurements. A v-notch weir with a 20° opening was place at the exit point, level within the weir box was measured and converted to discharge by equation (1).

$$Q = C_d \frac{8}{15}\sqrt{2g}\tan\frac{\theta}{2}H^{\frac{5}{2}} \qquad (1)$$

Where;

Cd - is the coefficient of discharge.

∅/2- Is half the enclosed angle of the vee.

H - Head above the bottom of the notch.

To gather growing media characteristic, porosity, density, water holding and capacity laboratory testing was conducted following the ASTM and FLL guidelines, see Table 2 for a list of approved standard.

Table 2
Standard Approved

Identification	Description
E 2396	Test Method for Saturated Water Permeability of Granular Drainage Media.
E 2397	Practice for Determination of Dead Loads and Live Loads Associated with Green Roof Systems.
E 2398	Test method for water capture and media retention of geocomposite drain layer for green roof systems.
E 2399	Test Method for Maximum Media Density for Dead Load Analysis of Green Roof systems
E 2400	Guide for Selection, Installation and Maintenance of Plant for Green Roof System.

A water balance using Green Ampt infiltration model was developed to establish an understanding of the growing media hydrology. The calculation done used some of the soil characteristics gathered in the laboratory. The first step was to establish the moisture deficiency of the growing media (2);

$$M = \theta s - \theta i \qquad (2)$$

Where;

Ɵs - Soil Porosity (unitless)

Ɵi - Moisture Content (unitless)

M - Moisture Deficiency (unitless)

The cumulative infiltration at the time of surface ponding, Fp, can be obtained from (3);

$$Fp = \frac{Sav\ x\ M}{\frac{i}{Ks} - 1} \qquad (3)$$

Where;

Sav - Capillary Suction Head (in)

i - RainFall intensity (in)

Ks - Hydraulic Conductivity (in/hr)

While the total cumulative infiltration can be obtained from (4);

$$Ks(t - tp - T'p) = F - M * Sav * \ln\left(1 + \frac{F}{M * Sav}\right) \qquad (4)$$

Where;
tp - Time of Surface ponding (hr)
T’p - Equivalent time to infiltrate Fp. (hr)

Runoff is then computed as follows (5);

$$RO = i\Delta t - \Delta f - \Delta s \quad (5)$$

Where;
i Δt- Rainfall in time interval (in)
Δf - Infiltration (in)
Δs - Storage (in)
RO - Runoff (in)

The Total Volumetric Discharge (TVD) calculated from the Green Ampt equation was then compared with physical model.This comparison was conducted to verify that storage and discharge were similar.

Meanwhile the moisture daily loss rate was gathered by the two moisture sensor place within the growing media at the physical model, see figure (5). The daily loss was evaluated and compared with several lysimeter studies conducted in the university of Pennsylvania [9].

Once the growing media hydrology was established within the green roof, discharge amount and rates where also analyzed against the NRCS TR-55 method [10]. This was done to determine the Curve Number from the physical data. Trial and error calculation where performed until a hydrograph of similar behavior was reach. It must be mention that the use of green Ampt within the TR-55 was used to establish moisture deficiency, important parameter to determine the Storage capacity, base for the CN determination. In other words, alteration of the growing media characteristic will provide different storage results, producing a totally different CN. For the continuos model, the first sets of data was calculated using the TR-55, the rest was simply done by following pulse method for water budgets.

Equation (6), (7), (8) and (9) were use to determine the TVD and the peak discharge of a single event.

$$S = \frac{1000}{CN} - 10 \quad (6)$$

$$Q = \frac{(P - .2S)^2}{(P + .8S)} \quad (7)$$

$$PR = \frac{tr}{2} + tp \quad (8)$$

$$Q = \frac{484 * A}{PR} \quad (9)$$

Where;
S - Storage (in)
CN - Curve Number
Q - Discharge (in)
P - Precipitation (in)
PR - Period of Rise (hr)
tr - Rainfall Duration (hr)
tp - Lag time (hr)

Time of concentration was calculated using the sheet flow Equation (10), since the discharge path of the experimental roof didn’t exceed the 300 ft requirement. For the Old San Juan model sheet and shallow concentration was used. The only changing parameter between the pre and post condition was the Manning coefficient value in the sheet equation. Post model assumed that the 300ft from sheet flow were green roofs.

The lag time is defined as the difference in time between the center of mass of rainfall excess and center of mass of the rainfall discharge. Usually Lag time is .60 of the time of concentration. The lag time was use to determine the period of rise PR from equation (9).

$$Tt = \frac{.42 * (nL)^{.8}}{P2^{.5} S^{.4}} \quad (10)$$

Where;
S - Storage (in)
n - Manning's Roughness Coefficient
P - Precipitation (in)
L - Length of Path (ft)

A synthetic Unit Hydrograph was developed based on the peak discharge calculation. This graphical representation was then compared to the physical behavior of the roof. A standard deviation of +/-5 was used to fit the graphical behavior. Coefficients like the Curve Number (CN), Manning Roughness Coefficient (n) and were adjusted to values that better represent the graphical comparison. Since the daily moisture loss of the system affected the result of the calculation, different moisture conditions were used in the events calculation model. These parameter were later used to estimate the benefit of green roofs in the Old San Juan area.

Benefit were calculated for several single event and for a continuos model.

RESULTS

There were many data evaluated with the physical model, but for this project a constant 30 minute 1.03 inches rainfall event was evaluated for parameter calculation. The rainfall distribution is presented below, see Table 3.

Table 3
Artificial Rainfall Distribution Data.

Time (min)	Intensity (in/hr)	Volume (in)	Cumulative Volume (in)
0	0	0.00	0.00
5.0	2.06	0.17	0.17
10.0	2.06	0.17	0.34
15.0	2.06	0.17	0.52
20.0	2.06	0.17	0.69
25.0	2.06	0.17	0.86
30.0	2.06	0.17	1.03
35.0	0	0.00	1.03

The constant rain event was done 1 hour after an actual rain event. Soil moisture content was at 0.23 prior to the test. Maximum moisture content observed in the experimental data was 0.285, and a minimum of 0.043, as seen in Figure 8.

The average evapotranspiration was around 0.069 in/day. It is important to mention that evapotranpiration could vary depending of moisture availability and solar radiation. Prior studies indicated findings ranging from 0.059 to 0.11 in/day*.

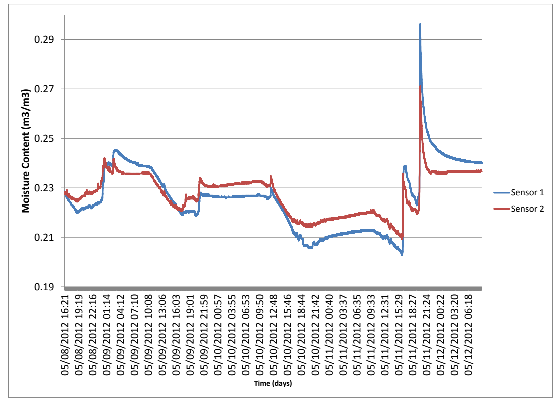

Figure 8
Moisture Condition Evaluation

The Growing media had a measured porosity of 0.43, with a capillary suction force of 1.95 in. The hydraulic conductivity was a 1.5 in/hr for the sample. Moisture deficiency was calculated at 0.23 prior to the artificial rainfall event.

Green Ampt infiltration model based in the growing media parameter showed that 0.30 inches of rainfall were discharged from the experimental plot. Figure 9 provides a graphical representation of the infiltration behavior of the growing media based in the Green Ampt infiltration model.

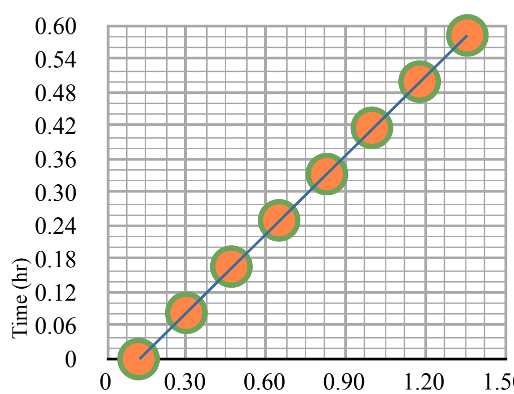

Figure 9
Graphical Solution of Cumulative Infiltration

A soil moisture balance was conducted with the infiltrated portion of the rain. This is account how much of the 0.30 inches was traveling below grade and how much was overland discharge, see Figure 10.

The actual volume discharged from the physical model was 0.303 inches, with an average peak discharge of 0.018, see Figure 11. Turbulence in the superficial part of the water level within the weir box creates a margin of reading error of 1%. For that reason peak discharge is presented as the average fluctuation.

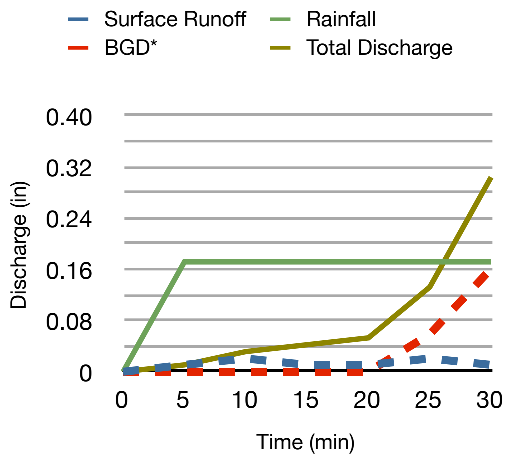

Figure 10
Green Ampt Discharge

A unit hydrograph was developed to simulate the physical hydrograph of the test plot. Based on the growing media moisture condition or the Antecedent Moisture Condition the corrected Curve Number was 89.

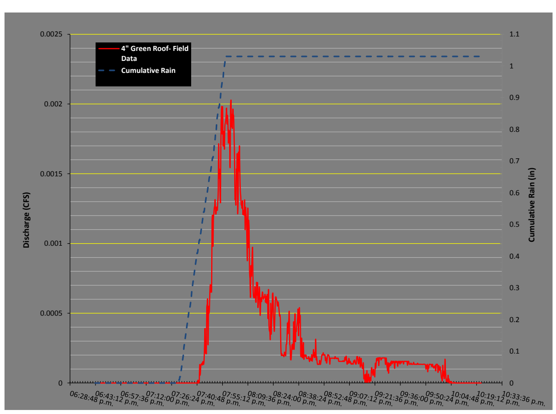

Figure 11
Physical Model Discharge

Manning's n value used to calculate Time of Concentration was 0.14, this value equal well established grass area. Volumetric Discharge for the theoretical model was 0.317 inches. Figure 12 provides a hydrograph comparison.

A typical Curve Number for concrete roof is 98. A comparison between a concrete roof and a green roof was developed to account for the benefit. The green roof reduced 0.0062 cfs of the peak discharge and 0.52 in. of the discharge depth. This represents a 75% peak reduction and 63% of the total volume.

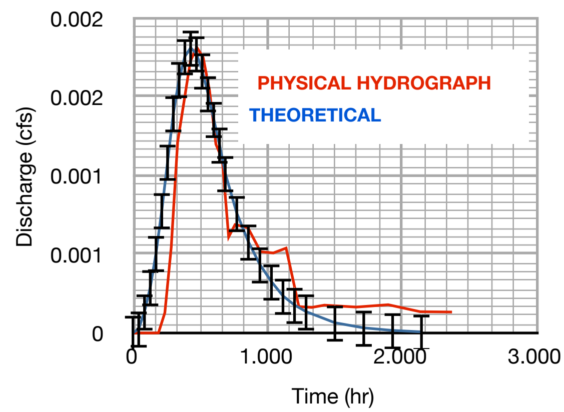

Figure 12
Physical and Theoretical Comparison

Figure 13 provides the comparison between the concrete roof and the green roof.

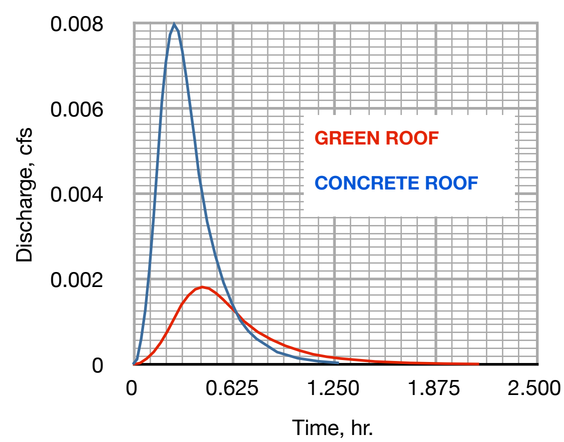

Figure 13
Hydrograph Comparison Between Green roof and the Concrete Roof

Curve number could vary widely depending in the moisture deficiency of the growing media, see Figure 14.

The average Antecedent Moisture Condition gathered from the humidity sensor was used to establish the average CN value of 83. This was equal to 25% of the moisture deficiency. Similar finding were given by Jarrett A.R, in a study done in the University of Pensilvania, were a CN of 79 was established in his report [11]. Another project that showed similarity in CN was conducted by Stovin V [7]. professor at the university of Sheffield, she publish result for a experimental site in London with average CN between 81 to 99, fluctuation based in the Antecedent Moisture Condition.

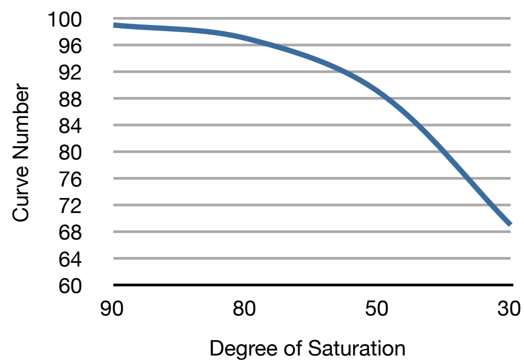

Figure 14
CN Behavior Graph Based in Degree of Saturation in a Soil Porosity of 0.43

Evaluation of Green Roof in Old San Juan Urban Setting

To establish the actual benefit of green roof in Old San Juan several site analysis where conducted prior to value calculations. The average slope of 2.39 is based on the travel path of 3,438 linear feet and a change of elevation of 30 mts, see Figure 15.

Time of concentration values for the site where calculated using equation (10), Table 4 show the results.

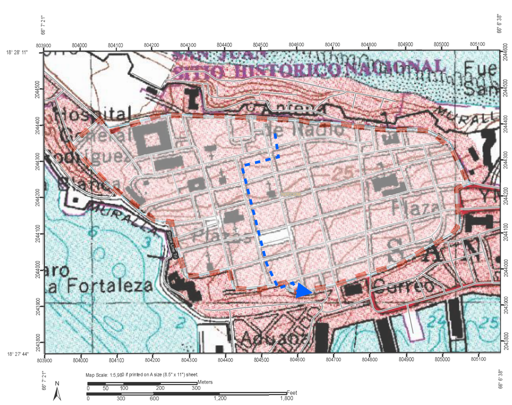

Figure 15
Topographic Map and Path evaluation

Several assumption were used to generate the time of concentration. Building in old San Juan were done prior to the building code, roof slope could vary significantly. It was a assumed that each city block was the sum of all building with a minimum slope of 2% which is the code requirement. 5% of each block area was considered as interior gardens.

Table 4
Time of Concentration Calculation.

CONDITION	PRE-INST.	POST-INST.
SHEET FLOW (hr)	0.007	0.048
SHALLOW CONCENTRATED FLOW (hr)	0.513	0.513
TIME OF CONCENTRATION (hr)	0.519	0.560
TIME LAG (hr)	0.312	0.336

All 300 ft of sheet flow calculation were considered as green roof, while the shallow concentrated was analyzed as glazed brick. Figure 16 show a descriptive picture of shallow concentration, Figure 7 in page 7 show the pre and post condition.

Figure 16
Descriptive Photography

A weighted average was done to calculate the correct CN since multiple surfaces are contributing to the stormwater discharge, see Table 5.

The individual storm evaluation was done for typical scenarios used in conventional Hydrologic an Hydraulic studies in Puerto Rico. A 2-yr, 10-yr and 100-yr recurrence rainfall with a 24hr duration. The total volumetric rainfall based in the TP-42 [13] is 4.75, 7 and 10 inches respectively for each of the design storm. In addition to single event model, a continuos yearly model was also analyzed.

Table 5

Curve Number Calculation Table.

PRE-INSTALLATION CONDITION

Soil Description	CN	AREA (acres)	Product of CN x Area
Green Space (Plaza)	89	1.08	95.74
Roof Tops	98	70.64	6,922.73
Side Walk, Street and other	98	25.73	2,521.14
		97.44	9,539.62
Curve Number to be used	98		

POST-INSTALLATION CONDITION

Soil Description	CN	AREA (acres)	Product of CN x Area
Green Space (Plaza)	89	1.08	96.12
100% Green Roof Cover	83	70.64	5,863.12
Side Walks, Streets and Etc.	98	25.73	2,521.54
		96.37	8,384.66
Curve Number to be used	87		

Single event will provide the discharge mitigation effect of the green roof, while the annual analysis will provide the economical yearly benefit of treating the combined sewer.

The average peak reduction for each individual event was around 7 to 9 cfs, with a average volumetric discharge reduction of 3,358,137 gallons of water. Figure 17, 18 and 19 shows the the comparison hydrograph for each single event.

Rainfall events from 2007 to 2011 were evaluated to estimate the yearly discharge of the pre and post condition. The annual volumetric reduction is 25% or 17,191,954 cu.ft., see Figure 20.

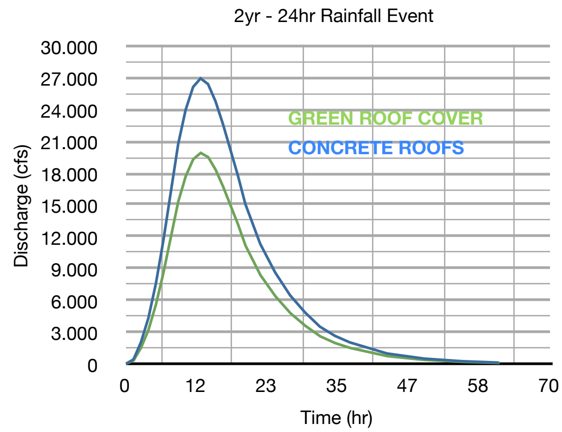

Figure 17

2yr-24hr Discharge Hydrograph Comparison.

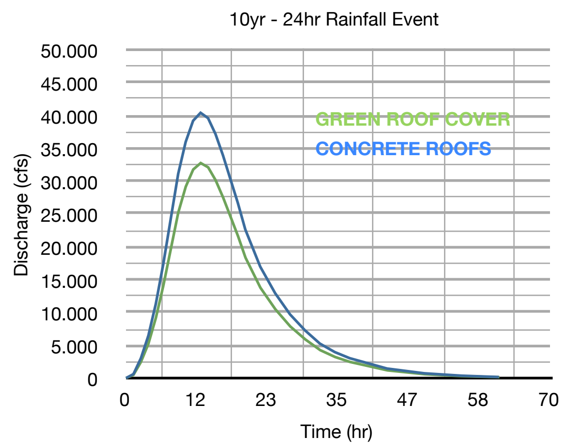

Figure 18

10yr-24hr Discharge Hydrograph Comparison

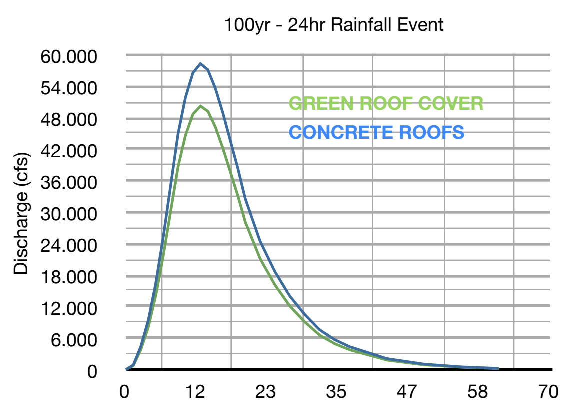

Figure 19

100yr-24hr Discharge Hydrograph Comparison

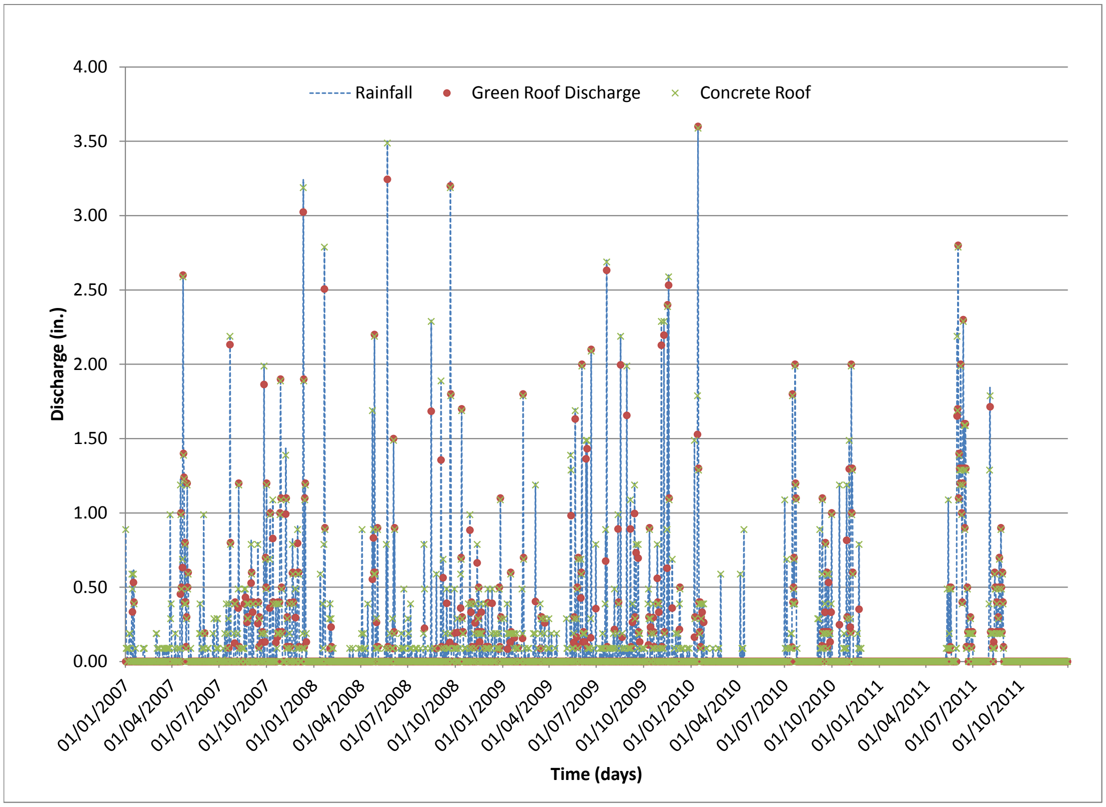

Figure 20
Annual Discharge Depth Evaluation

CONCLUSION

Green Roofs are complex systems that require further investigation to quantify their economical and environmental benefits for a tropical scenario. This paper was focused on the ability to retain and reduce storm. But in fact green roof can offer other benefits that play a significant role in our daily lives. that can also impact our daily living, as mentioned throughout the course of this paper. Temperature and energy reduction are other benefits plays another significant role in our daily life's. 24% of our energy expense are related to space cooling, this represent 4,670,400 MW-h/yr for the total population, green roof can offset roof temperature by more that 40°F. A previous experiment done showed that green roof reduce energy consumption for a residence by up to 10% in summer and 60% in winter.

In addition green can reduce surface runoff by storing excess rainfall and contribute to temperature reduction caused by evapotranspiration, prolong the waterproofing membrane for more than 50 years, reduce waste from re-roofing work and create a urban habitat for depleting ecosystem, then is reasonable to say that green roofs are a feasible alternative to implement in a mandatory scale. An average re-roofing work in Puerto Rico is between $3 to $6 the square foot, and is done at interval between 5 to 10 years. In a total of 50 year the average cost of re-roofing is around $30/sqft. The average cost of a green roof is around $15/sqft.

The conclusion for this paper is that a reduction peak discharge between 12% to 30% was observed and 25% volumetric was achieved for old san Juan, with the correct media and depth. This could represent an annual treatment saving of $103,150.

A green roof alone has the ability of reducing 75% of the peak discharge and 63% of it volume generated only by the roof. In places where storm water fees are applicable this reduction has a significant economical impact, but such is not the case for Puerto Rico.

Another important result is that Antecedent Moisture Condition plays an important role in stormwater management in a tropical scenario, this parameter cause the curve number to vary from 99 to as low as 68. Although the NRCS TR-55 is not intended for green roof is a good tool to predict green roof discharge, once the correct CN is established, which can be defined once the performance of the media is known. This implies that the green for media properties and depth are crucial to establish the performance of a green roof. But keep in mind that media also has to maintained biological life. It is clear that a more complex evapotranspiration study must be conducted for tropical scenario. Since the complexity of plant transpiration and soil evaporation are the replenishing source for green roof mitigation characteristics.

In conclusion green roof are are good BMP to use in Puerto Rico. There performance is based in plant, growing media and the correct combination of underlying material. A design guideline should be created to further develop the use of this technique. It has been clearly establish that not all green roof are created equal, so careful attention should be present when design a green roof for storm water or temperature management.

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