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Modeling Urban Hydrology: A Comparison of New Urbanist and Traditional Neighborhood Design Surface Runoff

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Abstract

Urban development affects the amount of potential surface runoff generated during storms by changing the amount of impervious cover across the landscape. However, the degree of surface runoff alteration depends on the type of urban development in place. New urbanist developments are designed with higher densities and encourage a diversity of land uses, while traditional neighborhood developments have a monotone land use pattern with medium-to- low densities. Two neighborhoods within the city of Austin, Texas- Mueller, a new urbanist development, and Circle C Ranch, a traditional neighborhood development- were used to study the effect of development type on potential surface runoff. Using satellite imagery coupled to the HEC-HMS model nested within the Watershed Modeling System (WMS), potential surface runoff was calculated for the two different neighborhoods for a 10-year 24 hour storm scenario. Results initially suggest that total runoff volume and peak surface runoff significantly increase for the new urbanist neighborhood over the traditional development as a function of the higher density urban footprint associated with the new urbanist design. However a higher number of residential units are available at Mueller over the same area as Circle C Ranch. When taking this into account the increased potential surface runoff is negated at the new urbanist site. Although new urbanist neighborhoods will usually contain more residential units than traditional developments when compared at the same scale, the higher urban density associated with these developments necessitates the construction of more efficient stormwater retention measures within these neighborhoods.

Keywords: Urban Hydrology; New Urbanism; Runoff Modeling; Land Use

1. Introduction

Urban development affects the amount of potential surface runoff generated during storms by changing the amount of impervious cover across the landscape [1-3]. In addition to increasing surface runoff, urban developments also modify the volume of groundwater recharge, lower water tables, increase peak discharge, and decrease base flows in dry periods [4-5]. These modifications depend on the type of urban development in place.

New urbanism is a type of sustainable development that is designed to reduce automobile use, increase walking and cycling, and increase the diversity of land uses while incorporating traditional and new practices of planning at all scales [6]. Moreover, new urbanism is a type of low impact development (LID) that contains elements such as cluster development and bio-retention. LIDs can mitigate problems associated with storm water runoff by increasing resilience and utilizing best management practices [7-8]. Traditional neighborhood development (TND), on the other hand, is limited to the neighborhood scale and incorporates traditional planning practices such as large lot and single family zoning [9]. TND are not considered LIDs unless further steps have been taken to implement specific LID features. New urbanism is touted as a more environmentally sustainable development than traditional neighborhood developments, which will typically contain greater amounts of impervious cover [10].

While research implies that LID's do often reduce total stormwater runoff and increase the runoff lag time when compared to a traditional neighborhood designs [11-13], more research needs to be carried out which compares neighborhoods of similar size and scale in order to make further accurate assessments of LIDs and their impact on stormwater runoff. Several obstacles pertinent to stormwater runoff have been noted concerning LID planning. Many current zoning and regulatory statutes can hinder the implementation of LID concepts and philosophies [14]. These features include minimum street width for public services, concert curbs and gutters, the absence of runoff collection ponds due to public health concerns, and other elements that may not fit into the visually pleasing aesthetic design [14]. As a result, a comparison of three urban neighborhoods ranging from high to low density actually found that the medium density neighborhood displayed the longest peak runoff lag times due to more effective usage of stormwater retention systems [15].

An increase in geospatial and modeling capability has increased the opportunity of analyzing urban development impacts on stormwater runoff in recent years. Remote sensing data coupled with geographic information science (GIS) systems and runoff modeling software have been used more frequently to study the interaction between rainfall events and urban surfaces leading to runoff [16-18]. The purpose of this research is to utilize these techniques to model and compare the potential surface runoff for two similar-sized new urbanist and traditional neighborhoods in Austin, Texas.

2. Study Area

The study area includes two neighborhoods, one new urbanist, and one traditionally developed neighborhood in Austin, Texas **(Figure 1)**. Austin-Mueller (Mueller) is a new urbanist neighborhood located in north-central Austin approximately three miles from downtown Austin on the site of the city's old Robert Mueller airport. Today, Mueller is Austin's most recent master planned community that focuses on new urbanism as a vehicle for sustainability including a mixture of home types, sizes, and price ranges. Circle C Ranch is a traditional neighborhood development that originated in the late 1980s. The neighborhood contains mostly single-family homes that are situated on medium to large lots with traditional planning practices in place [19].

Regarding physical characteristics that may impact stormwater runoff, Austin receives, on average, 870mm precipitation annually [20]. The majority of this total occurs in the months of April and May when violent storms develop from Pacific cold fronts moving rapidly across the south-central Texas region, resulting in severe flooding [21]. Another important factor concerning runoff is the soil which heavily controls the amount of infiltration-to-surface-runoff ratio during storm events. Soils may be classified into one of four hydrologic groups (A, B, C, D) that reflect their drainage capability. Group A soils are characterized by high infiltration rates to give low runoff potential following precipitation, while group D soils have low infiltration rates to increase runoff potential [22]. Soil coverage across both sites is typical of the south-central Texas region.

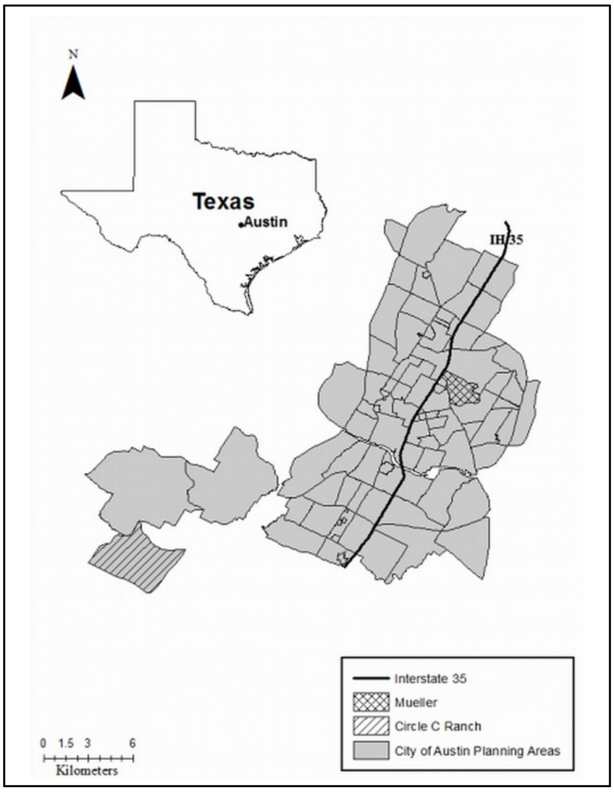

Figure 1. Study areas within Austin, Texas.

Mueller is dominated by the Lewisville and Altoga series soils which range from well to moderately drained silty-clay soils underlain by fractured chalk or limestone, classified in the B-C soil hydrologic groups. Smaller instances of the Houston Black and Patrick soil series are also present at these sites which are also classified into the moderately-to-poorly drained B-D soil hydrologic grouping. At Circle C Ranch, the Tarrant soil series dominates as a stony, clayey soil (hydrologic group C) with the moderately well-drained (C group) Speck series present to the south and west of the site [22].

3. Methods

Land use/cover data were obtained for both sites from 1m resolution Digital Orthophoto Quarter Quad (DOQQ) images from 2010. In order to directly compare the runoff generated between the two sites, the larger Circle C Ranch site was trimmed down to match the area of Mueller, using road boundaries within the sub-division as the new boundaries for Circle C Ranch. This gave two images covering an equal area of 0.7km^2 with the Mueller site containing 751 residential units and Circle C Ranch 511. The imagery was initially loaded in ArcMap before performing a supervised classification technique using the maximum likelihood algorithm. Following a visual inspection of the images, four land cover classes were identified as urban/impervious, forest, grass, and surface water **(Figure 2)**. The classification accuracy was verified by rechecking the classified images with the original imagery. The classified images were then loaded into the Watershed Modeling System (WMS) software and combined with a digital elevation model (DEM) to calculate slope and hydraulic length (the longest flowpath across each site, L) for both sites. Finally, soil coverages, containing the soil hydrologic groups for the soils at both sites, from the State Soil Geographic Database (STATSGO) were loaded into the model in order to calculate infiltration losses during storm activity, similar to previous research techniques [23], **(Figure 3)**.

Surface runoff was calculated using the HEC-HMS model for a 10-year 24 hour storm scenario based on the surface and soil hydrologic group cover for each site. The HEC-HMS model was originally developed by the U. S. Army Corps of Engineers (U. S. ACE) as a lumped-parameter model, capable of routing surface flow into a series of drainage basins to an outlet [23,24]. Various methods are available within HEC-HMS to determine runoff versus infiltration. The Soil Conservation Service (SCS) method was chosen for this study based on its success at modeling surface runoff in other urban runoff studies [18,25-26], and the availability of the necessary physical data at both study sites in Austin. It is also ideally suited for modeling drainage areas of less than 2000acres (~8km^2) [27].

Figure 2. Landcover classification from DOQQ imagery for Mueller (left) and Circle C Ranch (right).

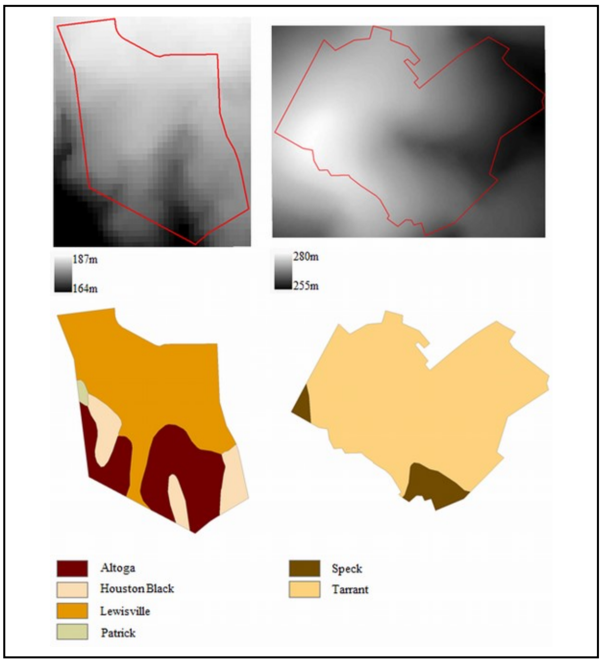

Figure 3. DEM and soil coverage for Mueller (left) and Circle C Ranch (right).

This method calculates initial precipitation losses (the initial abstraction) and ultimately the volume of water available for surface runoff based on soil permeability and land cover by prescribing a predetermined "curve number" to each surface and soil hydrologic group cover (Equations 1-2).

$$Q = \frac{(P - Ia)^2}{P - Ia + S} \tag{1}$$

Q = runoff depth
P = 24-hour storm precipitation depth
Ia = initial abstraction (0.2S)
S = infiltration/retention losses (Equation 2)

$$S = \left(\frac{1000}{CN}\right) - 10 \tag{2}$$

CN = curve number for areal soil and land cover

Higher curve numbers result from land cover and soil hydrologic groups that allow decreased infiltration, which result in a greater volume of water made available for surface runoff. By overlaying the classified land cover data with the soil hydrologic group coverage data, a composite curve number could be generated for each site (Equation 3), [24].

$$CN_{comp} = \frac{\sum A_i CN_i}{\sum A_i} \tag{3}$$

CN_{comp} = composite curve number
A_i = drainage area of each area with uniform land and soil coverage
CN_i = curve number of each A_i

Example curve numbers for soil hydrologic groups and various land cover surfaces are given in **Table 1**.

Runoff volumes were then generated to produce hydrographs which determined the peak runoff in cubic meters per second (cms) and lag time between peak precipitation and runoff at each site. A 10-year 24 hour-storm scenario for the Austin area was chosen based on the availability of local historical hydrological data for model calibration later **(Table 2)**. The SCS method initially estimates basin lag time using the physical basin parameters in Equation 4, **(Table 3)**:

$$T_{lag} = L^{0.8} \frac{(S+1)^{0.7}}{1900\sqrt{Y}} \tag{4}$$

T_{lag} = basin lag time
L = hydraulic length
S = infiltration/retention losses (Equation 2)
Y = mean slope

Table 1. Example runoff curve numbers for various land covers by soil hydrologic group [27].

Land cover	Soil hydrologic group			
	A	B	C	D
Impervious Surfaces	98	98	98	98
Woods/Forest	30	55	70	77
Grass	39	61	74	80
Surface Water	0	0	0	0

Table 2. Approximate precipitation depths for a 10-year 24 hour storm in the Austin area [28].

Time period	Precipitation depth (mm)
15 mins	35.6
1 hour	68.6
2 hours	86.4
3 hours	94.0
6 hours	109.2
12 hours	121.9
24 hours	152.4

Table 3. SCS model parameters.

Site	Hydraulic length, L (m)[a]	Infiltration losses, S	Slope, Y (%)	Basin lag time, $Tlag$ (hrs)
Mueller	994	1.6	1.8	0.5
Circle C Ranch	1020	3.2	2.3	0.62

a. Although meters are given, the equation requires L input in feet.

Calibration of the HEC-HMS model is normally achieved by comparing the modeled runoff with observed runoff obtained from a U.S. Geological Survey streamgauge at the outlet of the modeled catchment site [23,29]. This was not directly possible as neither site contained an active streamgauge for model comparison located at the site outlets. To account for this, calibration of the runoff model took place by comparing the peak flow generated from a storm event that matched the characteristics of the 10-year 24 hour storm with the observed peak flow from the nearest active streamgauge, (Boggy Creek USGS# 08158035) located approximately 2.4km downstream from the Mueller site. In this case the model was run using the initial conditions calculated by HEC-HMS from the physical site data, before adjusting the key parameter, initial abstraction, as necessary, to match the proportional observed peak runoff generated at Boggy Creek. This took into account the larger catchment area of the Boggy Creek gauge location. Initial peak runoff was overestimated, and subsequent lag times underestimated, as a result of low initial abstraction parameter values generated by the model. This was corrected by increasing the initial abstraction value until the peak runoff value at Mueller proportionally matched the value at the Boggy Creek site, similar to the approach adopted by previous urban runoff modeling research [23,29]. Adjustment of the initial abstraction value for Circle C Ranch followed based on the lower CN value for that site **(Table 4)**. **Figure 4** shows the conceptual workflow of the methodology.

Table 4. Curve numbers and initial abstraction values used in model.

Site	Default Initial Abstraction (Ia)	Calibrated Initial Abstraction (Ia)	Curve Number
Mueller	0.2	0.26	86
Circle C Ranch	0.2	0.32	78

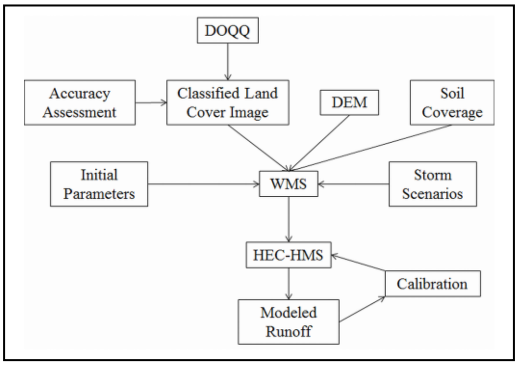

Figure 4. Methodology workflow.

4. Results

The Mueller site contained a much greater proportion of urban/impervious cover, totaling 50% compared to the Circle C Ranch coverage of 36% **(Figure 2, Table 5)**. The impervious area of the Mueller neighborhood is also clustered around a central area, surrounded by non-impervious surfaces, which typify new urbanist developments.

The Circle C Ranch site displays a much more uniform spread of all surfaces, including impervious surfaces across the entire site. While Mueller does display 17% more grass coverage, the majority of the Circle C Ranch site is covered in forest, totaling 51% compared to Mueller's 16%. Mueller also includes 4% surface water coverage in the form of two ponds located to the south and northwest of the site.

Regarding runoff, initially the two hydrographs produced by the model appear similar, but closer inspection reveals three key differences between Mueller and Circle C Ranch in response to the 10-year storm scenario **(Figure 5)**. Firstly, the peak runoff increased by 64% from 0.99cms at Circle C Ranch to 1.55cms at the Mueller site. Secondly, the storm lag time displayed a lower value by 31 minutes at Mueller, which equated to a 59% decrease in time from Circle C Ranch storm response. Lastly, the runoff coefficient (proportion of rainfall to runoff), increased by 5.9% at Mueller, again highlighting that a greater proportion of rainfall during the storm becomes surface runoff at this location. The results suggest that the new urbanist site at Mueller actually generates the greater volume of stormwater runoff (42000m^3 vs. 35700m^3 at Circle C Ranch). Furthermore, with both sites displaying similar physical properties in terms of area, relief, hydraulic length and soil hydrologic group characteristics, the greater extent of impervious surface coverage compared to the traditional site at Circle C Ranch is chiefly responsible for this.

However, it must be addressed that new urbanist developments focus on clustered development practices that have a higher density of residential development than a traditional urban development practice over a similar area. In this case Mueller contains 751 residential units compared to Circle C Ranch's 511, a total difference of 240 units over the 0.7km^2 area. Taking this into account Circle C Ranch would theoretically generate a greater volume of runoff at 69863m^3 per 1000 units vs. 55925m^3 per 1000 units at Mueller, a difference of just under 14000m^3. As a result Circle C Ranch and other similar traditional urban developments, taken as a whole, will likely generate a greater volume of surface runoff than their new urbanist counterparts in terms of their total footprint on the landscape.

Table 5. Proportion of surface cover at Circle C Ranch and Mueller sites.

Surface cover	Circle C Ranch	Mueller
Impervious	36%	50%
Forest/Woods	51%	16%
Grass	13%	30%
Water	0%	4%

Of further note are the landscaped retention systems in place at the Mueller site which are designed to limit the effects of stormwater runoff, practices that are often not included across traditional developments. Bio-retention ponds are key features of new urbanist developments which aim to capture and store excess runoff following storm events. Mueller has two such ponds in place, to the north and south which have been aesthetically landscaped into the development blueprint. While the DEM datasets used do not capture any of these large-scale landscaping changes implemented at the Mueller site, assuming that the majority of stormwater runoff will follow the original topography and drainage patterns, the purpose of this paper was to investigate the potential surface runoff generated from this kind of development in comparison to a traditional neighborhood. The fact that new urbanist sites will often cluster their development in a bid to reduce the overall footprint of the site means that without these kinds of retention systems in place a greater volume of runoff could potentially be generated and lag times reduced following storm events as seen in this study.

5. Conclusions

A modeling framework has been developed to analyze the impacts of urban neighborhood design on storm runoff for the city of Austin, Texas. By layering a series of datasets that represent the physical landscape (land cover, soil, and relief) within the Watershed Modeling System (WMS) the HEC-HMS runoff model has generated peak runoff and storm lag times for a new urbanist and traditional neighborhood. The results imply that when directly comparing these types of urban design on a similar scale, the new urbanist neighborhood has the propensity to generate larger peak flows and shorter lag times as a function of the high density urban footprint associated with this type of neighborhood. Consequently it is imperative that flood retention or reduction measures are included in these neighborhood designs in order to mitigate the impacts of potential flooding both within and surrounding these new urbanist neighborhoods. Furthermore, while new urbanist neighborhoods have LID elements designed within them, and at a larger scale are meant to reduce runoff and pollutants, these results suggest more research is needed to determine how well, at the smaller scale, these elements work with other

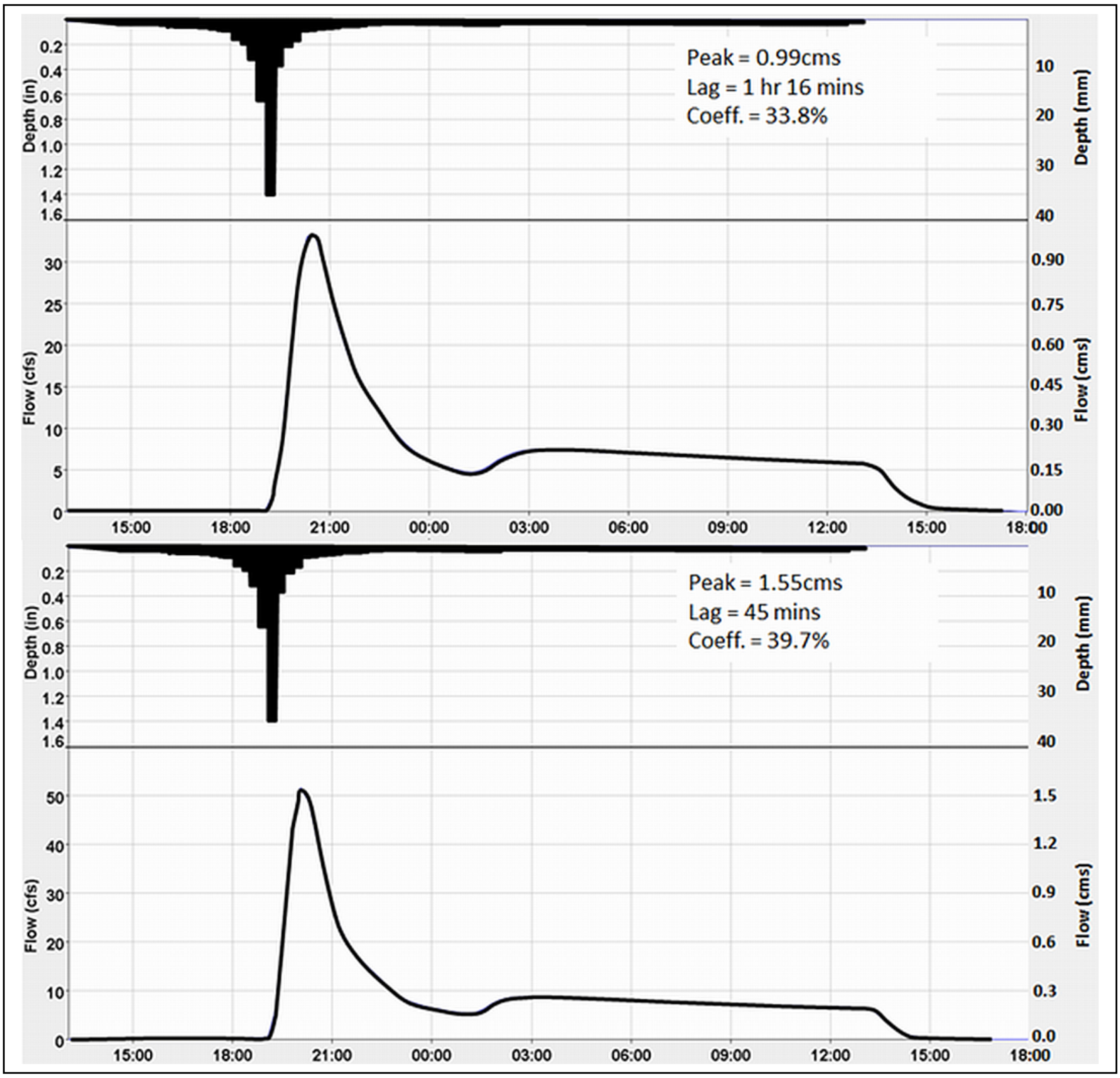

Figure 5. Modeled runoff hydrographs for Circle C Ranch (top) and Mueller (bottom).

neighborhood designs and to what level they reduce or increase pollutant runoff.

The methodology employed in this research demonstrates the potential of combining and manipulating a series of datasets within GIS and modeling software to ascertain the potential surface runoff generated within urban areas at the sub-drainage basin scale. However further research should also be conducted that compares potential runoff output from infiltration abstraction methods other than the SCS method as employed in this research. Also with the increase in development of new urbanist neighborhoods within US cities, similar research may be conducted that compares the potential runoff between these neighborhoods. Their non-traditional development and design often makes them unique from one another and thus could generate significantly different runoff outputs from similar storm scenarios.

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