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Urban green infrastructure and local flooding: The impact of landscape patterns on peak runoff in four Texas MSAs

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ABSTRACT

Even though there is a general acknowledgement that green infrastructure can have a positive role in reducing stormwater runoff, few studies have explored how specific spatial configurations of landscape—one of the critical components of green infrastructure—could influence runoff generation. This study attempts to address this gap by examining the landscape patterns in terms of size, shape, isolation, and connectivity across the four largest metropolitan areas in Texas, using landscape ecology metrics. The outcomes indicate that larger, less fragmented, and more connected landscape patterns are likely to mediate the mean annual peak runoff. In contrast, larger developments of complex shapes with more edges, clustered, and connected are likely to augment the peak runoff. The findings of this paper provide empirical evidences for policy makers to further the importance of interconnection and clusters of green infrastructure and plan strategic green hubs and corridors to more effectively manage stormwater runoff.

1. Introduction

The U.S. has experienced a rapid urbanization. The urban population increased by 12.1 percent from 2000 to 2010 and 82 percent of the U.S. population resided in urban areas as of 2014 (US Census, 2012; United Nations, 2014). The expansion of urban areas prompted the conversion or modification of undeveloped land, which has caused significant environmental degradation such as loss of natural areas, hydro-modification, and habitat displacement (Arnold & Gibbons, 1996; Gearheart, 2007; Schueler, 1994; Shuster, Bonta, Thurston, Warnemuende, & Smith, 2005). These adverse effects from developments and nature degradation have led to an increased interest in "green infrastructure" and its impacts on water management. Although different types of green infrastructure have been examined in previous studies, green infrastructure generally refers to a variety of greening strategies from rain gardens, bio-retentions, and street side vegetation to urban forests, parks, and wetlands (CLEAR, 2013). Specific action plans and policies in terms of green infrastructure have been made at all levels of government. In particular, the U.S. Environmental Protection Agency (EPA) made significant efforts to manage urban flooding, urban heat, biodiversity, and clean water through well-established green infrastructure.

Previous studies reported that green infrastructure could minimize surface runoff and increase flood storage that resulted from excessive stormwater runoff (Gill, Handley, Ennos, & Pauleit, 2007), moderate the urban heat island effect (Connors, Galletti, & Chow, 2013; Debbage & Shepherd, 2015; Liu & Weng, 2008), improve air quality (Bereitschaft & Debbage, 2013), and reduce insured losses caused by floods (Brody, Kim, & Gunn, 2013; Brody, Gunn, Peacock, & Highfield, 2011). Green infrastructure also contributes to conserving habitats and maintaining a natural ecological process (Benedict & McMahon, 2006; Hoellen, 2010; McDonald, Allen, Benedict, & O'Connor, 2005; USEPA, 2010). Even though the existing studies are rich in addressing the importance of a collective configuration of green infrastructure with other infrastructure systems, few researchers specifically examined the impacts of landscape patterns, one of the important components of green infrastructure, on stormwater management. To fill this gap, this paper attempts to empirically examine the extent to which spatial composition of landscape patterns (i,e., size, shape, isolation, and connectivity) influences stormwater management using landscape ecology metrics. This study focused on an urban woody area composed of trees, forest, shrub, and grassland, which is one of the critical subsets of landscape. Peak runoff measures were used as a substitute measure of stormwater management since the main purpose of green infrastructure is to effectively manage the peak

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runoff—which is a maximum rate of flowing runoff for a fixed period of time— (USEPA, 2012; 2014) and is frequently used as a surrogate measure for urban flooding.

The following sections 1) introduce the literature on landscape ecology, landscape patterns, and surface runoff; 2) describe methods including study area, data collection and measures, and data analysis; and 3) explain the results and include a discussion. The study concludes by providing suggestions for regional and local planners about how to implement strategic policies for the development of green infrastructure in order to reduce the volume of peak runoff and mitigate damage from local flooding. Finally, the study limitations and guidance for future research are presented.

2. Landscape ecology and runoff

2.1. Landscape ecology and its optimal condition

Landscape ecology is a theoretical and operational approach to understanding the interrelationships of landscape and many sorts of aggregated landforms (Forman & Godron, 1981). The focus of landscape ecology lies in identifying spatial patterns, flows and movements, and the spread of disturbances (Marsh, 2005). Recent advances in measurement tools such as aerial photographs, land classification systems, the Geographic Information System (GIS), satellite images, remote sensing, and FRAGSTATS (computer software designed to calculate landscape patterns) enables us to graphically and statistically measure the spatial patterns of landscapes so that geographers, landscape architects, urban planners, and wildlife biologists can use the concepts and methodology of landscape ecology. Based on analyses using landscape ecology metrics, suggestions for sustainable development to meet recent challenges such as habitat fragmentation, landscape degradation, or urban sprawl have often been made (Ndubisi, 2002).

From a landscape ecology perspective, the three major components of landscape are *matrixes*, *patches*, and *corridors*, which is called the patch-corridor-matrix model (Barnes, 2000, pp. 1–8; Ndubisi, 2002). *Matrix* is the dominant component in the landscape and is typically made up of a background cover type or extensive cover type. *Patches* are the most critical component among matrixes, patches, and corridors and refers to relatively homogeneous areas that are different from the surroundings in nature or appearance (Forman, 1995; Turner, Gardner, & O'neill, 2001). Simply stated, a patch could be defined as an aggregated or clustered distribution of species. *Corridor* refers to a strip of land which connects separate patches and helps organisms transfer smoothly from one patch to another through paths, streams, or strips, but sometimes newly installed corridors could be a drawback for the ecosystem by separating one existing patch into several (Forman & Godron, 1981; Forman, 1995; Turner et al., 2001). The collective configuration of these three components creates the complete characteristics of landscape, which in turn determines function (Mills, Ndubisi, Fife, & Hunter, 2001).

The concept of patch-corridor-matrix is also applicable to understanding the spatial congifuration of land uses or land covers. To illustrate, patch is similar to homogeneous urban districts with smilar land use types. Matrix is not too dissimilar from patch, but matrix highlights the contextural surroundings of a specific type of patch. Corridors are similar to streets, roads, or streams that connect or separate patches. As demonstrated in Fig. 1, if a park is surrounded by extensive residential developments, the neighborhood is a matrix and the park becomes a patch. If there is a connecting street between parks, this is called a corridor.

Then the question arises, what is the optimal condition of patches, corridors, and matrixes? Although there is no global standard for specifically identifying the best condition of landscape patterns to reduce flood damage, several scholars have attempted a general definition of “desirable” conditions for patches, corridors, and matrixes. The patch-matrix model emphasizes the diversity of the landscape (Turner, 1989). By contrast, the habitat network model—which focuses on sustaining interactions among species in landscape mosaics through continued intensification—prioritizes the connectivity of patches, emphasizing the functional flows and movements of energy, species, and other materials (Ndubisi, 2002). In land-use planning, the habitat network model has received significant attention because enhancing ecological networks with greenway connectivity can preserve nature and provide open green space for residents. Last, the spatial guidelines proposed by Diamond (1975) and Shafer (1994) simply visualized and generalized the idea of “better” and “worse” landscape patterns. They argued that desirable landscape patterns are 1) larger patches, 2) more connected and unfragmented patches and corridors, 3) wide corridors, and 4) heterogeneous areas of nature throughout human-developed areas (Forman & Godron, 1986). This paper used these four criteria to measure landscape patterns and set hypotheses.

2.2. Landscape pattern and its impact on runoff

A number of studies have demonstrated the positive impacts of green spaces, such as surface runoff reduction (Booth, Hartley, & Jackson, 2002; Fox et al., 2012; Gill et al., 2007; Hirsch, Walker, Day, & Kallio, 1990; Sung & Li, 2010), air quality improvement (Nowak, Crane, & Stevens, 2006), reducing the urban heat island effect (Debbage & Shepherd, 2015), and increases in property values (Kong, Yin, & Nakagoshi, 2007; Sander, Polasky, & Haight, 2010). In particular, the impacts of urban green spaces on hydrology are well known. Yang, You, Ji, and Nima (2013) investigated the effects of urban green space on stormwater runoff by utilizing experimental lab data of soil columns in Tianjin, China. They found that conserving urban green spaces could be an effective way to minimize the volume of stormwater runoff. By using the Soil and Water Assessment Tool (SWAT), Coutu and Vega (2007) verified that a loss of forestlands increased surface runoff in Chester County, Pennsylvania. Highfield (2012) found that a one percent increase in paludal scrub/shrub could decrease the peak annual stream flows by 16.9–18.7 percent in coastal Texas. In addition, a great number of studies have demonstrated that deforestation and an increase in impervious surfaces exacerbate stream flow, peak discharge, and flood magnitude (Braden & Johnston, 2004; Brody, Highfield, Ryu, & Spanel-Weber, 2007; Carlson, 2004; Paul & Meyer, 2001). For instance, Fox et al. (2012) revealed that hydrologic impacts from urbanization, such as runoff and peak flow change, were not significant in a Mediterranean catchment due to the vast amount of green spaces and afforestation. Brun and Band (2000) found similar results studying impervious cover and soil saturation in Baltimore, Maryland.

Although several studies have reported the positive impacts of green infrastructure in reducing runoff or local flooding, few of them examined the impacts of the spatial configuration of green infrastructure. Gill et al. (2007) determined that a network of green space can reduce surface runoff and increase flood storage using an energy exchange model. Matrix—which is defined by a large amount of vegetation around an urbanized area—contributes to an increase in rainwater infiltration. Brody et al. (2013) did not directly test the effects of green infrastructure, but rather studied the influences of development patterns, often called “impervious cover,” on flooding using flood loss data. This paper adopted landscape ecology metrics such as the number of patches, total class area, patch density, proximity, and connectedness. They found that connected and clustered development patterns result in a decrease

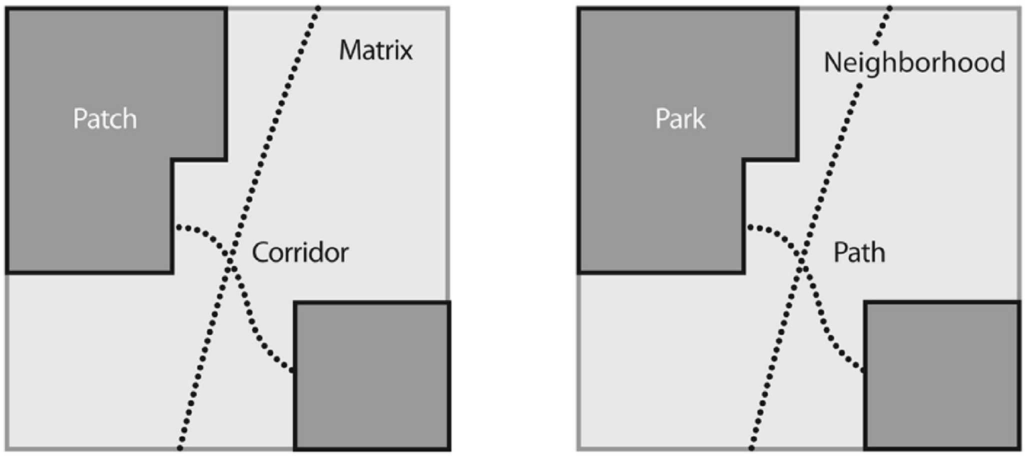

Fig. 1. Analogy of the patch-matrix model to a city.

in flood related losses. Gill et al. (2007) and Brody et al. (2013) revealed the possibility of different impacts of dissimilar spatial patterns of green infrastructure, but did not specifically observe landscape patterns and the impacts on surface runoff.

3. Research design

3.1. Research question

This paper examines the impacts of landscape patterns on local flooding specifically focusing on the size, the shape of edges, the level of clustering, and the connectivity of the landscape. These four characteristics are closely related to the ease of infiltration and level of disturbance. When urban woody areas cover a large expanse, have complex edges, and are connected and clustered, they are likely to contribute to an increase in streamflow and reduce its speed. Based on this research question, we established four hypotheses.

Hypothesis 1. A larger size landscape reduces peak runoff.

Hypothesis 2. A more convoluted landscape mediates peak runoff.

Hypothesis 3. Less fragmented and clustered landscape patterns decrease peak runoff.

Hypothesis 4. Highly connected landscapes reduce peak runoff.

3.2. Study area

The target population of this study is watersheds (or sub-basins) within the four largest metropolitan statistical areas (MSAs) in Texas, Dallas-Fort Worth-Arlington (Dallas MSA), Houston-Sugar Land-Baytown (Houston MSA), Austin-Round Rock-San Marcos (Austin MSA), and San Antonio-New Braunfels (San Antonio MSA). These four MSAs were ranked 4th, 5th, 25th and 33rd of population as of 2015, respectively, and have shown a more than 10% population growth since 2010. Given these facts, a significant number of natural areas have been converted to impervious surfaces in the four MSAs and these changes may greatly influence the landscape patterns and hydrological processes (Bellot, Bonet, Sanchez, & Chirino, 2001; Fu, Zhao, Chen, Liu, & Lu, 2005).

Watersheds were delineated based on data retrieved from the United States Geological Survey (USGS) gauge stations by using ArcHydro, an extension of ArcGIS 10.3. The digital elevation models (DEM; at a 30-meter resolution), flow accumulation, and flow direction raster data obtained from the National Hydrography Dataset (NHD) Plus were also used. For the final collection of sampled watersheds, four factors were carefully double-checked. First, watersheds that overlapped by more than 50 percent with the boundaries of MSAs were included. Second, watersheds that did not have a full record of peak flow from 2009 to 2011 were excluded. Third, watersheds that had dams or reservoirs at their outlets were excluded. Finally, watersheds larger than 600 km^2 were excluded to minimize the contextual differences among the samples. Fig. 2 shows the 108 watersheds sampled.

3.3. Data collection and measures

3.3.1. Dependent variable

The mean annual peak runoff depth was determined based on the following steps. First, the maximum daily stream flows from the water years 2009–2011 were obtained from the USGS and were converted to an average annual peak flow. Second, the unit of stream flow (m^3/s) was converted into a runoff depth (mm) to standardize the size of the watersheds and for better interpretation. Third, the values of the runoff depths were natural log-transformed to approximate a normal distribution.

3.3.2. Independent variables

Land cover data for 2011 from the USGS's National Land Cover Database (NLCD) with classification codes of 41 (Deciduous Forest), 42 (Evergreen Forest), 43 (Mixed Forest), 52 (Shrub/Scrub), and 71 (Grassland/Herbaceous) were grouped as one landscape. FRAGSTATS 4.2 and ArcGIS 10.3 were used for data mining and measuring.

To identify the spatial structure of the landscape, eight landscape ecology metrics were selected, based on Kupfer's study (2012), which summarized the strengths (e.g., measuring different aspects under the same characteristics) and weaknesses (e.g., possibility of a high correlation) of different types of landscape ecology metrics on related research (Brody et al., 2013; Flores, Olivas, & Chávez, 2008; Gustafson & Parker, 1994; Herold, Scepan, & Clarke, 2002; Luck & Wu, 2002). The explanation of each metric was retrieved from McGarigal (2015). As shown in Fig. 3 landscape patterns could be measured differently due to the spatial composition of each patch in an area. Each area has the same number of patches (PLAND), 40%, but the edge densities and shapes are different. An area on the left in Fig. 3 has a simpler and lower edge density than an area on the right. This is why this paper used

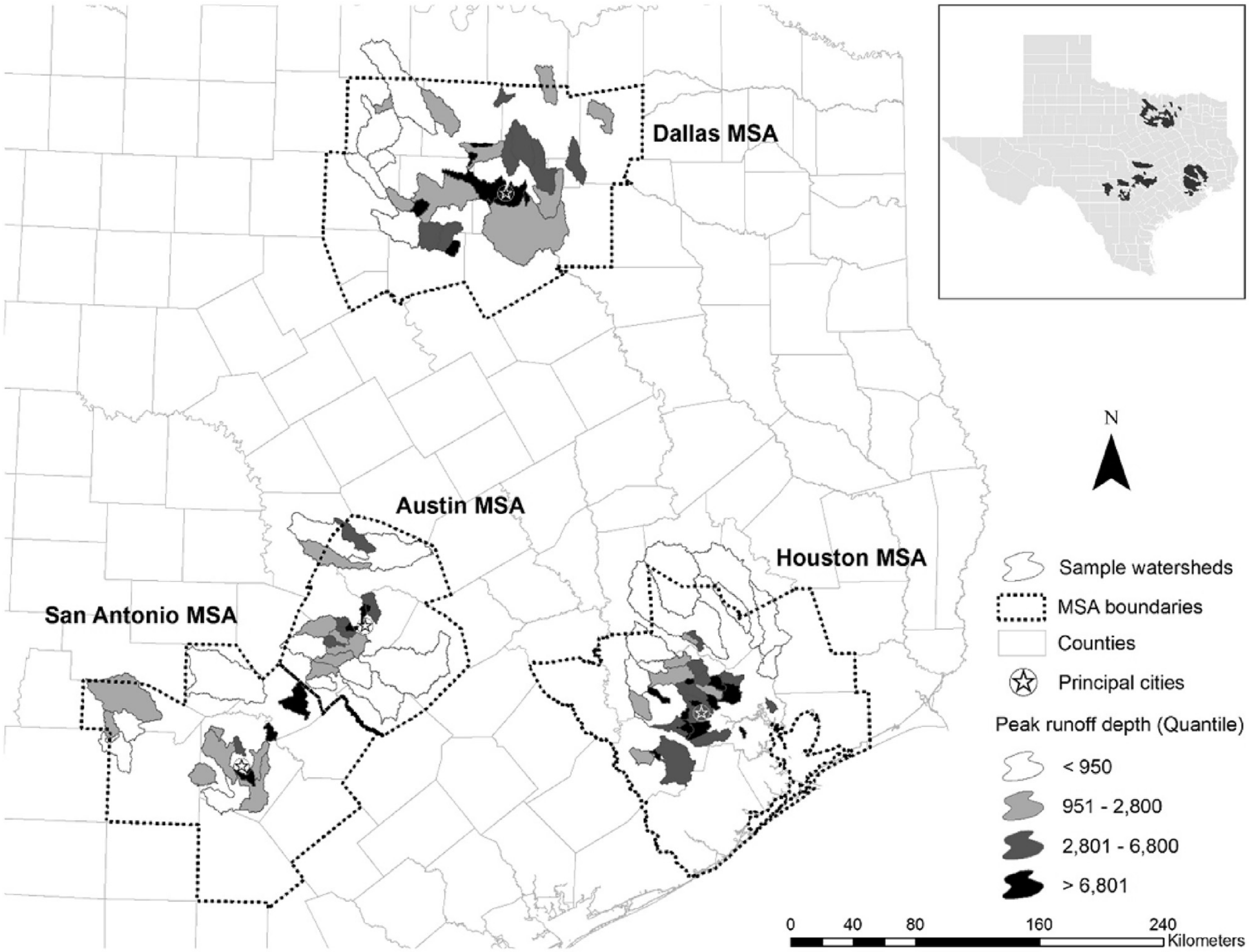

Fig. 2. Study area with delineated watersheds and peak runoff depths.

different landscape ecology metrics to carefully identify spatial patterns.

3.3.3. Control variables

Other correlates of runoff such as precipitation, soil, slope, floodplain, wetland, drainage density, and impervious rate were also measured. Data on mean annual precipitation were obtained from the Parameter-elevation Regressions on the Independent Slopes Model (PRISM) Climate Group for three water years taken from 2009 to 2011. The surface precipitation was calculated based on the climatologically-aided interpolation (CAI) method. Soil permeability was calculated with the data derived from the Natural Resources Conservation Service's (NRCS) State Soil Geographic Database (STATSGO). The average slope was computed by using the GIS with 30-meter resolution DEM data obtained from the NHD Plus. For the floodplain, the percentage of area within a watershed boundary was measured. The data was acquired from the Federal Emergency Management Agency (FEMA) Map Service Center. Natural drainage density—the ratio of total stream length to basin area—was measured by the national hydrography dataset obtained from the United States Department of Agriculture (USDA). Wetlands were extracted from the NLCD with classification codes of 90 and 95 (woody and emergent herbaceous wetlands, respectively) and the proportion area was calculated using the Geospatial Modeling Environment (GME) extension (Beyer, 2010), a tool that weights the values based on the proportional areas and produces both mean and total values within a specific watershed boundary. Impervious cover was calculated for the proportional areas of developed area with land cover classification codes of 21 (low intensity), 22 (medium intensity), and 23 (high intensity) in the NLCD. Table 1 shows the overall summary of each variable's measurement, source, and descriptive statistics.

3.4. Data analysis

The association between landscape patterns and runoff were analyzed in two phases. First, the general characteristics of the peak runoff during the three-year period (2009–2011) in four MSAs were observed. Then the impacts of landscape patterns on the variations in the mean annual peak runoff depth were analyzed using an ordinary least squares (OLS) regression analysis. Additionally, the same analysis procedure was employed with developed patterns for further comparison. Landscape and development patterns could not be simultaneously observed because of a multicollinearity issue between the patterns. This is why the impervious rate, one of the control variables, was excluded in the landscape pattern model. To reduce the statistical conclusion validity threat from the number of samples and avoid multicollinearity issues among landscape pattern characteristics, four separate models grouped by the characteristics of landscape were assessed. A violation of the OLS assumptions such as model specification, heteroscedasticity, and spatial autocorrelations were also

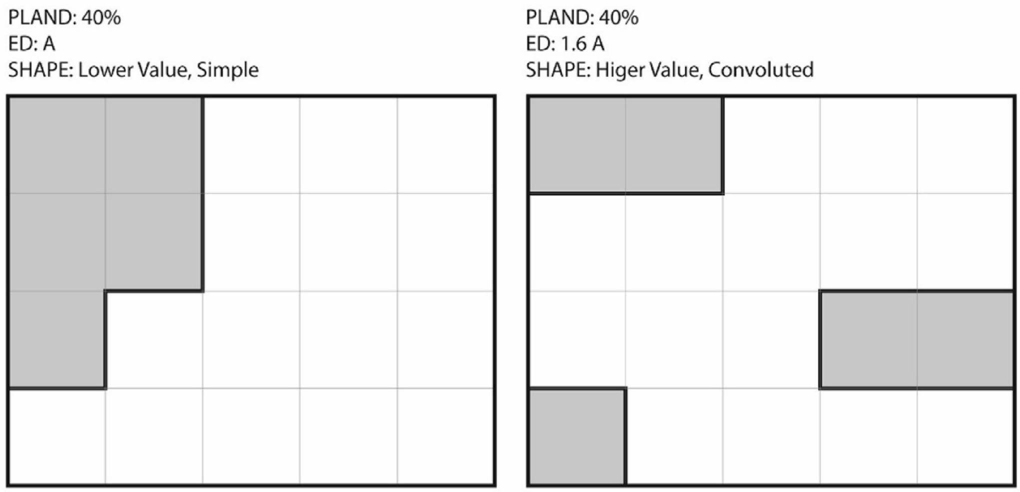

Fig. 3. Different indexes of landscape metrics with the same number of patches.

- **Size and Edges** were observed by a percentage of landscape (PLAND) and Edge Density (ED). PLAND calculates the percentage of a particular patch type. PLAND provides the single most important information for showing the richness of some types of patches and therefore it frequently appeared in previous studies (e.g., proportion of vegetation or impervious rate). However, it is less useful in showing the spatial distribution. ED measures the ratio of the total perimeter of patches to a unit area. Unlike PLAND, ED is useful for taking into account the shape and size of patches. The high value of PLAND and ED indicate a landscape with larger and complex shapes.
- **Shape** metrics describe whether patches have convoluted shapes. The Shape Index (SHAPE) and Congruity Index (CONTIG) were used to make the shape measurements. SHAPE calculates the patch perimeter and area simultaneously, while CONTIG assesses patch shape based on the spatial connectedness or contiguity of cells within a patch. If a patch is more convoluted in shape, its SHAPE and CONTIG would increase in value.
- **Isolation** metrics help identify the tendency for patches to be isolated in space from other patches. Proximity (PROX) and mean Euclidean Nearest-Neighbor Distance (ENN) were used to identify the level of isolation or nearness of landscapes. PROX measures the distance between the focal patch and neighboring patches of the same type and size within the search radius. An 800-meter radius was employed as a search radius since previous studies had frequently adopted this value (Brody et al., 2013; Rylands, Groves, Mittermeier, Cortés-Ortiz, & Hines, 2006). PROX increases when a specific patch type is near the same type of patches. Mean ENN factors the average of the straight-line distance between nearest neighbor patches of the same type. When the value of ENN approaches zero, the distance to the nearest neighboring patch decreases.
- ***Connectivity*** refers to the functional and spatial connectivity among patches. Connectivity of patches were observed by cohesion (COHESION) and connectedness (CONNECT). COHESION calculates the physical connectedness of the corresponding patch types in an area. CONNECT measures each pair of patches that are either connected or not within a certain search radius. Similar to PROX, an 800-meter radius was used to define a search area.

diagnosed.

4. Results

4.1. Descriptive statistics by MSA

As shown in Table 2, the San Antonio MSA generated the highest mean peak runoff during the period of 2009–2011, followed by the Dallas, Houston, and Austin MSAs. The median value tells a different story. On average, the Houston MSA had the highest peak runoff, followed by the Dallas, Austin, and San Antonio MSAs. This is because an outlier exists in the San Antonio and Dallas MSAs, a relatively large sized watershed. Interestingly, the volume of runoff did not directly correspond with the surface impervious rate whether we consider median or mean value: 33 percent in Dallas, 29 percent in Houston, 16 percent in San Antonio, and 14 percent in the Austin MSA. This indicates that the impervious rate had a positive association with the peak runoff, but it was not the only condition. In each region, the average peak runoff was likely to be high near the center of the principal cities in the MSAs (see Fig. 2). This implies that more strategic land use and innovative flood mitigation approaches, such as low impact development (LID) techniques or best management practices (BMP), are required in highly developed areas in order to mitigate urban flooding.

4.2. Regression results

The outcomes of the OLS explain the impacts of landscape in terms of size, shape, isolation/cluster, and connectivity on local flooding, while controlling for other environmental conditions. As shown in Table 3, which shows the standardized impacts, landscape patterns have significant impacts on the mean annual peak runoff. As was frequently found in previous research, an increase of the proportional ***size*** of a landscape significantly reduces runoff ($\beta_{PLAND} = -0.56$, $p < 0.01$). Moreover, the size of a landscape has the largest impact when compared to other conditions such as precipitation, soil, and slope and is believed to have a close association with runoff. An increased capability of infiltration, storage, and interception of urban green infrastructure may possibly reduce runoff (Mansell, 2003; Zhang, Xie, Zhang, & Zhang, 2012). The ***shape*** of landscape patterns measured by the shape index ($\beta_{SHAPE} = -0.09$, $p>0.1$) and contiguity ($\beta_{CONTIG} = -0.05$, $p>0.1$) do not show statistically significant impacts; even though the impacts were insignificant at an 0.1 level, the signs of both indexes were still negative. As expected, landscape ***clustering*** had a positive effect in decreasing the peak runoff. A proximity index revealed that a less fragmented landscape—a higher value of PROX—tended to reduce the amount of the peak runoff ($\beta_{PROX} = -0.38$, $p < 0.01$). A nearest distance index, another measure of isolation, showed non-significant effects, but still had a positive sign on runoff ($\beta_{ENN} = 0.065$, $p>0.1$). A higher value for ENN refers to scattered and fragmented patches, which are likely to increase runoff. The ***connectivity*** of landscapes measured by CONNECT and COHESION appeared to have an effect on runoff, but their directions are opposite. Increased CONNECT had positive ($\beta = 0.258$, $p < 0.05$), while COHESION had negative effects ($\beta = -0.194$, $p < 0.05$). Similar spatial patterns were found between landscape and development when examining CONNECT. Their CONNECT indexes were positive and statically correlated ($r = 0.46$, $p < 0.05$). Simply said, a place that showed linearly connected development patterns were likely

Table 1
Concept measurements and descriptive statistics.

Variable		Measurement	Source; Analytical tools	Range	Mean	S.D.
Mean annual peak runoff depth		Average maximum daily runoff (mm) at each USGS gauge stations (2009–2011), by water year (log-transformed)	USGS gauge stations, Arc GIS	2.02–4.92	3.41	0.59
Size/Edge	Percentage of landscape	The percentage share of the area (ha) of class, units in percentages	NLCD 2011; FRAGSTATS 4.2.1	0.03–99.44	39.77	31.98
	Edge density	Total length of edge of a particular class per unit $ED = \frac{E}{A}$ • E = the sum of edges • A = total area	NLCD 2011; FRAGSTATS 4.2.1	0.11–101.68	43.30	24.80
Shape	Shape index	Normalized ratio of patch perimeter to area $SHAPE = \frac{p_{ij}}{\min p_{ij}}$ • p_{ij} =perimeter of patch i in class j in terms of number of cell surfaces.	NLCD 2011; FRAGSTATS 4.2.1	1.20–2.22	1.79	0.15
	Contiguity index	Average contiguity value for the cells in a corresponding patch $CONTIG = \frac{\left[\frac{\sum_{r=1}^{z} c_{ijr}}{a_{ij}}\right]-1}{v-1}$ • c_{ijr} = contiguity value for pixel r in patch ij • a_{ij} = area of patch ij in terms of number of c • v = sum of the values in a 3-by-3 cell template	NLCD 2011; FRAGSTATS 4.2.1	0.33–0.99	0.53	0.08
Isolation	Proximity	Sum of all patches of the corresponding patch type whose edges are within an 0.5-mile radius of the focal patch, of each patch size divided by the square of its distance from the focal patch $PROX = \sum_{i=1}^{n} \frac{S_i}{z_i}$ • S_i = area • z_i = edge to edge distance from patch i to its nearest neighbor indexed patch identified within the buffer	NLCD 2011; FRAGSTATS 4.2.1	0.00–35057.59	3643.15	7288.11
	Euclidean nearest distance	$ENN = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} h_{ij}}{N'}$ • h_{ij} = the edge-to-edge distance from patch i in class j to the nearest neighboring patch of the same class • N' = the number of patches in the landscape that have nearest neighbors	NLCD 2011; FRAGSTATS 4.2.1	61.77–8464.31	197.51	813.99
Connectivity	Connectedness	Number of functional joins between patches of the same type within 0.5 miles divided by the total number of possible joins between all corresponding patches multiplied by 100 $CONNECT = \left[\frac{\sum_{j=k}^{n} c_{ijk}}{\frac{n_i(n_i-1)}{2}}\right] \times 100$ • c_{ijk} = joining between patch j and k (0 = unjoined, 1 = joined) of the corresponding patch type (i), based on a user specified threshold distance. • n_i = number of patches in the landscape of the corresponding patch type	NLCD 2011; FRAGSTATS 4.2.1	64.33–832.08	9.29	13.56
	Cohesion	Proportional to the area-weighted mean perimeter-area ratio divided by the area-weighted mean patch shape index $COHESION = \left(1 - \frac{\sum p}{\sum p\sqrt{a}}\right)\left(1 - \frac{1}{\sqrt{N}}\right)^{-1}$ • p = patch perimeter • a = patch area • N = the number of pixels on the map	NLCD 2011; FRAGSTATS 4.2.1	55.73–99.90	94.95	6.40
Precipitation		Mean annual precipitation; units in mm	PRISM Climate Group	43.67–87.89	69.49	11.19
Slope		Average watershed slope; units in percentages	USEPA - NDHPlus V2	0.21–20.1	3.27	3.40
Soil permeability		Average watershed soil permeability; units in inches per hour	NRCS - STATSGO	0.10–4.88	1.18	0.88
Floodplain area		Area within the FEMA-defined 100-year floodplain; units in percentages	FEMA Flood Map Service Center	4.25–46.72	15.35	9.15
Natural drainage density		Ratio of total stream length to basin area	USDA	0.57–3.29	1.50	0.50
Wetland		Proportion of wetland; units in percentages	USGS	0.00–20.29	2.78	4.00
Impervious rate		Proportion of wetland; units in percentages	NLCD 2011; FRAGSTATS 4.2.1	0.03–87.97	31.37	30.01

to have connected landscape patterns.

Other correlates such as precipitation, soil types, and slopes were significant determinants of runoff across analyses. Specifically, precipitation had a significantly positive effect on the peak runoff and was a strong predictor consistently across all models. Compared to precipitation, average slope was a relatively

Table 2
Descriptive statistics of impervious rate and annual peak runoff depth.

MSA name	N	Impervious rate	Annual peak runoff depth				
			Mean	Median	S.D.	Max.	Min.
Dallas-Fort Worth-Arlington	29	32.8%	6536.74	2834.67	14,846.77	83,133.97	105.06
Houston–Sugar Land–Baytown	40	29.3%	5165.85	4895.73	4306.14	14,104.08	140.27
Austin-Round Rock	23	14.2%	4828.24	2485.24	7404.46	34,552.50	169.70
San Antonio-New Braunfels	16	16.3%	8373.19	1796.32	18,572.39	75,757.31	548.90

Table 3
Results of regression analysis for landscape and development patterns.

Characteristics		Landscape pattern				Development pattern			
		Beta coeff. (S.E.)	Beta coeff. (S.E.)	Beta coeff. (S.E.)	Beta coeff. (S.E.)	Beta coeff. (S.E.)	Beta coeff. (S.E.)	Beta coeff. (S.E.)	Beta coeff. (S.E.)
Size/Edge	% Area	−0.563*** (0.002)				0.186* (0.002)			
	Edge density	0.068 (0.002)				0.428*** (0.002)			
Shape	Shape		−0.054 (0.330)				0.446*** (0.300)		
	Contiguity		−0.090 (0.760)				−0.140 (1.220)		
Isolation	Proximity			−0.378*** (6.79E-06)				−1.89E-06 (5.33E-06)	
	Nearest distance			0.065 (5.04E-05)				−0.239*** (0.001)	
Connectivity	Connectedness				0.285** (0.005)				0.383*** (0.004)
	Cohesion				−0.194** (0.008)				0.301*** (0.005)
Other conditions	Precipitation	0.358*** (0.005)	0.547*** (0.005)	0.461*** (0.005)	0.413*** (0.005)	0.309*** (0.004)	0.520*** (0.005)	0.466*** (0.005)	0.376*** (0.004)
	Soil	−0.228*** (0.053)	−0.325*** (0.057)	−0.261*** (0.053)	−0.314*** (0.054)	−0.263*** (0.045)	−0.293*** (0.053)	−0.338*** (0.057)	−0.282*** (0.048)
	Slope	0.455*** (0.017)	0.293** (0.020)	0.369*** (0.016)	0.030 (0.023)	0.343*** (0.013)	0.254*** (0.015)	0.300*** (0.017)	0.336*** (0.018)
	Floodplain	−0.133 (0.006)	−0.153 (0.007)	−0.118 (0.007)	−0.152 (0.007)	0.011 (0.005)	−0.097 (0.007)	−0.133 (0.007)	−0.048 (0.006)
	Wetland	−0.112 (0.013)	−0.054 (0.015)	−0.078 (0.013)	−0.036 (0.014)	−0.074 (0.012)	−0.074 (0.013)	−0.069 (0.015)	−0.007 (0.012)
	Drainage density	0.037 (0.087)	0.029 (0.102)	0.059 (0.089)	0.043 (0.090)	0.049 (0.077)	0.045 (0.091)	0.042 (0.097)	0.038 (0.081)
Adj. R^2		0.598	0.386	0.484	0.471	0.508	0.637	0.520	0.424
Degree of freedom		107	107	107	107	107	107	107	107

Notes: D.V.: Mean annual peak runoff; *$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

weak predictor of the peak runoff, but showed that steeper slopes were likely to increase runoff. Soil permeability negatively predicted the peak runoff, meaning that more permeable soils significantly lowered the peak runoff ($p < 0.01$). Although floodplains, wetlands, and natural drainage density had insignificant relationships with peak runoff, their directions were consistent across all models. Wetland was statistically insignificant, but facing in a negative direction, which supports the findings of previous studies that wetlands play a substantial role in attenuating surface runoff and flooding (Highfield, 2012). Also, the association between floodplain and the peak runoff was negative, which was contrary to expectations. That is, a watershed that incorporates a higher percentage of a 100-year floodplain may generate less peak runoff. In contrast, natural drainage density was positively related with the peak runoff. This result corresponds with previous studies (Bell, 2004; Horton, 1932) that watersheds cut apart by streams respond promptly to rainfall events.

The impacts of development patterns exhibited contradictory directions of landscape, except for CONNECT. Pair correlations between landscape and development patterns first assured that they had an inverse relationship; size ($r_{SIZE} = -0.80$, $r_{ED} = -0.17$), shape ($r_{SHAPE} = -0.46$, $r_{CONTIG} = -0.17$), cluster ($r_{PROX} = -0.23$, $r_{ENN} = -0.08$), and connectivity ($r_{COHESION} = -0.34$) were negatively correlated. This implies that landscape degradation occurs in highly developed areas. Regression results indicated that developments that were larger ($\beta_{SIZE} = 0.19$, $p < 0.1$), had more edges on the ground ($\beta_{ED} = 0.43$, $p < 0.01$), had a more complex shape ($\beta_{SHAPE} = 45$, $p < 0.01$), were more clustered ($\beta_{ENN} = -0.24$ $p < 0.05$), and were more connected were likely to increase runoff.

5. Discussion and conclusion

- The outcomes of this study support three hypotheses out of four: that the size, fragmentation, and connectivity of landscape affects peak runoff, but the sign of the impacts was different in terms of connectivity. To summarize the findings:
- A larger size landscape is likely to reduce peak runoff. Possibly, the amount of trees, shrubs, and grass definitely increases the infiltration and storage of an area during flooding.
- A less fragmented and clustered landscape pattern is likely to decrease peak runoff. Presumably, a scattered landscape is less likely to have a synergy of agglomeration in terms of storage,

interception, and evaporation. In addition, a landscape becomes highly fragmented as a result of human developments that increase the impervious cover and divide, intercept, or cut-off the overall landscape patterns (Nowak & Greenfield, 2012).

- A highly connected landscape is likely to reduce or augment peak runoff depending on the scale of observation; in other words, connectivity of a landscape at the micro-scale could increase peak runoff, while at the macro-scale decrease it. There is no scholarly evidence to support this conflicting result, but there are some conceivable reasons. The connectedness measure specifically observed the connectivity of landscapes at the micro-scale delineated by about an 800-meter (0.5-mile) radius, while the cohesion index observed the overall connectivity of landscapes in one watershed. Considering the average size of watersheds in this study, which included about 253 km^2 (62,400 acres), an area defined by an 800-meter radius (almost 4 km^2, 1000 acres) accounts for only 2 percent of an entire watershed. This may imply that the linear connectivity measured at the micro-level identifies different types of "connectivity" at the macro-level. The simple sum of highly connected small pieces of landscape are not as powerful as connectivity with a large scale. Another possibility is the dissimilar association between development and landscape patterns at different spatial scales. This might be because trees, shrubs, or grass turfs are likely to be planted alongside roads, streets, or sewage lines that have linear shapes and are therefore able to channel runoff more quickly (see example in Fig. 4). Or the impacts of development patterns outweigh landscape patterns during peak runoff. In contrast, the connectivity of landscape and development patterns observed at a macro-scale show the opposite aspects ($r = -0.34$, $p < 0.05$). Taken together, linearly connected landscapes could increase runoff at the micro-level, while decreasing runoff at the macro-level.

The findings of this study are expected to assist regional and local planners who create long-term directions for green infrastructure policies and guidelines, especially to MSAs that have similar geographical and biophysical characteristic to Texas. Since interconnecting the network of existing green elements is the major concern of green infrastructure, both the roles of landscape configuration and composition should be addressed to promote the effectiveness of policies. Recent efforts by several municipalities to adopt green infrastructure have been vigorous, but these endeavors focus on making suggestions for design and construction standards. As shown in this study, implementing a few green infrastructure elements throughout a region would be less effective without provision for an overall networking and clustering plan. Therefore, state- or regional-level plans need to address and map targeted

Fig. 4. Highly connected landscapes and developments at a micro-scale (aerial photo, land cover).

- A more convoluted landscape does not show any specific impacts on peak runoff. Possibly, the complex shape of a landscape could mediate the peak runoff because uneven edges can delay the flow allowing time for infiltration. This statement becomes more true if we only consider grassland and shrub. The jagged edges of grass and shrubs are more effective in disturbing the flow because they are closely located to the ground. Even though tree canopies create edges in a two-dimensional land cover map like grass or shrubs, they are actually located above the ground and have less contact with flows on the ground.

areas where green infrastructure should be strategically preserved and connected. A state-level hazard mitigation plan, comprehensive plan, or regional growth and development plan can manage a section of green infrastructure planning. Also, the development of independent green infrastructure plans are advised. The green infrastructure plans from Maryland and Florida are good examples. For instance, the Maryland Department of Natural Resources (DNR) recommends a hub and corridor network called the Green Print Map that has a high ecological value (Amundsen, Allen, & Hoellen, 2009). Counties in Maryland have also updated local green infrastructure that are consistent and concurrent with the state plan. The Florida Greenways Commission displayed the statewide ecological network by employing a GIS modeling tool (Benedict & McMahon, 2006). These state plans show the merits of having regional level planning initiatives, but they do not emphasize the value of green infrastructure in mitigating stormwater runoff. The findings of this study are expected to serve as evidence that can be used to update regional green infrastructure plans. Local plans can integrate the goals, policies, and suggestions of regional plans with local land use plans. A land use plan (comprehensive plan), stormwater management plan, and post-disaster redevelopment plan could all contain sections related to green infrastructure and local flooding. In addition, the interconnections of green infrastructure with other elements such as landscapes, parks, farms, wetlands, or waterways could be one method; integrating green infrastructure into existing built environments could be another. Multiple land conservation and acquisition tools and policies such as the transfer and purchase of development rights, cluster developments, conservation easement, and zoning with overlay districts could be utilized for implementation.

References

Amundsen, O. M., Allen, W., & Hoellen, K. (2009). *Green infrastructure planning: Recent advances and applications. Planners advisory Service memo*. Chicago, IL: American Planning Association.

Arnold, C. L., & Gibbons, C. J. (1996). Impervious surface coverage: The emergence of a key environmental indicator. *Journal of the American Planning Association, 62*(2), 243–258.

Barnes, T. G. (2000). *Landscape ecology and ecosystems management*. Kentucky Cooperative Extension Service. Retrieved Apr. 17, 2016 from www.ca.uky.edu/agc/pubs/for/for76/for76.pdf.

Bell, F. G. (2004). *Engineering geology and construction*. New York, NY: Spon Press.

Bellot, J., Bonet, A., Sanchez, J. R., & Chirino, E. (2001). Likely effects of land use changes on the runoff and aquifer recharge in a semiarid landscape using a hydrological model. *Landscape and Urban Planning, 55*(1), 41–53.

Benedict, M., & McMahon, E. (2006). *Green infrastructure: Linking landscapes and communities*. Washington, DC: Island Press.

Bereitschaft, B., & Debbage, K. (2013). Urban form, air pollution, and CO_2 emissions in large U.S. metropolitan areas. *Professional Geographer, 65*(4), 612–635.

Beyer, H. L. (2010). *Geospatial modelling environment, Version 0.5.2 (Software)*. Retrieved Feb. 19, 2016 from http://www.spatialecology.com/gme.

Booth, D. B., Hartley, D., & Jackson, R. (2002). Forest cover, impervious-surface area, and the mitigation of stormwater impacts. *Journal of the American Water Resources Association, 38*, 835–845.

Braden, J., & Johnston, D. (2004). Downstream economic benefits from storm-water management. *Journal of Water Resources Planning and Management, 130*(6), 498–505.

Brody, S. D., Gunn, J., Peacock, W., & Highfield, W. (2011). Examining the influence of development patterns on flood damages along the Gulf of Mexico. *Journal of Planning Education and Research, 31*(4), 438–448.

Brody, S. D., Highfield, W., Ryu, H.-C., & Spanel-Weber, L. (2007). Examining the relationship between wetland alteration and watershed flooding in Texas and Florida. *Natural Hazards, 40*(2), 413–428.

Brody, S. D., Kim, H., & Gunn, J. (2013). Examining the impacts of development patterns on flooding on the Gulf of Mexico coast. *Urban Studies, 50*(4), 1–18.

Brun, S., & Band, L. (2000). Simulating runoff behavior in an urbanizing watershed. *Computers, Environment and Urban Systems, 24*(1), 5–22.

Carlson, T. (2004). Analysis and prediction of surface runoff in an urbanizing watershed using satellite imagery. *Journal of the American Water Resources Association, 40*(4), 1087–1097.

Center for Land Use Education and Research (CLEAR). (2013). *LID versus green infrastructure. Center for land use education and research*. University of Connecticut. Retrieved Jan. 20, 2014 from http://blog.clear.uconn.edu/2013/12/10/lid-vs-green-infrastructure.

Connors, J. P., Galletti, C. S., & Chow, W. T. L. (2013). Landscape configuration and urban heat island effects: Assessing the relationship between landscape characteristics and land surface temperature in Phoenix, Arizona. *Landscape Ecology, 28*(2), 271–283.

Coutu, G., & Vega, C. (2007). Impacts of land use changes on runoff generation in the east branch of the Brandywine Creek Watershed using a GIS-based hydrologic model. *Middle States Geographer, 40*, 142–149.

Debbage, N., & Shepherd, J. M. (2015). The urban heat island effect and city contiguity. *Computers, Environment and Urban Systems, 54*, 181–194.

Diamond, J. M. (1975). The island dilemma: Lessons of modern biogeographic studies for the design of natural reserves. *Biological Conservation, 7*(2), 129–146.

Flores, E. S., Olivas, A. G., & Chávez, J. (2008). Land cover change and landscape dynamics in the urbanizing area of a Mexican border city. In *Paper presented at the ASPRS 2008 annual Conference, Portland, Oregon*.

Forman, R. T. T. (1995). *Land mosaics: The ecology of landscapes and regions*. Cambridge, UK: Cambridge University Press.

Forman, R. T. T., & Godron, M. (1981). Patches and structural components for a landscape ecology. *Bioscience, 31*(10), 733–740.

Forman, R. T. T., & Godron, M. (1986). *Landscape ecology*. Hoboken, NJ: Wiley.

Fox, D. M., Witz, E., Blanc, V., Soulie, C., Penalver-Navarro, M., & Dervieux, A. (2012). A case study of land cover change (1950–2003) and runoff in a Mediterranean catchment. *Applied Geography, 32*(2), 810–821.

Fu, B. J., Zhao, W., Chen, L., Liu, Z., & Lu, Y. (2005). Eco-hydrological effects of landscape pattern change. *Landscape and Ecological Engineering, 1*(1), 25–32.

Gearheart, G. (2007). *A review of low impact development policies: Removing institutional barriers to adoption*. Beltsville, Maryland: Low Impact Development Center. December 2007. Retrieved Apr. 14, 2015 from http://cacoastkeeper.org/document/removing-policy-barriers-to-lid.pdf.

Gill, S., Handley, J., Ennos, A., & Pauleit, S. (2007). Adapting cities for climate change: The role of the green infrastructure. *Built Environment, 33*(1), 115–133.

Gustafson, E. J., & Parker, G. R. (1994). Using an index of habitat patch proximity for landscape design. *Landscape and Urban Planning, 29*(2–3), 117–130. http://dx.doi.org/10.1016/0169-2046(94)90022-1.

Herold, M., Scepan, J., & Clarke, K. C. (2002). The use of remote sensing and landscape metrics to describe structures and changes in urban land uses. *Environment and Planning A, 34*(8), 1443–1458.

Highfield, W. (2012). Section 404 permitting in coastal Texas: A longitudinal analysis of the relationship between peak streamflow and wetland alteration. *Environmental Management, 49*, 892–901.

Hirsch, R., Walker, J., Day, J., & Kallio, R. (1990). The influence of main on hydrological systems. In M. G. Wolman, & H. C. Riggs (Eds.), *Surface water hydrology* (pp. 329–359). Boulder, CO: Geological Society of America.

Hoellen, K. (2010). *Green infrastructure applications in the U.S. European Commission Conference on green infrastructure implementation Brussels*. Nov. 19, 2010. Retrieved May 28, 2013 from http://ec.europa.eu/environment/nature/ecosystems/docs/4_KH_GI_191110.pdf.

Horton, R. E. (1932). Drainage basin characteristics. *Transactions of the American Geophysical Union, 13*, 350–361.

Kong, F., Yin, H., & Nakagoshi, N. (2007). Using GIS and landscape metrics in the hedonic price modeling of the amenity value of urban green space: A case study in jinan city, China. *Landscape and Urban Planning, 79*(3–4), 240–252.

Kupfer, J. A. (2012). Landscape ecology and biogeography: Rethinking landscape metrics in a post-FRAGSTATS landscape. *Progress in Physical Geography, 36*, 400–420.

Liu, H., & Weng, Q. (2008). Seasonal variations in the relationship between landscape pattern and land surface temperature in Indianapolis, USA. *Environmental Monitoring and Assessment, 144*(1–3), 199–219.

Luck, M., & Wu, J. (2002). A gradient analysis of urban landscape pattern: A case study from the phoenix metropolitan region, Arizona, USA. *Landscape Ecology, 17*(4), 327–339.

Mansell, M. G. (2003). *Rural and urban hydrology*. London: Thomas Telford.

Marsh, W. M. (2005). *Landscape planning: Environmental applications* (4th ed.). New York, NY: John Wiley & Sons.

McDonald, L., Allen, W., Benedict, M., & O'Connor, K. (2005). Green infrastructure plan evaluation frameworks. *Journal of Conservation Planning, 1*, 6–25.

McGarigal, K. (2015). *FRAGSTATS help*. Retrieved Apr. 17, 2016 from http://www.umass.edu/landeco/research/fragstats/documents/fragstats.help.4.2.pdf.

Mills, A., Ndubisi, F., Fife, E., & Hunter, M. C. R. (2001). The nature of dialogue and the dialogue of nature: Designers and ecologists in collaboration. In B. R. Melnick, & K. H. Johnson (Eds.), *Ecology and design: Frameworks for learning* (1st ed., p. 560). Island Press.

Ndubisi, F. (2002). *Ecological planning: A historical and comparative synthesis*. Baltimore, MD: Johns Hopkins University Press.

Nowak, D. J., Crane, D. E., & Stevens, J. C. (2006). Air pollution removal by urban trees and shrubs in the United States, Urban Forestry & Urban Greening. *4 (3-4*, 115–123.

Nowak, D. J., & Greenfield, E. J. (2012). Tree and impervious cover change in US cities. *Urban Forestry & Urban Greening, 11*(1), 21–30.

Paul, M., & Meyer, J. (2001). Streams in the urban landscape. *Annual Review of Ecological Systems, 32*, 333–365.

Rylands, A. B., Groves, C. P., Mittermeier, R. A., Cortés-Ortiz, L., & Hines, J. J. (2006). Taxonomy and distributions of Mesoamerican primates. In A. Estrada (Ed.), *New perspectives in the study of Mesoamerican primates* (pp. 29–79). Springer.

Sander, H., Polasky, S., & Haight, R. G. (2010). The value of urban tree cover: A hedonic property price model in ramsey and Dakota counties, MN, USA. *Ecological*

Economics, 69, 1646–1656.
Schueler, T. (1994). The importance of imperviousness. *Watershed Protection Techniques, 1*(3), 100–111.
Shafer, C. (1994). Beyond park boundaries. In E. Cook, & H. N. v. Lier (Eds.), *Landscape planning and ecological networks* (pp. 201–223). Elsevier Science.
Shuster, W., Bonta, J., Thurston, H., Warnemuende, E., & Smith, D. (2005). Impacts of impervious surface on watershed hydrology: A review. *Urban Water Journal, 2*(4), 263–275.
Sung, C. Y., & Li, M.-H. (2010). The effect of urbanization on stream hydrology in hillslope watersheds in central Texas. *Hydrological Processes, 24*, 3706–3717.
Turner, M. G. (1989). Landscape ecology: The effect of pattern on process. *Annual Review of Ecology and Systematics, 20*(1), 171–197.
Turner, M. G., Gardner, R. H., & O'neill, R. V. (2001). *Landscape ecology in theory and practice: Pattern and process*. New York, NY: Springer.
United Nations. (2014). *World urbanization prospects: The 2014 revision*. Department of economic and social affairs, population division. highlights (ST/ESA/SER.A/352). Retrieved Apr. 8, 2016 from http://esa.un.org/unpd/wup/Publications/Files/WUP2014-Highlights.pdf.
US Census. (2012). *Growth in urban population outpaces rest of nation, census bureau reports*. Retrieved Mar. 3, 2016 from https://www.census.gov/newsroom/releases/archives/2010_census/cb12-50.html.
US Environmental Protection Agency (USEPA). (2010). *Green infrastructure case studies: Municipal policies for managing stormwater with green infrastructure*. EPA-841-F-10–004. Washington, DC: Office of Wetlands, Oceans and Watersheds.
US Environmental Protection Agency (USEPA). (2012). *Monitoring and assessing water quality – volunteer monitoring*. Retrieved July 25, 2016, from https://archive.epa.gov/water/archive/web/html/index-18.html.
US Environmental Protection Agency (USEPA). (2014). *Addressing green infrastructure design challenges in the Pittsburgh Region*. EPA 800-R-14–003. Retrieved July 25, 2016, from https://www.epa.gov/sites/production/files/2015-10/documents/pittsburgh-united-abundant-rainfall-508.pdf.
Yang, X., You, X., Ji, M., & Nima, C. (2013). Influence factors and prediction of stormwater runoff of urban green space in Tianjin, China: Laboratory experiment and quantitative theory model. *Water Science & Technology, 67*(4), 869–876.
Zhang, B., Xie, G., Zhang, C., & Zhang, J. (2012). The economic benefits of rainwater-runoff reduction by urban green spaces: A case study in Beijing, China. *Journal of Environmental Management, 100*, 65–71.