MODELING THE IMPACTS OF GREEN ROOF SYSTEMS ON STORMWATER MITIGATION

by

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TABLE OF CONTENTS

Page

LIST OF TABLES

Tables **Page**

LIST OF FIGURES

Figure **Page**

1. INTRODUCTION

Flooding is a major problem for many cities around the world and causes property damage as well as loss of life. San Marcos, Texas, is not immune to this hazard as it is located along the Balcones Escarpment, also known as the “Flash Flood Alley” (Flood Safety 2005). . The geological and topographical features of this area are naturally predisposed to flash floods (Caran and Baker 1986). As of 2015, San Marcos was the fastest growing small city in the United States three years in a row, adding impervious surfaces to an already stressed area and increasing stormwater runoff (Bernstein 2015).

To cope with the additional surface runoff associated with urban development, traditional stormwater management has focused on systems of runoff conveyance, e.g. curbs, gutters, and other grey infrastructure. However, increased impervious surface in urban environments, has overloaded these structural systems causing flooding (Kong et al. 2017). To mitigate this problem, Low Impact Development (LID) has been adopted in many urban areas. LID slows down stormwater runoff and allows for infiltration into the ground, returning to a more natural hydrologic cycle (Eckart, McPhee, and Bolisetti 2017).

One example of LID practices are green roofs, also known as eco-roofs or living roofs. Green roof systems consist of vegetation in a layer of growing material, over a series of filter layers, drainage layers, roof barriers and waterproofing (Liu, Li, and Li 2017). Green roof technology has many benefits associated with its implementation. For example, studies have shown that green roof systems reduce stormwater quantity, improve stormwater quality, and reduce the effects of heat islands (Liu and Li 2016; Castleton et al. 2010; Masseroni and Cislaghi 2016). In other words, green roofs reduce the amount of water runoff, improve the quality of the water coming off them by filtering out pollutants, and help cool the surrounding area by absorbing heat instead of reflecting it like a traditional roof would.

Furthermore, green roof systems are easier to adapt onto an existing developed landscape than many LID practices, which makes them ideal additions to an urban environment (Jato-Espino et al. 2016; Castiglia Feitosa and Wilkinson 2016).

Green roof systems have been implemented much more frequently in the northern area of the United States and Europe, where the overall environment is not as harsh and unforgiving as the Texas climate (Dvorak and Volder 2010). However, with new research examining the best plants to use for establishing green roofs in Texas, green roofs have become a viable reality to reduce stormwater runoff in this area (Simmons et al. 2008; Volder and Dvorak 2014).

The purpose of this study was to investigate the potential mitigation of stormwater runoff by adopting green roof technology. GIS-based stormwater modeling provides a mechanism through which to quantify the impacts of implementing a new type to infrastructure before engaging in the labor intensive and monetarily expensive activity of physically changing the landscape. Moreover, GIS modeling can be used to evaluate the site suitability for green roof systems and their location in a study area. Located in Flash Flood Alley, San Marcos is ideal as a case study to demonstrate the potential for implementing green roof technology especially to other places with flooding potential and problems. While green roof systems have other benefits as mentioned, this study focused specifically on the benefit of reducing stormwater runoff and provided recommendation for Texas State regarding the positive impacts green roof systems would have in mitigating stormwater runoff and flooding on Texas State's campus.

The study sought to find the answer to the following question: What is the potential hydrologic response of installing green roof systems on mitigating stormwater runoff? To accomplish this, this study (1) identified suitable locations for installation of green roof systems and (2) analyzed the total stormwater runoff, amount and time of peak runoff, that these installations will have on designed rainfall events. The null hypotheses of this study were as follows: There were no significant differences in total stormwater runoff, amount and time of peak runoff with or without the addition of green roof systems. In addition, there were no significant differences between storm intensity with or without the addition of green roof systems. The null hypotheses formatted as equations are as follows:

H1a: $Q_{p\ baseline} = Q_{p\ Green\ roof}$

H1b: $T_{p\ baseline} = T_{p\ Green\ roof}$

H1c: $Q_{baseline} = Q_{Green\ roof}$

…

H2a: $Q_{p\ return\ interval\ 2} = \ldots = Q_{p\ return\ interval\ 100\ldots}$

H2b: $T_{p\ return\ interval\ 2} = \ldots = T_{p\ return\ interval\ 100\ldots}$

H2c: $Q_{return\ interval\ 2} = \ldots = Q_{return\ interval\ 100\ldots}$

2. LITERATURE REVIEW

This study drew on two relevant bodies of literature: site suitability, and design of green roof systems. As mentioned earlier, green roof systems were chosen based on their ease of retrofit implementation in urban environments and potential stormwater mitigation (Jato-Espino et al. 2016; Castiglia Feitosa and Wilkinson 2016).

2.1 Impacts of Green Roof Systems on Hydrologic Response

Many studies on the impact of green roof systems on stormwater runoff have documented their ability to reduce the total volume of runoff as well as reduce and delay the peak runoff (Table 1) (Bliss, Neufeld, and Ries 2009; Castiglia Feitosa and Wilkinson 2016). Depending on factors like the depth of substrate and type of vegetation grown, green roofs could reduce stormwater volumes anywhere from 30%-90% (Masseroni and Cislaghi 2016; Bliss, Neufeld, and Ries 2009). However, most of these studies have been located in Europe and the northern part of the United States; only a handful of studies have been undertaken in the subtropical climate of Texas where plants must survive harsh summers and periods of drought.

In a study conducted in College Station Texas, Volder and Dvorak (2014) found the average retention across three different test roofs with different vegetation to be 36%. Another study in Austin, Texas, reported a reduction of runoff up to 88% for the smallest rainfall events and up to 44% for the largest events studied (Simmons et al. 2008). Therefore, these studies demonstrate that green roof systems can reduce stormwater runoff in the surrounding regions of Texas as well.

However, many studies, like Simmons et al., have shown green roof systems effectiveness to reduce stormwater decreases as storm intensity increases (Table 1). Lui et al. (2017) found for a 10-year storm green roofs reduced the ponding area, depth, and time, but for a 50-year storm only the ponding area was reduced. When using a 2-year and 20-year storm event respectively, similar results were found that the runoff reduction rates decreased from 44% to 17% (Zhou et al. 2017).

Table 1. Stormwater modeling for Low Impact Development (LID).

Stormwater Model	**Study**	**LID Tested**	**Results**
SWMM	Kong et al. (2017)	Green roof, Permeable Pavement, Vegetative Swale, and Rain Gardens	For a 10-year storm event LID reduced total volume, peak flow, and delayed peak flow of runoff.
	Jia et al. (2011)	All	LID reduced total volume, and peak flow rate of runoff
	Jato-Espino et al. (2016)	Permeable Pavement	Permeable Pavement Systems reduced total volume and peak flow of runoff.
	Xie et al. (2017)	Grassed Swales and Permeable Pavement	LID reduced total runoff volume at outfall with different scenarios of rainfall intensity. However, as rainfall intensity increased, runoff reduction efficiency decreased for LID.
	Liu and Chu (2017)	Permeable Pavement	Permeable Pavement reduced total volume of runoff however, greater reductions found in drier climate verses a wetter climate.
SCS-CN	Liu et al. (2017)	Green Roofs	For a 10-year storm event green roofs reduced the area, depth, and time to ponding. For a 50-year storm event they only reduced the area of ponding.
	Zhou et al. (2017)	Green Roofs	Green Roofs reduced runoff volume in all areas of the study site.
L-THIA + SCS-CN	Eaton (2017)	All	Most effective LID practice were bioretention and rain gardens followed by permeable pavement due to predominantly low-density residential land cover.

2.2 Site Suitability of Green Roof Systems

Site suitability of green roof systems consist of two main factors: roof slope and building structure. Roof slope affects stormwater runoff mitigation. A study by Getter et al. (2007), looked at the effect of slope on stormwater retention of green roof systems. The study found that as slope increased, the amount of stormwater retained decreased. For heavy rainstorms 2%, 7%, and 15% slopes retained an average of 71.4%, 66.4%, and 58.4% of runoff respectively (2007). Therefore, the smaller the slope, the greater the stormwater reduction.

Depending on the depth of the growing material, commercial and concrete framed buildings are the most favorable building structure for green roof retrofitting because most do not need any additional modifications (Castleton et al. 2010). In general, the optimal depth of growth medium for stormwater mitigation is the largest thickness that a building could support without needing structural modifications (Castiglia Feitosa and Wilkinson 2016). An extensive green roof with a soil depth under 150mm (6 in.) can be installed on existing buildings without needing structural modifications (Liu, Li, and Li 2017). Therefore, the maximum depth of 150mm, was be used in this study so that all buildings could be potentially converted given the right slope.

Based on the literature reviewed, this study examined how green roof systems installation will mitigate stormwater runoff and therefore reduce flooding. This study added to the growing body of literature on LID being applied to stormwater mitigation and provided empirical evidence within the "flash flood alley".

3. METHODOLOGY

3.1 Study Area

The study area of this research is a 23.1 acre (9.35 ha) section of the Texas State University campus in San Marcos, Texas (Figure 1).

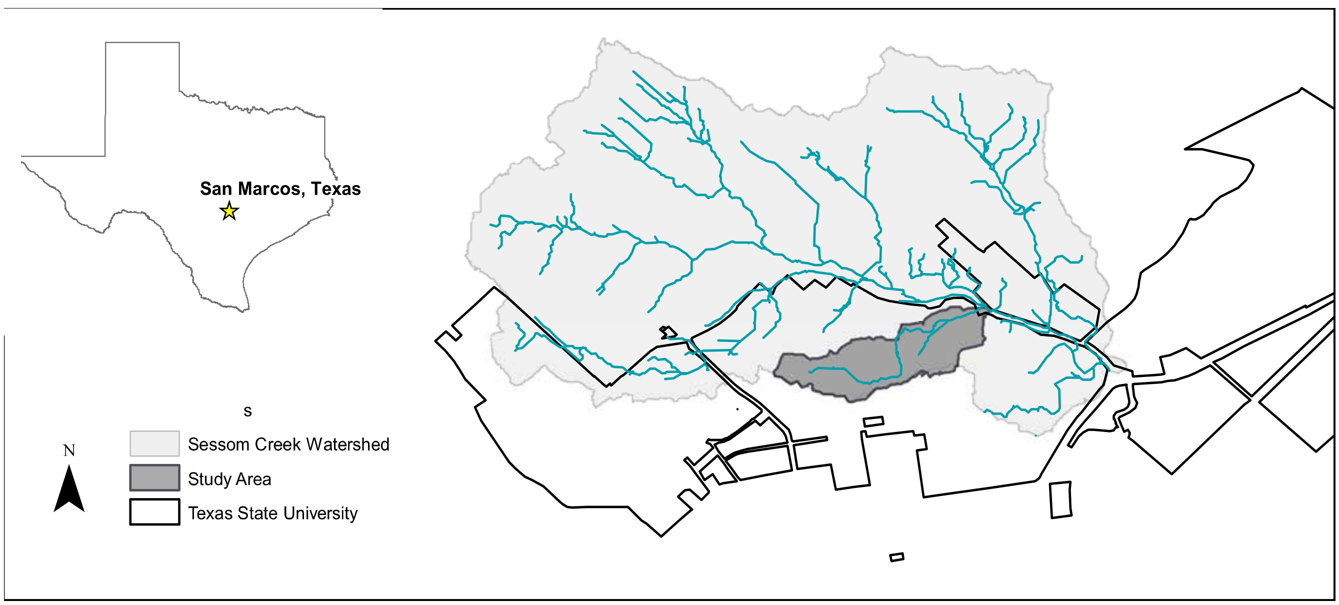

Figure 1. Map of Study Area. The study area is a 23.1 acre (9.35 ha) section of Texas State University located within the Sessom Creek Watershed, which flows into the San Marcos River.

It is located along the Balcones Escarpment and the region known as "Flash Flood Alley" (Caran and Baker 1986; Flood Safety 2005). This area is one of the most severely flooded areas in the United States (Leopold, Wolman, and Miller 1964, Fig. 3-16). For example, in May 2015, the Blanco River, immediately north of San Marcos experienced a peak discharge of 175,000 ft^3 /sec, more than one fourth the mean annual discharge of the Mississippi River, from a drainage basin of only 355 mi^2 (USGS 2018). The reasons for such recurring high intensity flooding events are threefold. First, the intensity of rainfall events are sometimes supplemented by tropical storms and hurricanes that make their way inland from the Gulf of Mexico (Caran and Baker 1986). Second, the rainfall from these high intensity storms are then whisked quickly downstream due to the natural topography, thin layer of topsoil, and geologic characteristics that lead to high stormwater runoff levels (Caran and Baker 1986). Third, underassessment of rainfall intensities that rely on outdate information still are the legal basis for defining flood probabilities, complicating the problem further (Earl and Vaughan 2015).

San Marcos, in particular, suffered two historic flooding events in 2015 alone, the "Memorial Day Floods" and the "All Saints Day Flood". The "Memorial Day Floods" being of special note because of its water velocity comparable to that of Niagara Falls and the "All Saints Day Flood" dropping close to six inches of rain in an hour during some parts of the storm (Smith and Bell, 2015). Texas State University is not immune to flooding—— the university canceled classes on September 26, 2016, when many of the parking lots and streets in low lying areas flooded.

Texas State University campus is 491 acres with buildings for potential green roofs throughout. Its most unique feature is that the spring of the San Marcos River is located on site. Besides the physical constraints and property damage associated with flooding, stormwater runoff washes campus pollutants and trash downstream into the San Marcos River. Therefore, reducing stormwater runoff on Texas State's campus could help to protect the water quality of the San Marcos River.

3.2 Data and Processing

Four main data sources were used for this study: elevation, land cover, drainage, and rainfall data. For elevation, 2008 Lidar data at 140cm nominal post-spacing from the Capital Area Council of Governments (CAPCOG) produced a 3-meter Digital Elevation Model (DEM). This data was acquired from Texas Natural Resources Information System (TNRIS). Land cover was digitized from ESRI base map imagery, which features a 0.3m resolution imagery in the continental United States, along with a building footprint shapefile from the City of San Marcos. Data for the drainage network was acquired from the City of San Marcos including outlet, manhole, and pipe location. These datasets were overlaid in GIS to locate the buildings on campus suitable for green roof systems, namely flat roofs, as well as, drainage network and land cover input for SWMM parameters. All inputs were projected into Albers Equal Area Conic, where San Marcos is close to the standard parallel at about 29 degree. The study area was delineated into 53 different sub-catchments shown below (Figure 2).

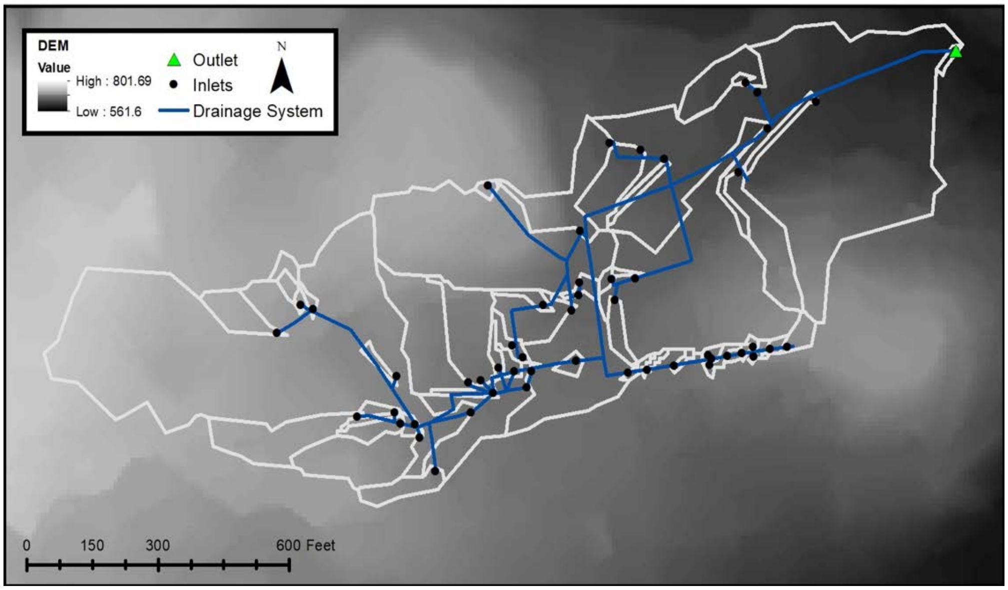

Figure 2. The sub-catchments and drainage for the study area overlaid on the terrain.

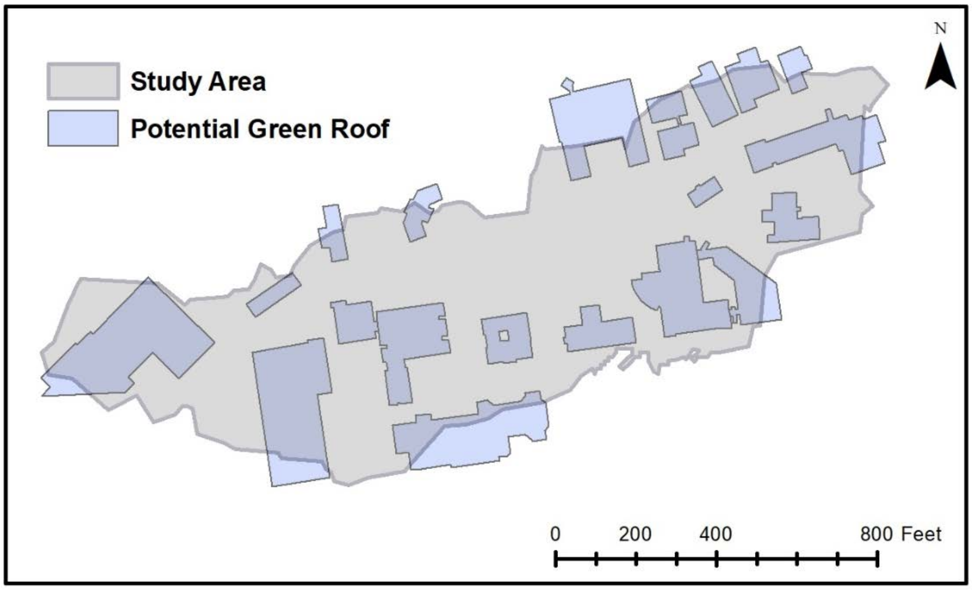

Figure 3. Potential Green Roof Installation. These potential green roofs make up 31% of the total study area.

For rainfall, five 24-hr. designed storms, 2-, 10-, 25-, 50-, and 100-year events, were adopted using the rainfall intensity-duration-frequency (IDF) coefficients for Hays County provided by the Texas Department of Transportation (TxDOT) (Table 2).

Table 2. Designated 24-hr storms for Hays County, TX (Asquith et al, 2005).

Recurrence Interval	in. 24 hrs.	mm/24 hrs.
2 years	4.1	103.2
10 years	6.6	168.0
25 years	7.9	201.6
50 years	9.4	240.0
100 years	10.2	261.6

The IDF was then used to create a hyetograph for each storm event using the L-gamma Dimensionless Hyetograph method defined by the equation:

$$p(F) = F^{b} e^{c(1-F)}$$

Where:

e = 2.718282

p = normalized cumulative rainfall depth, ranging from 0 to 1

F = elapsed time, relative to storm duration, ranging from 0 to 1

b = distribution parameter b defined by storm duration (0.783 for 24-hr. storm)

c = distribution parameter c defined by storm duration (0.4368 for 24-hr. storm)

as created by Asquith et al. specifically for use in Texas (Figure 4) (2005).

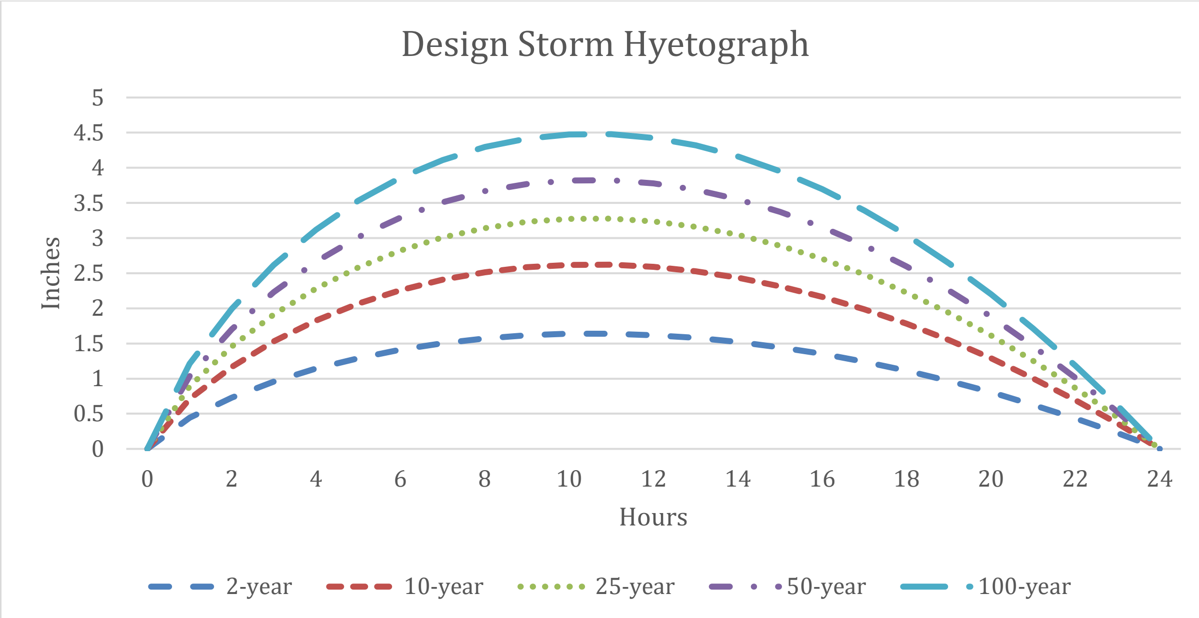

Figure 4. Hyetograph for designed rainfall events.

3.3 SWMM Modeling

The stormwater management model (SWMM), a hydrologic model developed by the United States Environmental Protection Agency, was chosen to model runoff volume, amount and time of peak flow. SWMM was chosen because it has been found to be a very suitable model for a small urban setting and can effectively model the performance of LID practices, such as green roof systems (Chun and Ting Fong 2017; Kong et al. 2017).

Table 3 shows the input parameters of green roof systems in SWMM, which were similar to the inputs in Kong et al. (2017). These parameters line up with green roof characteristics mentioned earlier, namely soil depth of 150mm (6 in.) (the maximum soil depth for an extensive green roof). For roof slope, building were categorized in either flat or small slope based on field inspection. Both of these characteristics were chosen to maximize the stormwater retention of green roof systems as derived from

Kong et al. (2017). Other input parameter for SWMM was derived from land cover of the existing area (Table 3).

Table 3. Parameters used for green roof controls in the SWMM.

Surface	Berm height (mm) 75	Vegetation (%) 100	Manning's n 0.1	Surface slope (%) 0.3 (low slope); 16.67 (medium slope)	
Soil	Thickness (mm) 150	Porosity 0.5	Conductivity Slope 5	Conductivity (mm/hr) 72	Suction Head (mm) 20
Drainage Mat	Thickness (mm) 75	Void (%) 30	Roughness (Manning's n) 0.1		

Table 4. Input Parameters for the SWMM.

Parameter	**Type**	**Symbol**	**Value**
Manning's n	Overland flow	Imp-n	0.010
		Per-n	0.100
	Conduit flow	Con-n	0.010
	Open channels		0.400
Depression storage	Per-DS		2.54-7.62 (mm)
	Imp-DS		1.27-2.54 (mm)
Soil infiltration	Horton infiltration parameters	Max. Infil. Rate	76.2 (mm/hr)
		Min. Infil. Rate	3.18 (mm/hr)
		Decay constant	3.12 h
		Drying time	7 d
		Max. Infil. Vol.	0

Two scenarios were tested in this study. The baseline scenario adopts the current campus building structures and alternative scenario has the addition of green roof systems. These scenarios were then evaluated based on designed rainfall events of 2-, 10-, 25-, 50-year, and 100-year events, mentioned above. Results from scenarios were then evaluated for any significant differences in total stormwater runoff along with peak discharge and time of the peak runoff. Modeled hydrographs were tested for normal distribution using the Shapiro-Wilk test and all were found to have a probability value (*p*) less than 0.0010 and were therefore not normally distributed. Therefore, non-parametric tests were used to determine any significant differences associated with the hypotheses.

4. Results

All 22 building in the study area had the potential for green roof installation based on roof slope and building type. However, only 21 buildings were used in modeling because one building had an unsuitable use as it was a parking garage with parking spots on its roof.

All storm events showed a reduction in total runoff volume for the green roof scenario. A 2-year storm event saw the largest reduction in total runoff volume at 24.4% reduction with all other storm events showing a reduction of 22-21%. The Mann Whitney test results revealed that there was a significant difference between the original and green roof scenarios for the 2-year storm event with a *p* value of 0.0019 (Figure 5A). There were no significant differences between the baseline and green roof scenarios with *p* values of 0.1502, 0.3303, 0.4419, and 0.5401 for 10-year, 25-year, 50-year, and 100-year storm events respectively.

Table 5. Hydrologic results for sub-catchment 49.

Storm Intensity	Original Scenario Rv 10^6L (10^gal)	Original Scenario Qp cms (cfs)	Original Scenario Tp (hrs)	Green Roof Scenario Rv 10^6L (10^gal)	Green Roof Scenario Qp cms (cfs)	Green Roof Scenario Tp (hrs)
2-year	14.88 (3.93)	0.26 (9.06)	11	12.45 (3.29)	0.25 (8.79)	13.5
10-year	24.34 (6.43)	0.42 (14.74)	11	21.96 (5.8)	0.42 (14.86)	11
25-year	30.7 (8.11)	0.52 (18.53)	11	28.28 (7.47)	0.53 (18.65)	11.25
50-year	35.96 (9.5)	0.61 (21.68)	11	33.58 (8.87)	0.62 (21.81)	11.25
100-year	42.32 (11.18)	0.72 (25.47)	11	39.9 (10.54)	0.72 (25.6)	11.25

When looking at all sub-catchments there was not a significant difference for total runoff and peak runoff between the baseline and green roof scenarios. However, for sub-catchment 49, located at the outlet, total runoff did show decreases of up to 16% for the 2-year storm event (Table 5) with green roof installation. Within the outlet sub-catchment, peak runoff actually increased or stayed the same for

E

Figure 5: Modeled hydrodraphs of sub-catchment 49. Each storm event is shown with the original scenario and with the addition of green roofs.

all but the 2-year storm event within the green roof scenario (Table 5). For time to peak discharge, the 2-year storm event showed the most difference with a 2.5hr delay for sub-catchment 49 located at the outlet. All other storm events showed only up to a 15min delay in peak runoff for the same outlet sub-catchment (Table 5). Hydrographs of the runoff in Figure 5 show green roofs are effective until they become saturated, which happens much quicker the higher the storm intensity (Figure 5).

5. Findings

This study identifies 21 buildings for potential green roof installation. 15 of these buildings were highly suitable as they were the right building type and had low to no roof slope. These buildings maximized the reduction of stormwater runoff because of their low roof slope. The other 6 buildings were slightly less suitable as they had low to medium roof slopes (Table 5). A total of 21 buildings for potential green roof installation out of 22 buildings shows potential for high suitability of buildings on the rest of the campus as well.

Table 6. Suitability of buildings for green roof installation. Buildings were ranked first by slope then by area.

Rank	Building	Slope Classification	Area (sq m)	Area (sq ft)
1	LBJ Student Center	Low	5,726.34	61,638.32
2	Alkek Library	Low	5,000.74	53,827.97
3	Evans Liberal Arts	Low	4,105.51	44,191.71
4	Music Building	Low	3,390.97	36,500.4
5	Centennial Hall	Low	3,018.12	32,487.04
6	Agriculture Building	Low	2,628.15	28,289.41
7	Derrick Hall	Low	2,487.55	26,775.99
8	Chemistry	Low	1,752.17	18,860.36
9	Comal	Low	1,188.98	12,798.18
10	Sabinal	Low	1,128.93	12,151.8
11	Boiler Plant	Low	1,045.71	11,256.02
12	Trinity	Low	909.18	9,786.41
13	Math Computer Science	Low	876.58	9,435.51
14	Pecos	Low	516.18	5,556.16
15	Medina	Low	294.24	3,167.2
16	Taylor-Murphy History	Medium	1,125.84	12,118.54
17	Honrnsby	Medium	673.35	7,247.93
18	Smith Hall 1	Medium	596.35	6,419.11
19	Pedernales	Medium	574.23	6,181.01
20	Colorado	Medium	528.77	5,691.68
21	Arnold Hall A	Medium	506.23	5,449.06
		Total Area:	38,074.12	409,829.83

While the green roof reduction of stormwater is highest at 2-year storm events, the results show that it becomes less effective at reducing stormwater as storm intensity increases (Table 5). This is consistent with the literature reviewed, which showed stormwater reduction was most noticeable with smaller rainfall events, whereas, larger rainfall events did not show much difference (Simmons et al. 2008; Lui et al. 2017). Zhou et al. (2017) showed a much more dramatic drop from 44% reduction for a 2-year event to only a 17% reduction for a 20-year event. This study showed a much modest drop from 24% to 22% for a similar interval of a 2-year to 25-year storm event, respectively. Not only was there less reduction between storm intensities, but also results from this study show green roofs were less effective with comparable storm intensities from Zhou et al. (2017). For example, the reduction was 24% for the 2-year storm event compared to 44% reduction reported by Zhou et al. (2017). This decrease in effectiveness could be due to study area size, as the study area for Zhou et al. (2017) was a large highly urbanized city, which means more potential buildings for implementation. Green roof technology is more effective in highly dense urban areas for this reason.

However, the results from peak runoff were unexpected, as literature showed green roof systems reducing peak runoff. Bliss, Neufeld, and Ries (2009) showed reductions of peak runoff up to 85% for a green roof verses a control roof. Therefore, reductions in peak flow at the sub-catchment level were also expected when in fact results showed no change or increase in peak runoff (Table 4). This could be the result of how SWMM models green roof technology, as once the green roof becomes saturated, the hydrologic response is to bounce back to the original state. This can be seen in Figure 5 as the modeled hydrographs were almost identical after the peak flow between the two scenarios in all storm events. This failure of the model to predict a reduction in peak runoff could be attributed to the modeled rainfall intensity (Figure 4) that has the peak rainfall intensity approximately mid-point in the 24-hour period whereas flood events are typically produced by heavy rainfall earlier during the flood period, when green roofs would reduce the peak runoff unless the infiltration and storage capacity of the roof had already been exceeded.

Time to peak showed its greatest delay with the smallest intensity storm, at the 2-year storm event, just like total and peak runoff. The 2-year storm event showed a 2.5hr delay in peak runoff, while all other storm events showed only up to 0.25hrs of delay (Table 4). This is consistent with the literature reviewed as Bliss, Neufeld, and Ries (2009) found delay for peak runoff of 2hrs during lower intensity storm and found no delay during higher intensity storms.

Even with stormwater runoff reductions of 21-24% for the study area, and reductions in peak runoff and time to peak for 2-year storm events, this maybe not be enough to reduce flooding significantly for the Sessom Creek watershed. Although the rest of campus, located in the watershed, does have similar building types to the study area, the rest of the watershed outside of campus is majority residential. While residential buildings can still be adapted to green roof technology, there are barriers to implementation, namely the burden of cost to the individual resident as well as factors that reduce effectiveness, such as increased roof slope and smaller roof area.

Furthermore, since green roof systems provide many other benefits besides stormwater runoff reduction, more research is needed to support or reject implementation when looking at the cost verses benefits. In addition to stormwater reduction, the total cost will need to be weighed against the total benefits. Green roofs help reduce energy costs for the building, improve water quality, and reduce the heat island effect. Although green roofs may not be cost effective when looking just at stormwater reduction their combined benefits may make the high price for installation worth it.

This study has several limitations. First, this study used synthetic rainfall scenarios instead of an empirical rainfall event. These scenarios are helpful when comparing data across studies however, they are only estimates could actually be underestimations of rainfall intensity for this area as explained by Earl and Vaughan (2015). Also, as described above, synthetic rainfall scenarios do not take into effect variations in intensity in the same event like actually rainfall data would. Variation in rainfall intensity within the same storm could change the effectiveness of green roof technology. Second, this study was not able to calibrate and validate the modeled hydrologic response due to the abandonment of USGS stream gauge on Sessom Drive and the unfit size of watershed of nearby gauges. This model will have to be verified upon green roof installation. Lastly, this study includes different forms of simplifications, namely using a simplified drainage system and Horton infiltration that are common when employing modeling. Although other studies have used these methods previously it is important to note that simplifications are being made of a complex system.

6. Conclusions

In conclusion, it is important in flood prone areas to minimize flooding impacts. In these regions that are naturally predisposed to flood, minimizing the impact of developing impervious surfaces is essential for reducing flood risks. This study identified 21 buildings with the potential for green roof instillation, which makes up 31% of the study area. Although with all storm events, green roofs showed a reduction in stormwater runoff, only the 2-year storm event showed significant difference between scenarios for the study area. This is consistent with the literature reviewed, which showed stormwater reduction was most noticeable with smaller rainfall events, whereas, larger rainfall events did not show much difference.

This study only looked at extensive green roofs to maximize potential installation. Future research could include intensive green roofs with a structural assessment by an engineer to measure the substrate depth each roof could hold in order to maximize the amount of water retention even further. Also, this study only considers one example of LID practices. There are many more LID practices that could further reduce stormwater runoff, such as, permeable pavements, which along with green roofs are easier to adapt onto the existing urban landscape. Future research could include permeable pavements as well as other types of LID, along with green roof systems. Lastly, this study only looks at a small sub-catchment of the Sessom Creek Watershed. Further study could include study at the Sessom Creek watershed level to assess green roof implementation at a greater scale.

REFERENCES

Asquith, W. H., Roussel, M. C., Thompson, D. B., Cleveland, T. G., and Fang, X.. 2005. Summary of dimensionless Texas hyetographs and distribution of storm depth developed for Texas Department of Transportation Research Project 0–4194, U.S. Geological Survey Water Resources Division Report 0–4194-4.

Bliss, D. J., Neufeld, R. D., and Ries, R. J. 2009. Storm water runoff mitigation using a green roof. Environmental Engineering Science 26 (2): 407-18.

Caran, C. S., and Baker, V. R. 1986. Flooding along the Balcones Escarpment, central Texas. The Balcones Escarpment-Geology, Hydrology, Ecology and Social Development in Central Texas: Geological Society of America: 1-14.

Castiglia Feitosa, R., and Wilkinson ,S. 2016. Modelling green roof stormwater response for different soil depths. Landscape and Urban Planning 153 (Sep): 170-9.

Castleton, H. F., Stovin, V., Beck, S. B. M., and. Davison, J. B. 2010. Review: Green roofs; building energy savings and the potential for retrofit. Energy & Buildings 42 (10): 1582-91.

Earl, R. A., and Vaughan, J. W.. 2015. Asymmetrical Response to Flood Hazards in South Central Texas. Papers In Applied Geography Vol.1, (4): 404-412. Supple

Eaton, T. T. 2018. Approach and case-study of green infrastructure screening analysis for urban stormwater control. Journal of Environmental Management 209 (March 1, 2018): 495-504.

Flood Safety 2005. Flash Flood Alley, Flood Safety, Inc., Boulder, Colorado.

Jato-Espino, D., Sillanpaa, N., Charlesworth, S. M. and Andres-Domenech, I. 2016. Coupling GIS with stormwater modelling for the location prioritization and hydrological simulation of permeable pavements in urban catchments. Vol. 8 (451): 1-17.

Jia, H., Yao, H. Tang, Y., Yu, S. L., Field, R., and Tafuri, A. N.. 2015. LID-BMPs planning for urban runoff control and the case study in china. Journal of Environmental Management 149 : 65-76.

Jia, H., Yao, H., Tang, Y., Yu, S., Zhen, J., and Lu, Y. 2013. Development of a multi-criteria index ranking system for urban runoff best management practices (BMPs) selection. Environmental Monitoring and Assessment 185 (9) (Sep): 7915-33.

Kong, F., Ban, Y., Yin, H., James P., and Dronova, I. 2017. Modeling stormwater management at the city district level in response to changes in land use and low impact development. Environmental Modelling and Software 95, 132-142.

Liu, C. and Li, Y. 2016. Measuring eco-roof mitigation on flash floods via GIS simulation. Built Environment Project and Asset Management 6 (4) (Sep 5,): 415-427.

Liu, C., Li, Y., and Li, J. 2017. Geographic information system-based assessment of mitigating flash-flood disaster from green roof systems. Vol. 64, 321-331.

Liu, C. Y. and Chui, T.F.M.. 2017. Factors influencing stormwater mitigation in permeable pavement. Water (20734441) 9 (12): 1-9.

Masseroni, D., and Cislaghi, A. 2016. Green roof benefits for reducing flood risk at the catchment scale. Environmental Earth Sciences 75 (7): 1-11.

Poongothai, S., and Nagarajan, N. 2012. Spatial mapping of runoff from a watershed using SCS-CN method with remote sensing and GIS. Journal of Hydrologic Engineering 17 (11) (Nov 1,): 1268-77.

Robert B.. 2015. Ten U.S. cities now have 1 million people or more; California and Texas each have three of these places. Targeted News Service (TNS), May 22, 2015. https://www.census.gov/newsroom/press-releases/2015/cb15-89.html.

Simmons, Mark T., Brian Gardiner, Steve Windhager, and Jeannine Tinsley. 2008. Green roofs are not created equal: The hydrologic and thermal performance of six different extensive green roofs and reflective and non-reflective roofs in a sub-tropical climate. *Urban Ecosystems*(4): 339-348.

Smith, K. B. and Bell, K. E. 2015. Hays County 2015 flooding events after action report. Hays County / San Marcos, and Joint EOC Operations.. http://www.co.hays.tx.us/data/sites/1/pdf/press-releases/2016/hays-county-may-october-2015-flooding-aar.pdf

U.S. Geological Survey (USGS). 2018. Texas Water Science Center. http:tx.usgs.gov.

Volder, A., and Dvorak, B. 2014. Event size, substrate water content and vegetation affect storm water retention efficiency of an un-irrigated extensive green roof system in central Texas. Vol. 10, 59-64.

Xie, J., Wu, C., Li, H., and Chen, G. 2017. Study on storm-water management of grassed swales and permeable pavement based on SWMM. Water, Vol 9 (11): 840.

Zhou, D., Liu, Y., Hu, S., Hu, D., Neto, S., and Zhang, Y. 2017. Assessing the hydrological behaviour of large-scale potential green roofs retrofitting scenarios in beijing. Urban Forestry & Urban Greening.