Hierarchical controls on watershed stormwater: land use/ cover composition and connectivity

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Abstract

Understanding the relative importance of land use/ cover pattern characteristics on runoff response is key to interpreting catchment hydrology and guiding land use planning. The spatial distribution of land use/cover can significantly affect the process of the watershed stormwater. While many studies focus on the impacts of land use/ cover pattern connectivity (functional and physical) and composition change on watershed stormwater, how the combination of these factors may affect runoff dynamics is poorly understood. In this study we related runoff response variability across scales and across storm events to the characteristics of land use/ cover pattern composition and connectivity using a land use pattern simulation modeling approach and a fully-distributed hydrological modelling approach in a catchment located near the city of Atlanta, Georgia. A new metric was developed to quantify the functional connectivity of land use pattern at the catchment scale. Landscape metrics were used to measure the characteristics of land use/ cover composition and physical connectivity. The results suggest that the peak flow of runoff at the catchment outlet is mainly controlled by the functional connectivity of land use pattern under all scales, while the total volume has different controlling factors at different scales. The relationship between land use pattern and runoff represents different characteristics under different storm intensities. This study provides a simple tool for evaluating the differences in runoff response from land use/ cover patterns with different composition and connectivity across scales and rainfall conditions.

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1. Introduction

Stormwater management is the key to keep natural hydrologic system healthy, reduce pollution in the stream and avoid flooding in the process of urbanization. Land use pattern optimization is an efficient way to manage stormwater in the urban area. Changes in land use composition, physical connectivity or functional connectivity can significantly affect the hydrologic process (Fiener and Auerswald, 2006; Ogden et al., 2013; Ray et al., 2010). Land use composition can affect natural hydrologic systems by changing the infiltration rate of runoff and the degree of surface roughness (Niehoff et al., 2002; Lin et al., 2007; Ali et al., 2011; Valtanen et al., 2014). Land use physical connectivity is the fragmentation level of land use patches and can affect runoff by changing the hardness of land use patches' edges, an important element in the flow rate between spatial elements (Lee et al., 2009; Zhang et al., 2013, 2014). The functional connectivity of land use pattern is the accessibility of runoff from the source area to the stream and can affect runoff by changing the surface roughness of runoff pathways (Borselli et al., 2008). The relative effects of these factors on runoff is important to land use pattern optimization for stormwater management, which can significantly affect the efficiency and cost of the policy for stormwater management; however, the relative effects of these factors is still unknown. This study demonstrates how the combination of these factors affects runoff dynamics.

Scale and storm intensity may affect the relationship between land use pattern and the hydrologic process. Studies have shown land use pattern characteristics at different scales explain differences in the ecological process (Zhou et al., 2012; Zhang et al., 2013; Lin et al., 2008). The physical connectivity of land use pattern has specifically been proven to impact the hydrologic process, a fundamental component of the ecological process, in different degrees under different scales (Zhang et al., 2013). Hierarchical patch dynamics (HPD) paradigm has been proposed and widely applied to detect the complex relationship among scales (Wu and Loucks, 1995; Peng et al., 2012; Li et al., 2013). In this theory, the complexity of landscapes is broken down by providing a hierarchical structure and multi-scale to landscapes (Wu and David, 2002). The upper level, or larger scale, exerts constraints (e.g. boundary conditions) to the lower level, or small scale, whereas the lower level, or smaller scale, provides mechanisms to the upper level, or larger scale (Wu and David, 2002). Using this paradigm, in this study the catchment's land use patterns were analyzed for different scales in different spatial resolutions. The relationships between land use pattern and hydrologic response were discussed under each scale for detecting the mechanism of hydrologic change in the catchment. Additionally, storm intensity has been proven to affect the relationship between land use pattern and hydrologic process (Ogden et al., 2011; Niehoff et al., 2002; Reaney et al., 2007). However, the impact of land use composition, physical connectivity and functional connectivity on runoff at different scales and under different storm intensities is still unknown.

To advance the understanding of the hydrologic impacts of land use pattern, we examine how the hydrologic impacts of land use pattern composition, functional connectivity, and physical connectivity changes across scales and events. We hypothesize that: (1) the functional connectivity of land use pattern will significantly affect runoff at the catchment outlet, and (2) the relationship between land use pattern and runoff will vary across scales and events. We use the SIMMAP model to simulate land use patterns with different land use composition, physical connectivity and functional connectivity. Landscape metrics, percentage area of forestland and percentage area of impervious surface are used to quantify the land use pattern composition and physical connectivity. A new index is developed to measure functional connectivity at the catchment scale. We use the calibrated gridded surface/subsurface hydrologic analysis (GSSHA) model to predict impacts of land use pattern change on runoff. Multivariate linear stepwise regression analyses is used to describe the relationship between land use pattern characteristics and runoff response at the catchment outlet. Scale effects and impacts of storm intensity are discussed based on five scales and four storm events. We address two questions:

- How does functional connectivity of land use pattern relate to runoff at the catchment outlet?
- What factors contribute most to difference in runoff across scales and events?

2. Study area and data

2.1 Study area

This study was conducted in one of the catchments (S.F. Peachtree Creek Johnson Road) in the Peachtree Creek watershed (33°49′10″N, 84°24′28″W) located near the city of Atlanta, Georgia (Figure 1). The research area (71.5 km2) consists of four sub-catchments: Burnt Fork Creek, Lullwater Creek, Peavine Creek and South Fork

Peachtree Creek. The study area has a humid, subtropical climate, with an average annual precipitation of 1280 mm. The precipitation is generally evenly distributed throughout the year with a slightly drier period in spring and early fall.

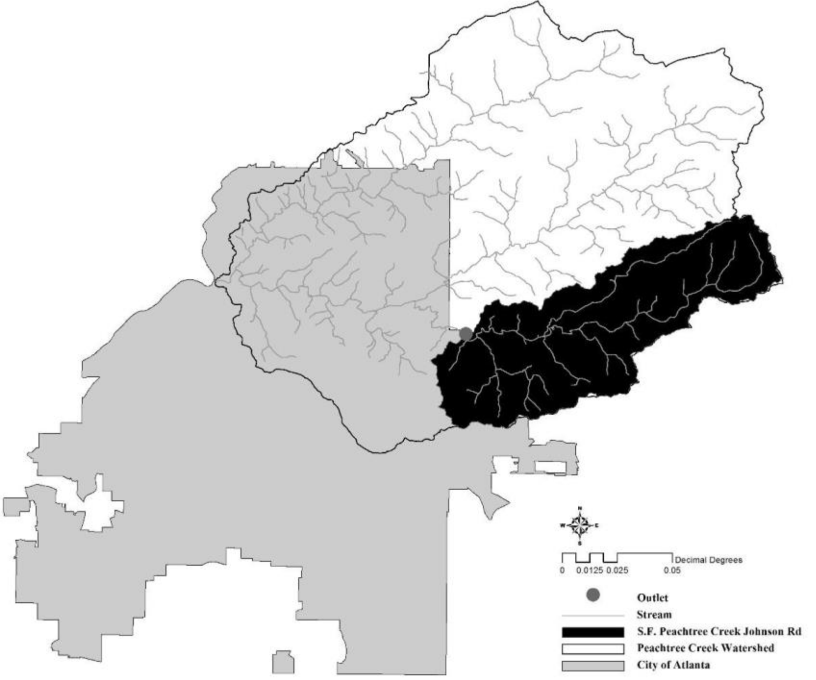

Figure 1. S.F. Peachtree Creek Johnson Road catchment in Peachtree Creek watershed, Georgia, USA.

The study catchment area is characterized by low-sloping (average slope ~ 4.6 degree) hillsides and high urbanized land uses. The main land cover types are: forest, developed land with open space, developed land with low intensity, developed land with medium intensity and developed land with high intensity. These land cover types occupy about 99.1% of the research area. The most common type of land use in the study area is developed land with open space. This kind of land use typically includes large lots, single-family housing units, parks, golf courses and vegetation in developed areas for recreation, erosion control or aesthetic purposes. The developed land with different levels of intensities is classified based on the percentage of impervious surface. Low, medium and high intensity developed land have 20-49%, 50-79% and 80-100% of impervious surface respectively. The major soil groups in the research area are sandy loam, clay loam, clay, sandy clay loam and silt loam. Historic records dating from October 1, 2007 to the present are available for precipitation and discharge variables. Hydrological monitoring of the catchment is conducted at 15 minute intervals and stored by a gauge.

The S.F. Peachtree Creek Johnson Road catchment is an ideal study are to explore the relationship between urban land use patterns and runoff response because it is a typical urban area with a full range of urban land cover/use types and relatively gentle slopes. The smooth slopes can reduce the impacts of topography on the run-off results. Additionally, the high resolution of historical data provide rich information regarding past hydrological response to climate and land use change.

2.2 Data

Stream gauge and rain gauge data were obtained from U.S. Geological Survey (USGS) water data for one gauging station 02336240 (http://waterdata.usgs.gov/nwis/). Data from two typical rainstorms were used to calibrate and validate the hydrologic model in this study. One occurred on February 17, 2008, and the other occurred on December 8, 2008. Both storms were comparatively large and generated a large amount of stormwater. Because there was a limited number of rain gauges in the study area, the stormwater distribution data were not available. Thus, it is assumed in this study that precipitation was evenly distributed throughout the study catchment area, as the study area is quite small. Four additional storm events on December 22, 2007 (10.668 mm); February 26, 2008 (20.32mm); March 19, 2008 (16.256mm) and December 8, 2008 (45.974mm) were used to detect the impacts of storm intensity on the relationship between land use pattern and runoff.

Digital elevation model (DEM) with a resolution of ten meters was obtained from USGS for the Peachtree Creek watershed area. Using the hydrology toolset in ArcGIS 10.0, the catchment boundary and stream lines were generated based on DEM. The USGS gauging station 02336240 at Peachtree Creek was designated as the outlet for the catchment.

Impervious data and land use/cover data were acquired from the National Land Cover Database. Soil data was obtained from the Natural Resource Conservation Service (NRCS) soil survey geographic database. U.S. Department of Agriculture (USDA) soil texture classifications were assigned to NRCS soil types with undeveloped land use/ cover types. The soil texture for developed land use/ cover types were assigned based on the land use/ cover, as the natural infiltration processes are significantly altered by the presence of impervious surface (Sharif et al., 2010). Multiple land use/cover designations assigned by the natural land cover data set were combined into nine land use/ cover types: open water, developed land with open space, developed land in low intensity, developed land in medium intensity, developed land in high intensity, barren land, forest, grassland/herbaceous and wetlands.

3. Methods

3.1 Land use patterns simulation

Hypothetical land use pattern simulation is a critical modeling component when exploring the relationship between land use patterns and hydrologic responses. Several models, such as the land use change model and the neutral landscape model have been frequently employed in past simulation modeling efforts (Ali et al., 2011; Ronfort et al., 2011; Ty et al., 2012). However, the land use patterns generated from the above two methods have some limitations, rendering them unsuitable for the purpose of this study. The land use patterns generated using the land use change model suffer from important information loss, and the land use patterns simulated using the neutral landscape model are not representative of real-world landscapes, indicating that the analysis based on these data may have limited practical implications (Li et al., 2004; Schroder and Seppelt, 2006; Rosindell and Cornell, 2007; Hagen-Zanker and Lajoie, 2008). Conversely, SIMMAP software generates a wide range of different land use patterns that tend to be more representative and realistic than the land use change model and neutral landscape model (Saura and Martinez-Millan, 2000). Thus, in this study we used the SIMMAP model to generate different and realistic land use patterns; these land use patterns are used as inputs in the hydrology model to determine the relationship between land use patterns and water runoff under various scenarios.

SIMMAP software is based on the modified random clusters simulation method (MRC) (Saura and Martinez-Millan, 2000). Four steps were processed during the simulation: generation of a percolation map based on the initial probability, identification of the clusters based on neighborhood relation, assignment of cluster type based on number and abundance of the classes and map gap fill based on the neighborhood criteria (Saura and Martinez-Millan, 2000). The simulated patterns were patchy with irregular shapes, and their spatial metrics can be replicated in real land use patterns (Saura and Martinez-Millan, 2001; Saura, 2002, 2004).

Based on previous studies, five parameters were predefined in the process of SIMMAP: initial probability, number and abundance of the land use types, grid size, study area size and neighborhood criteria (Saura, 2003). The initial probability controls the fragmentation level of the simulated patterns. We simulated the land use patterns for seven different values (0, 0.1, 0.2, 0.3, 0.4, 0.5, and 0.59) of initial probability to obtain a full range of land use patterns (Saura, 2003). Five main land cover types were considered in the study area: forest, developed land with open space, developed land with low intensity, developed land with medium intensity and developed land with high intensity. Six scenarios were generated for each land use type. For each scenario, the specific land use type was listed as a percentage of the watershed, starting at 0 percent and increasing in increments of 20 percent of the total watershed, up to 100 percent. The remaining percentage in each scenario was distributed evenly to the other four land cover types (i.e., 40%, 15%, 15%, 15%, 15%; 20%, 20%, 20%, 20%, 20%). To simulate the land cover patterns under different scales, five spatial resolutions were considered for each of these cases. The grid sizes of the land cover maps were systematically changed from 1*1 pixels (30 m) to 5*5 pixels (150 m). The extent was kept constant. The S.F. Peachtree Creek Johnson Road catchment was set as the study area. Four neighborhood criteria were chosen. Based on the different initial probabilities and percentage of each land cover type, a total of 210 land cover patterns were simulated for each scale.

3.2 Land use pattern composition and physical connectivity measurements

Many land use related variables have been utilized as proxies to quantify land use pattern composition and physical connectivity (Ogden et al., 2013; Onderka et al., 2012; Niehoff et al., 2002). As urbanization is most often the cause of land use change, impervious surface area has been widely used to quantify the impacts of land use pattern composition change (Pappas et al., 2008; Ogden et al., 2011; White and Greer, 2006; Olivera and DeFee, 2007; Zhou et al., 2013). As forest land is the main source of infiltration process in natural hydrological system, forest land area has been used as the main variable to explain and predict runoff and soil erosion change (Dye and Versfeld, 2007; Humann et al., 2011; Venkatesh et al., 2014). Additionally, some landscape metrics of forest land, such as patch density and the largest patch index, have been used to measure the fragmentation of land use patterns which is related to the hydrologic process (Nash et al., 2009; Zhang et al., 2013; Pitkanen et al., 2014). Thus, based on the previous research on the hydrologic impacts of land use pattern composition and physical connectivity, we calculated the percentage area of land use, number of patches (NP), patch density (PD), largest patch index (LPI), total edge (TE), edge density (ED), mean patch size (MPS) and patch size standard deviation (PSSD) for forest land with FRAGSTATS software and the percentage of impervious surface area for each land use pattern with ArcGIS 10.0 (Table 1). The amount of impervious surface of each land use type was derived from the percent developed imperviousness dataset in the National Land Cover Database.

Table 1. Metrics used in the Analysis with their Definitions

Landscape metrics	Definition	Abbreviation
Forest land area (%)	Percentage of catchment area covered by forest land	FLP
Impervious surface area (%)	Percentage of catchment area covered by impervious surface	ISP
Number of forest Patches	Number of forest patches in the landscape	NP
Total Edge of forest Patches	Sum of the lengths of all edge segments of forest patches in the landscape	TE
Edge Density of forest Patches	Sum of the lengths of all edge segments of forest patches in the landscape, divided by the total landscape area	ED
Largest forest Patch Index (%)	Percentage of the landscape comprised by the largest forest patch	LPI
Patch Size Standard Deviation of forest Patches	Root means squared error (deviation from the mean) in forest patch size	PSSD
Mean Patch Size of forest Patches	Total landscape area, divided by the total number of forest patches	MPS
Patch Density of forest Patches	Number of forest patches in the landscape divided by total landscape area	PD

3.3 Land use pattern functional connectivity measurements

No index exists to measure the functional connectivity of land use pattern at the catchment scale although some metrics have been developed to measure hydrologic connectivity change under plot, reach and catchment scales (Antoine et al., 2009; Van Nieuwenhuyse et al., 2011; Jencso and McGlynn, 2011; Borselli et al., 2008; Bracken et al., 2013). Most of the metrics were developed to detect the impacts of topography, vegetation type and soil property on hydrologic connectivity (Lane et al., 2009; Lana-Renault et al., 2011; Mayor et al., 2008; Reaney et al., 2014). Some of them can be used to measure the functional connectivity of land use pattern at the plot scale (Borselli et al., 2008). The index created for this study builds upon previous indices and measures and quantifies the functional connectivity of land use pattern at the catchment scale.The new index was developed based on the connectivity algorithm developed by Borselli et al (Borselli et al., 2008). The index proposed by Borselli et al., is considered suitable to evaluate land use pattern change on functional connectivity (Borselli et al., 2008; Lopez-Vicente et al., 2013). It includes most of the variables which have been proven to affect functional connectivity and introduces the impacts of land use change on functional connectivity (Jencso et al., 2009; Jencso and McGlynn, 2011; Smith et al., 2013; Borselli et al., 2008). However, this index was designed to be used at the plot scale. It cannot evaluate the impacts of land use pattern change on functional connectivity at the catchment scale; therefore it cannot be directly used to compare different land use development scenarios (Borselli et al., 2008). In this study, the functional connectivity at the catchment scale is computed as follows:

$$Connectivity = \overline{\sum_{k=1}^{j} \log_{10}\left(\frac{\overline{C_k}\,\overline{S_k}\sqrt{A_k}}{\sum_{i=1}^{m} \frac{d_i}{C_i S_i}} \right)} \tag{3.1}$$

where j is the number of cells in the catchment, m is the number of cells along the downslope path of the kth cell, Ck is the C-factor of the upslope contributing area of the kth cell, Sk is the slope gradient of the upslope contributing area of the kth cell, A is the upslope contributing area of the kth cell, di is the length of the ith cell along the downslope path, Ci is the C-factor of the ith cell and Si is the slope gradient of the ith cell. The C-factor was used to determine the relative effectiveness of crop management systems in terms of soil loss and can be used to measure the impedance to runoff of different land use types (Borselli et al., 2008). The C- factor is computed as follows:

$$C = 1.02 - 1.21 \times NDVI \tag{3.2}$$

Where NDVI is the normalized difference vegetation index which is used to measure the amount of vegetation (Karaburn, 2010). The average NDVI value of each land use type was computed based on Landsat 5 TM images acquired in June, 2010. All computations were conducted with ArcGIS 10.0.

3.4 Hydrologic response evaluations

Predicting the impacts of land use pattern characteristic change on runoff is an important component of this research. Because land use patterns can significantly affect infiltration and overland flow routing, the two main processes of single-event simulations targeting flood peaks and timing in urbanized catchment, we mainly focused on runoff under a single event in this study (Niehoff et al., 2002; Ogden et al., 2011). We compared various hydrologic models that predict the impacts of land use pattern characteristic change on runoff (Kirby and Durrans, 2007; Yan and Edwards, 2013; Chu et al., 2013; Pechlivanidis et al., 2011). The lumped model can be used to detect the impacts of land use pattern composition change on runoff (Paudel et al., 2011; Du et al., 2012). The semi-distributed model can detect the land use pattern composition change at the sub-catchment scale (Vaze et al., 2004; Franczyk and Chang, 2009). The fully-distributed model can detect the land use change at the grid scale and then be used to detect the land use composition and configuration change on runoff (Abu El-Nasr et al., 2005; Zhang et al., 2013). The GSSHA model is a fully-distributed and physical based model and has been widely used to simulate the surface water process under a single event (Downer and Ogden, 2004,; Zhang et al., 2013, 2014; Sharif et al., 2010; El Hassan et al., 2013). Several modules in this model have proven effective for modeling each step of runoff generation (Downer and Ogden, 2004). The GSSHA model was chosen to quantify the impacts of land use pattern composition and connectivity on runoff because the GSSHA model has specific hydrologic parameters for each spatial grid, and land use change can significantly influence these parameters (Downer and Ogden, 2004; Ogden et al., 2011; Sharif et al., 2010). In this study, we use the GSSHA model to predict the hydrologic response of different land use patterns under a single event. There are several alternative modules in GSSHA used to simulate each component of the hydrologic process. In this study, the Green and Ampt model was chosen to simulate infiltration in the catchment. The 1-D diffusive wave method was used to determine channel flow, and the alternating direction explicit scheme (ADE) method was used to model overland-flow routing.

Hydrologic modeling involves a four step process to develop parameters for soil infiltration and land use and channel flow parameters. First, the DEM was used to delineate the catchment boundary and stream. Second, land use data, soil data and rainfall data were input into the model to establish catchment characteristics (Downer and Ogden, 2006). Third, several parameters, including channel characteristics, hydrologic characteristics of land use and soil infiltration characteristics were predefined or calibrated before simulation (Downer and Ogden, 2006). Channel cross sections were simulated as trapezoidal and estimated by cross section analysis in ArcGIS. Trapezoidal cross sections had 1:2 side slopes and 25m bottom widths. The initial manning's roughness coefficient of the channel and the land use were determined based on the GSSHA user's manual. The initial saturated hydraulic conductivity, the capillary suction head, effective porosity, the pore distribution index, residual saturation, field capacity and wilting point of soil were determined based on the soil texture classifications of Rawls et al. (1983). Finally, after calibration, these parameter values were adjusted and verified based on observed data.

For calibration, the calibrated outflow hydrograph for the storm on February 17, 2008 was compared to the observed discharge as displayed in Figure 2. The model Nash-Sutcliffe efficiency for this simulation was 0.95. Assigned parameters were chosen to simulate the hydrologic process in study area. Assigned soil infiltration parameter values are presented in Table 2. Assigned land use and channel flow parameters are presented in Table 3.

For validation, the storm on December 8, 2008 was simulated with calibrated parameters in GSSHA to verify the results. The hydrograph for calibration verification is shown in Figure 3. The model Nash-Sutcliffe efficiency for this simulation was 0.98. The results indicate that the calibrated GSSHA model simulates the runoff with reasonable quality and can be used to evaluate the runoff response of land use change.

Table 2. Applied soil infiltration parameters for soil and land uses

Soil texture	Saturated hydraulic conductivity (cm/h)	Green-Ampt capillary suction head (cm)	Effective porosity	Initial soil moisture
Clay	0.03	31.63	0.475	0.39
Clay loam	0.5	20.88	0.464	0.39
Sandy clay loam	0.12	21.85	0.450	0.39
Sandy loam	1	11.01	0.453	0.39
Silt loam	0.3	16.68	0.501	0.39
Developed, Open Space	0.1	20	0.475	0.39
Developed,	0.05	31.63	0.475	0.39

Low Intensity				
Developed, Medium Intensity	0.03	32.63	0.475	0.39
Developed, High Intensity	0.01	33.63	0.475	0.39
Water	0.01	33.63	0.475	0.39

Table 3. Applied flow parameters for land use and channel

Land use	Manning's roughness coefficient
Open Water	0.01
Developed, Open Space	0.1
Developed, Low Intensity	0.05
Developed, Medium Intensity	0.03
Developed, High Intensity	0.01
Barren Land (Rock/Sand/Clay)	0.01
Mixed Forest	0.35
Grassland/Herbaceous	0.15
Woody Wetlands	0.25

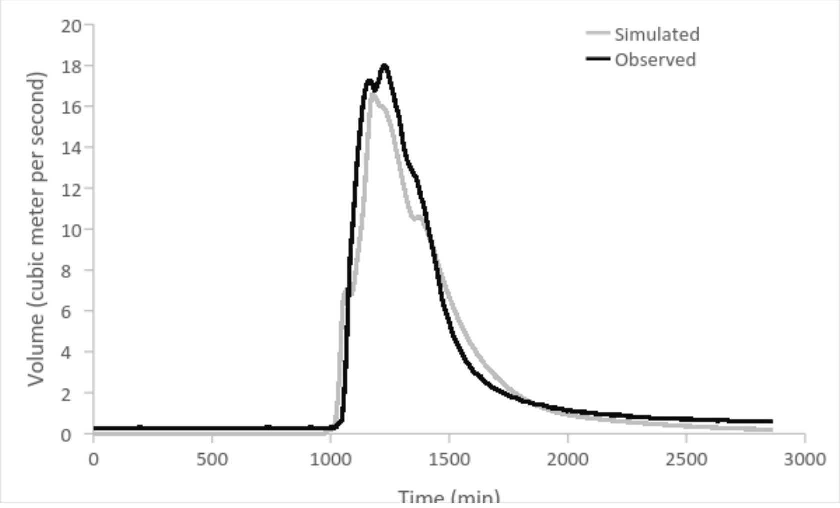

Figure 2. Observed and simulated hydrograph of the storm on February 17, 2008

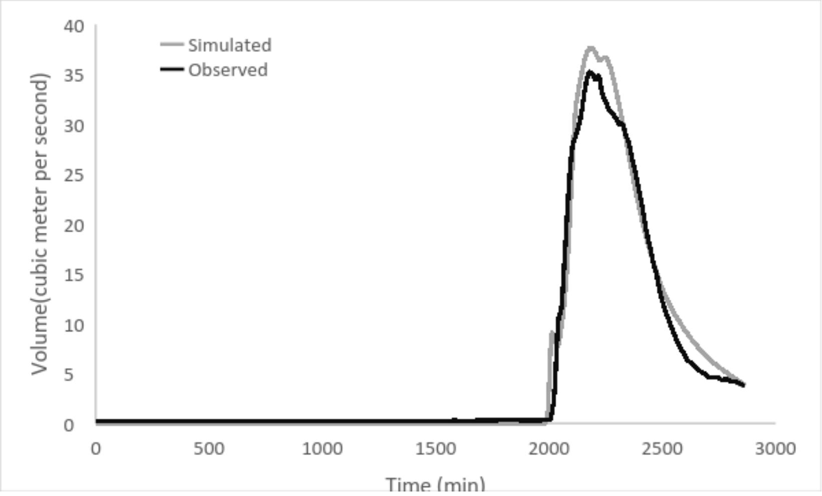

Figure 3. Observed and simulated hydrograph of the storm on December 8, 2008

3.5 Regression analysis

Relationships between land use pattern characteristics and runoff generation were assessed using multivariate linear stepwise regression analyses within SPSS software. Landscape metrics and functional connectivity were calculated as independent variables for each land use pattern simulated by SIMMAP software. The peak flow and total volume of discharge at the outlet of the catchment were simulated as dependent variables by the GSSHA model. We used regression analysis to detect the impacts of scale on the relationship between land use and runoff; landscape metrics and functional connectivity, calculated at 30*30m, 60*60m, 90*90m, 120*120m and 150*150m scales, were analyzed against the peak flow and total volume of runoff during the storm event on December 8, 2008 (45.974mm). We also used regression analysis to detect the impacts of storm intensity on the relationship between land use and runoff; landscape metrics and functional connectivity, calculated at the 30*30m scale, were analyzed against the peak flow and total volume of runoff during the storm events on December 22, 2007 (10.668 mm); February 26, 2008 (20.32mm); March 19, 2008 (16.256mm) and December 8, 2008 (45.974mm). The regression equation was selected based on the value of Akaike information criterion (AIC), and the variables were tested for multi-collinearity. The equation with a minimum AIC value and variables' variance inflation factor (VIF) value less than 10 was considered to be the best equation. The variables selected for each regression equation were those that were significant ($p < 0.05$) in explaining the difference in the runoff generation across scales and storm events.

4. Results

4.1 Predictors of runoff across different scales

Table 4 lists the combinations of significant predictors of runoff peak flow under 30*30m, 60*60m, 90*90m, 120*120m and 150*150m scales. The differences in runoff peak flow were explained by functional connectivity, percentage area of forest land and ED of forest land under the 90*90m scale, while they were explained by functional connectivity, percentage area of forest land and TE of forest land under other scales. Ninety three percent of the variance under the 30*30m scale was explained by land use metrics which increased to 97.2 percent with the increase of scale. Functional connectivity explained the most variability under different scales. Increasing functional connectivity was correlated to increasing runoff peak flow across scales. Runoff peak flow increased 238.2- 239.8 cubic meter per second at one increment of functional connectivity. Increasing percentage area of forest land, ED of forest and TE of forest land were correlated to decreasing runoff peak flow across scales.

Table 4. The estimated coefficient of the regression analysis between landscape metrics of land uses and runoff peak flow, under different scales

	30m*30m		60m*60m		90m*90m		120m*120m		150m*150m	
	β	Beta	β	Beta	β	Beta	β	Beta	β	Beta
C	155.22		178.59		213.15		243.95		262.94	
CON	238.67	0.70	238.93	0.70	239.83	0.7	238.56	0.7	238.19	0.7
TE	-2.18E-05	-0.26	-4.67E-05	-0.32	-	-	-8.74E-05	-0.35	-0.11E-03	-0.35
FLP	-0.41	-0.24	-0.34	-0.2	-0.32	-0.18	-0.31	-0.18	-0.30	-0.18
ED	-	-	-	-	-0.47	-0.34	-	-	-	-
R²	0.93		0.958		0.967		0.971		0.972	
P	< 0.01		< 0.01		< 0.01		< 0.01		< 0.01	

C constant, CON functional connectivity, FLP forest land area (%), TE total edge of forest patches, ED edge density of forest patches, - not significant and <0.05 significant levels in the model

Significant predictors of total runoff volume vary depending on the catchment scale. Table 5 lists the combinations of significant predictors of total runoff volume under 30*30m, 60*60m, 90*90m, 120*120m and 150*150m scales. The differences in total volume runoff were explained by functional connectivity and percentage area of forest land across all scales. Besides these two variables, significant predictors were: LPI of forest land under the 30*30m scale, MPS of forest land under all scales except the 150*150m scale, TE of forest land under the 60*60m, 90*90m and 150*150m scales and ED of forest land under the 120*120m scale. Ninety eight percent of the variance under the 30*30m scale was explained by land use metrics and increased to 99.2 percent with the increase of scale from 30m*30m to 120m*120m. Percentage area of forest land explained the most variability under different scales except the 150*150m scale. Functional connectivity explained the most variability under the 150*150m scale. Increasing percentage area of forest land, ED of forest and TE of forest land was correlated to decreasing total runoff volume across scales. Increasing hydrologic connectivity, LPI and MPS of forest land was correlated to increasing total runoff volume across scales. Total runoff volume increased from 2,412,718 to 2,434,111 cubic meters at one increment of functional connectivity.

Table 5. Estimated coefficient of the regression analysis between landscape metrics of land uses and total runoff volume, under different scales

	30m*30m		60m*60m		90m*90m		120m*120m		150m*150m	
	β	Beta	β	Beta	β	Beta	β	Beta	β	Beta
C	2.31E06		2.5E06		2.85E06		3.16E06		3.35 E06	
CON	2.42E06	0.51	2.42E06	0.51	2.43E06	0.51	2.42E06	0.51	2.41 E06	0.51
TE	-	-	-0.37	-0.18	-	-	-0.77	-0.22	-1.14	-0.27
FLP	-2.45E04	-1.03	-1.41E04	-0.6	-1.32E04	-0.56	-1.28E04	-0.54	-1.06 E04	-0.45
ED	-	-	-	-	-3983.82	-0.21	-	-	-	-
LPI	9359.03	0.42	-	-	-	-	-	-	-	-
MPS	67.27	0.14	57.84	0.14	41.6	0.11	32.86	0.09	-	-
R^2	0.984		0.987		0.99		0.992		0.991	
P	< 0.01		< 0.01		< 0.01		< 0.01		< 0.01	

. C constant, CON functional connectivity, FLP forest land area (%), TE total edge of forest patches, ED edge density of forest patches, LPI largest forest patch index, MPS mean patch size of forest patches , - not significant and <0.05 significant levels in the model

4.2 Predictors of runoff across events

The model showed a combination of significant predictors of peak runoff flow under different storm events with different intensities; Table 6 lists these combinations of significant predictors. The differences in peak runoff flow were explained by functional connectivity, TE and percentage area of forest land at the 45.974mm event; functional connectivity, TE and LPI of forest land at the 20.32mm event; LPI and ED of forest land and percentage area of impervious surface at the 16.256mm event and percentage area of impervious surface at the 10mm event. Ninety three percent of the variance at the 45.974mm event was explained by land use metrics and decreased to 61.8 percent with the decrease of storm intensity from 45.974mm to 10mm. Functional connectivity explained the most variability at the storm events of 45.974mm and 20.32mm, and percentage area of impervious surface explained the most variability at the storm events of 16.256mm and 10mm. Increasing functional connectivity, LPI of forest land and percentage area of impervious surface were correlated to increasing peak runoff flow across all events. Increasing ED of forest land and TE of forest land were correlated to decreasing peak runoff flow across all events. Peak runoff flow increased 238.7 cubic meters per second at one increment of functional connectivity at the 45.974mm event, but the peak runoff flow was only 161.5 cubic meter per second at the 20.32mm event.

Table 6. Estimated coefficient of the regression analysis between landscape metrics of land uses and peak runoff flow, under different storm intensities

	45.974mm		20.32mm		16.256mm		10mm	
	β	Beta	β	Beta	B	Beta	β	Beta
C	155.22		74.23		-13.11		-5.01	
CON	238.67	0.7	161.48	0.93	-	-	-	-
TE	-2.2E-05	-0.26	-1.1E-05	-0.26	-	-	-	-
FLP	-0.41	-0.24	-	-	-	-	-	-
ED	-	-	-	-	-0.05	-0.26	-	-
LPI	-	-	0.11	0.14	0.11	0.20	-	-

ISP	-	-	-	-	0.73	0.94	0.19	0.79
R²	0.93		0.908		0.88		0.618	
P	< 0.01		< 0.01		< 0.01		< 0.01	

. C constant, CON functional connectivity, FLP forest land area (%), TE total edge of forest patches, ED edge density of forest patches, LPI largest forest patch index, ISP Impervious surface area (%),- not significant and <0.05 significant levels in the model

The model presented a combination of significant predictors of total runoff volume under different storm events with different intensities; table 7 lists these combinations. The differences in total runoff volume were explained by LPI, MPS and percentage area of forest land and functional connectivity at the 45.974mm event, TE and percentage area of forest land and functional connectivity at the 20.32mm event, LPI and TE of forest land and functional connectivity at the 16.256mm event and LPI and percentage area of forest land and percentage area of impervious surface at the 10mm event. Ninety eight percent of the variance under the 30*30m scale was explained by land use metrics and increased to 82.9 percent with the decrease of storm intensity from 45.974mm to 10mm. Percentage area of forest land explained the most variability at the 45.974mm event. Functional connectivity explained the most variability at the 20.32mm and 16.256mm events. Percentage area of impervious surface explained the most variability at the 10mm event. Increasing percentage area of forest land and TE of forest land were correlated to decreasing total runoff volume across all events. Increasing hydrologic connectivity, LPI and MPS of forest land and percentage area of impervious surface were correlated to increasing total runoff volume across all events. Total runoff volume increased 2,422,915 cubic meters at one increment of hydrologic connectivity at the 45.974mm event, but the total runoff volume was only 1,499,034 cubic meters at the 16.256mm event, with the decrease of storm intensity.

Table 7. Estimated coefficient of the regression analysis between landscape metrics of land uses and total runoff volume, under different Storm intensities

	45.974mm		20.32mm		16.256mm		10mm	
	β	Beta	β	Beta	β	Beta	β	Beta
C	2305507	-	986462.5	-	663313	-	-81030.1	-
CON	2422915	0.513033	1516431	0.702505	1499034	0.954691	-	-
TE	-	-	-0.14564	-0.27417	-0.10708	-0.27712	-	-
FLP	-24493.3	-1.03354	-2479.96	-0.22895	-	-	-1434.21	-0.48317
LPI	9359.03	0.41908	-	-	1320.848	0.177895	1960.353	0.700821
MPS	67.26668	0.139023	-	-	-	-	-	-
ISP	-	-	-	-	-	-	3656.935	0.944693
R^2	0.984		0.937		0.927		0.829	
P	< 0.01		< 0.01		< 0.01		< 0.01	

. C constant, CON functional connectivity, FLP forest land area (%),TE total edge of forest patches, LPI largest forest patch index, ISP impervious surface area (%), MPS mean patch size of forest patches, - not significant and <0.05 significant levels in the model

5. Discussions

5.1 How does functional connectivity of land use pattern relate to runoff at the catchment outlet?

The indexes of hydrologic connectivity have been developed for different scales, but the functional connectivity of land use pattern at the catchment scale have not been measured yet. In this study, a new evaluation index was developed to measure the functional connectivity of land use patterns in the hydrologic process. It was based on the algorithm developed by Borselli et al. and designed to be used at the catchment scale (2008). Based on existing hydrologic connectivity metrics, this index includes all of the important factors related to hydrologic connectivity, such as upslope accumulated area, land use and slope (Jencso et al., 2007; Bracken et al., 2013). Therefore we used this index to measure functional connectivity of different land use patterns in the hydrologic process. The results indicate that the measured index represents different values under different land use development scenarios. Land use pattern change was found to significantly affect the surface roughness of the runoff pathway which is related to hydrologic connectivity (Fiener et al., 2011; Bracken and Croke 2007). Thus, it is reasonable that new index can capture the functional connectivity of land use pattern at the catchment scale. The results suggest that this new index can be used to measure functional connectivity of different land use development scenarios in different patterns. It can be used as an evaluation index in land use planning practice.

The relationships between hydrologic connectivity and runoff have been examined for several areas and scales, but the impacts of functional connectivity of land use pattern on runoff at the catchment scale have not been studied yet. In this study, the results of our regression analysis indicate that the functional connectivity of land use pattern can significantly affect the peak flow and total volume of runoff across scales and under large and medium storm events. These results are supported by previous research in related fields. Landscape ecologists have found land use pattern change can influence the ecological process by modifying flow connectivity (Schwarz et al., 1996; Eikaas et al., 2005; Martin and Soranno, 2006). As a fundamental process in an ecosystem, the hydrologic process can be affected by land use pattern change based on the reduction or enhancement of functional connectivity (Bracken and Croke, 2007). Additionally, the peak runoff flow at the catchment outlet can be reduced by 1520 percent based on land use patterns optimization (Yeo et al., 2004). The runoff flow rate and the total runoff volume are important to various fundamental hydrologic processes, including infiltration, interception, deposition, absorption, uptake and evaporation (Xiang, 1996). Thus, it is conceivable that functional connectivity of land use pattern can significantly affect the peak runoff flow and total runoff volume at the catchment outlet. Additionally, the results indicate that land use patterns with high functional connectivity presents positive impacts on peak runoff flow and total runoff volume across scales and storm intensities. Topographically driven hydrologic connectivity has been proven to significantly influence the catchment flow duration curve and exert positive effects on runoff magnitude at the catchment scale (Jencso et al., 2007; Jencso and McGlynn, 2011). Thus, it may reasonable that higher functional connectivity of land use pattern causes higher total runoff volume and peak runoff flow at the catchment outlet. However, the results also indicate that the relationship between functional connectivity and runoff is insignificantly correlated under the small storm event. This is possibly because the main hydrologic process at the small event is infiltration. At the small event, rainfall intensity is much less than the soil infiltration capacity in most areas of the catchment, and the outlet runoff mainly comes from the area near the outlet where rainfall intensity is more than the soil infiltration capacity. These results suggest that the functional connectivity of land use pattern should be considered to reduce the negative impacts of urbanization when developing land use planning policy.

5.2 What factors contribute most to difference in runoff across scales and events?

The relative importance of land use pattern composition, physical connectivity and functional connectivity on runoff from an urbanized catchment was examined under different scales and storm intensities. The results revealed that the functional connectivity of land use pattern was a first-order control on runoff peak flow under all scales and at large and medium storm intensities. Research on the relationship between functional connectivity of spatial elements and the ecological process support these results. For example, a significant correlation between the functional connectivity of habitat and animal migration has been reported (Collinge, 2000; Rosch et al., 2013). Similarly, the functional connectivity of landscape has been used to predict the speed of fire spreading on a regional scale (Gonzalez et al., 2008). Thus, the functional connectivity of spatial elements may be the primary reason flow rates increase and decrease. Therefore, it is conceivable that the functional connectivity of land use pattern was a first-order control on runoff peak flow under all scales and at large and medium storm intensities. However, the functional connectivity of land use pattern was also the most important factor in generating total runoff volume at the large scale and medium storm intensities. This is possibly because functional connectivity determines the efficiency of the runoff delivery from source area to catchment outlet which is the main hydrologic process at the large scale (Niu and Chen, 2009; Maxwell et al., 2014). The speed of runoff can affect multiple basic hydrologic processes which are related to the runoff generation (Xiang, 1996). Additionally, at the medium storm intensity, the runoff at the outlet comes from source areas far away from the outlet rather than the source areas near the outlet. The runoff which cannot be infiltrated locally is delivered to the outlet or infiltrated in other areas based on the overland delivery pathways. Thus, it is reasonable that the functional connectivity of land use pattern may be the most important controlling factor of total runoff volume at the large scale and medium storm intensities. The results suggest that the functional connectivity of land use pattern should be considered first to control flow rate which would affect soil erosion and water quality in the area where large storms occur frequently. The results also suggest that functional connectivity optimization can be used to minimize the total volume of runoff which can maximize underground water supply at the area where medium storms occur frequently.

The results also indicate that the percentage area of impervious surface was a first-order control on peak runoff flow and total runoff volume at the small storm intensity. This is possibly because rainfall intensity is much less than the soil infiltration rate of most areas in the catchment at the small storm intensity so the runoff at the outlet comes from some areas with very low infiltration rates. Previous studies have proven that an increased proportion of impervious surface results in higher peak runoff and total runoff volume (Ogden et al., 2013; Pappas et al., 2008; Shuster et al., 2005). Thus, it is conceivable that the percentage area of impervious surface determines the peak runoff flow and total runoff volume at the catchment outlet at the small storm intensity. The results suggest that impervious surface area should be considered first in areas where small storms occur frequently.

The results also indicate that the percentage area of forestland was the most important controlling factor on total volume at the small scale and large storm intensity. The percentage of forest land has been widely considered to be the largest controlling factor on total runoff volume (Iroume and Palacios, 2013). However, in this study, it only happens at the small scale and large storm intensity. That may be because the infiltration process is the main hydrologic process at the small scale and rainfall intensity greatly exceeds the soil infiltration capacity at the large storm intensity (Bracken et al., 2013). The runoff volume at the outlet is determined by the area of spatial elements which can keep water. Thus, it is conceivable that the percentage area of forestland was the most important controlling factor on total volume at the small scale and large storm intensity. The results suggest that forestland area should be considered first when developing land use planning policy to reduce negative impacts of urbanization on total volume in areas where large storms occur frequently.

6. Conclusions

The relative importance of land use pattern characteristics on runoff varies across scales and storm events, as shown by analysis of land use scenarios under different scales and storm events. We developed a connectivity metric as a measure of the functional connectivity of land use pattern at the catchment scale. A strong relationship between runoff and functional connectivity indicates that the runoff at the catchment outlet is significantly affected by functional connectivity change. Additional explanatory variables were introduced to explain the variability in runoff across scales and events. We used these variables to measure land use pattern composition and physical connectivity. Our results provide insight into the effects of the combination of land use pattern composition and connectivity on the hydrologic process. Based on our analysis, we conclude:

- The functional connectivity of land use pattern significantly affected the peak flow and total volume of runoff across scales and under large and medium storm events.
- High functional connectivity presented positive impacts on runoff peak flow and total volume.
- The relative importance of land use pattern composition and connectivity changed according to scale and storm intensity.
- The functional connectivity of land use pattern was a first-order control on runoff peak flow under all scales and at large and medium storm intensities.
- The functional connectivity of land use pattern was a first-order control on total runoff volume at the large scale and medium storm intensities.
- The percentage area of impervious surface was a first-order control on runoff peak flow and total volume at the small storm intensity.
- The percentage area of forestland was the most important controlling factor on total volume at the small scale and large storm intensity.

Our results suggest that the functional connectivity of land use pattern, percentage area of impervious surface and percentage area of forestland should be considered to reduce the negative impacts of urbanization when developing land use planning policy under different situations. This study extends the understanding of land use pattern impacts on runoff at the catchment scale, provides useful information to guide land use planning, develops a new metric to measure the functional connectivity of land use pattern at the catchment scale and uses that metric as an evaluation index to monitor runoff dynamics under specific conditions.

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References

Abu El-Nasr A., Arnold J.G., Feyen J., Berlamont J. (2005). Modelling the hydrology of a catchment using a distributed and a semi-distributed model. Hydrol Process, 19,573-587.

Aguilera F., Valenzuela L.M., Botequilha-Leitao A. (2011). Landscape metrics in the analysis of urban land use patterns: A case study in a Spanish metropolitan area. Landscape Urban Plan, 99,226-238.

Antoine M., Javaux M., Bielders C. (2009). What indicators can capture runoff-relevant connectivity properties of the micro-topography at the plot scale? Adv Water Resour, 32, 1297-1310.

Ali M., Khan S.J., Aslam I., Khan Z. (2011). Simulation of the impacts of land-use change on surface runoff of Lai Nullah Basin in Islamabad, Pakistan. Landscape Urban Plan, 102,271-279.

Borselli L., Cassi P., Torri D. (2008). Prolegomena to sediment and flow connectivity in the landscape: A GIS and field numerical assessment. Catena, 75,268-277.

Bracken L.J., & Croke J. (2007). The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. Hydrol Process, 21, 1749-1763.

Bracken L.J., Wainwright J., Ali G.A., Tetzlaff D., Smith M.W., Reaney S.M., Roy A.G. (2013). Concepts of hydrological connectivity: Research approaches, pathways and future agendas. Earth-Sci Rev, 119, 17-34.

Chu M.L., Knouft J.H., Ghulam A., Guzman J.A., Pan Z. (2013). Impacts of urbanization on river flow frequency: A controlled experimental modeling-based evaluation approach. J Hydrol, 495, 1-12.

Collinge S.K. (2000). Effects of grassland fragmentation on insect species loss, colonization, and movement patterns. Ecology, 81, 2211-2226.

Downer C.W., & Ogden F.L. (2004). GSSHA: Model to simulate diverse stream flow producing processes. J Hydrol Eng, 9,161-174.

Downer C.W., & Ogden F.L. (2006). Gridded Surface Subsurface Hydrologic Analysis (GSSHA) User's Manual; Version 1.43 for Watershed Modeling System 6.1 (No. ERDC/CHL-SR-06-1). ENGINEER RESEARCH AND DEVELOPMENT CENTER VICKSBURG MS COASTAL AND HYDRAULICS LAB.

Downer C.W., Ogden F.L., Martin W.D., Harmon R.S. (2012). Opportunity-driven hydrological model development in US Army research and development programs. Geol Soc Spec Publ, 362,267-286.

Du J.K., Qian L., Rui H.Y., Zuo T.H., Zheng D.P., Xu Y.P., Xu C.Y. (2012). Assessing the effects of urbanization on annual runoff and flood events using an integrated hydrological modeling system for Qinhuai River basin, China. J Hydrol, 464,127-139.

Dye P., & Versfeld D. (2007). Managing the hydrological impacts of South African plantation forests: An overview. Forest Ecol Manag, 251,121-128.

El Hassan A.A., Sharif H.O., Jackson T., Chintalapudi S. (2013). Performance of a conceptual and physically based model in simulating the response of a semi-urbanized watershed in San Antonio, Texas. Hydrol Process, 27, 3394-3408.

Eikaas H.S., McIntosh A.R., Kliskey A.D. (2005). Catchment- and site-scale influences of forest cover and longitudinal forest position on the distribution of a diadromous fish. Freshwater Biol, 50,527-538.

Fiener P., Auerswald K. (2006). Influence of scale and land use pattern on the efficacy of grassed waterways to control runoff. Ecol Eng, 27,208-218.

Forman R.T.T. (1995). Land mosaic: the ecology of landscape and regions. Cambridge University Press, New York

Franczyk J., & Chang H. (2009). The effects of climate change and urbanization on the runoff of the Rock Creek basin in the Portland metropolitan area, Oregon, USA. Hydrol Process, 23,805-815.

Franklin D.H., Cabrera M.L., Calvert V.H. (2006). Fertilizer source and soil aeration effects on runoff volume and quality. Soil Sci Soc Am J, 70, 84-89.

Gonzalez J.R., del Barrio G., Duguy B. (2008). Assessing functional landscape connectivity for disturbance propagation on regional scales - A cost-surface model approach applied to surface fire spread. Ecol Model, 211,121-141.

Hagen-Zanker A., & Lajoie G. (2008). Neutral models of landscape change as benchmarks in the assessment of model performance. Landscape Urban Plan, 86,284-296.

Humann M., Schuler G., Muller C., Schneider R., Johst M., Caspari T. (2011). Identification of runoff processes - The impact of different forest types and soil properties on runoff formation and floods. J Hydrol, 409,637-649.

Iroume A., & Palacios H. (2013). Afforestation and changes in forest composition affect runoff in large river basins with pluvial regime and Mediterranean climate, Chile. J Hydrol, 505,113-125.

Jencso K.G., McGlynn B.L., Gooseff M.N., Wondzell S.M., Bencala K.E., Marshall L.A. (2009). Hydrologic connectivity between landscapes and streams: Transferring reach-and plot-scale understanding to the catchment scale. Water Resour Res, 45.

Jencso K.G., & McGlynn B.L. (2011). Hierarchical controls on runoff generation: Topographically driven hydrologic connectivity, geology, and vegetation. Water Resour Res, 47.

Karaburun A. (2010). Estimation of C factor for soil erosion modeling using NDVI in Buyukcekmece watershed. Ozean journal of applied sciences, 3(1), 77-85.

Kirby J.T., & Durrans S.R. (2007). PnET-II3SL/SWAT: Modeling the combined effects of forests and agriculture on water availability. J Hydrol Eng, 12,319-326.

Lana-Renault N., Latron J., Karssenberg D., Serrano-Muela P., Regues D., Bierkens M.F.P. (2011). Differences in stream flow in relation to changes in land cover: A comparative study in two Sub-mediterranean Mountain catchments. J Hydrol, 411,366-378.

Lane S.N., Reaney S.M., Heathwaite A.L. (2009). Representation of landscape hydrological connectivity using a topographically driven surface flow index. Water Resour Res, 45.

Lin Y.P., Hong N.M., Wu P.J., Wu C.F., Verburg P.H. (2007). Impacts of land use change scenarios on hydrology and land use patterns in the Wu-Tu watershed in Northern Taiwan. Landscape Urban Plan, 80,111-126.

Lin Y.P., Wu P.J., Hong N.M. (2008). The effects of changing the resolution of land-use modeling on simulations of land-use patterns and hydrology for a watershed land-use planning assessment in Wu-Tu, Taiwan. Landscape Urban Plan, 87, 54-66.

Li X.Z., He H.S., Wang X.G., Bu R.C., Hu Y.M., Chang Y. (2004). Evaluating the effectiveness of neutral landscape models to represent a real landscape. Landscape Urban Plan, 69,137-148.

Li C., Li J.X., Wu J.G. (2013). Quantifying the speed, growth modes, and landscape pattern changes of urbanization: a hierarchical patch dynamics approach. Landscape Ecol, 28, 1875-1888.

Lee S.W., Hwang S.J., Lee S.B., Hwang H.S., Sung H.C. (2009). Landscape ecological approach to the relationships of land use patterns in watersheds to water quality characteristics. Landscape Urban Plan, 92, 80-89.

Lopez-Vicente M., Poesen J., Navas A., Gaspar L. (2013). Predicting runoff and sediment connectivity and soil erosion by water for different land use scenarios in the Spanish Pre-Pyrenees. Catena, 102, 62-73.

Martin S.L., & Soranno P.A. (2006) .Lake landscape position: Relationships to hydrologic connectivity and landscape features. Limnol Oceanogr, 51,801-814.

Mayor A.G., Bautista S., Small E.E., Dixon M., Bellot J. (2008). Measurement of the connectivity of runoff source areas as determined by vegetation pattern and topography: A tool for assessing potential water and soil losses in drylands. Water Resour Res, 44.

Maxwell R.M., Putti M., Meyerhoff S., Delfs J.O., Ferguson I.M., Ivanov V., Kim J., Kolditz O., Kollet S.J., Kumar M., Lopez S., Niu J., Paniconi C., Park Y.J., Phanikumar M.S., Shen C.P., Sudicky E.A., Sulis M. (2014). Surface-subsurface model intercomparison: A first set of benchmark results to diagnose integrated hydrology and feedbacks. Water Resour Res, 50, 1531-1549.

Nash M.S., Heggem D.T., Ebert D., Wade T.G., Hall R.K. (2009). Multiscale landscape factors influencing stream water quality in the state of Oregon. Environ Monit Assess, 156,343-360.

Niehoff D., Fritsch U., Bronstert A. (2002). Land-use impacts on stormrunoff generation: scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany. J Hydrol, 267, 80-93.

Niu J., & Chen J. (2009). Application of Vic and a Routing Scheme to Pearl River Basin in South China. Advances in Water Resources and Hydraulic Engineering, Vols 1-6:72-76.

Ogden F.L., Pradhan N.R., Downer C.W., Zahner J.A. (2011). Relative importance of impervious area, drainage density, width function, and subsurface storm drainage on flood runoff from an urbanized catchment. Water Resour Res, 47.

Olivera F., & DeFee B.B. (2007). Urbanization and its effect on runoff in the Whiteoak Bayou watershed, Texas. J Am Water Resour As, 43,170-182.

Ogden F.L., Crouch T.D., Stallard R.F., Hall J.S. (2013). Effect of land cover and use on dry season river runoff, runoff efficiency, and peak storm runoff in the seasonal tropics of Central Panama. Water Resour Res, 49, 8443-8462.

Onderka M., Wrede S., Rodny M., Pfister L., Hoffmann L., Krein A. (2012). Hydrogeologic and landscape controls of dissolved inorganic nitrogen (DIN) and dissolved silica (DSi) fluxes in heterogeneous catchments. J Hydrol, 450, 36-47.

Pappas E.A., Smith D.R., Huang C., Shuster W.D., Bonta J.V. (2008). Impervious surface impacts to runoff and sediment discharge under laboratory rainfall simulation. Catena, 72,146-152.

Paudel M., Nelson E.J., Downer C.W., Hotchkiss R. (2011). Comparing the capability of distributed and lumped hydrologic models for analyzing the effects of land use change. J Hydroinform, 13,461-473.

Pappas E.A., Smith D.R., Huang C., Shuster W.D., Bonta J.V. (2008). Impervious surface impacts to runoff and sediment discharge under laboratory rainfall simulation. Catena, 72,146-152.

Peng S.L., Zhou T., Liang L.Y., Ren W.T. (2012). Landscape Pattern Dynamics and Mechanisms during Vegetation Restoration: A Multiscale, Hierarchical Patch Dynamics Approach. Restor Ecol, 20, 95-102.

Pechlivanidis I.G., Jackson B.M., Mcintyre N.R., Wheater H.S. (2011). Catchment Scale Hydrological Modelling: A Review of Model Types, Calibration Approaches and Uncertainty Analysis Methods in the Context of Recent Developments in Technology and Applications. Global Nest J, 13,193-214.

Pitkanen T.P., Mussaari M., Kayhko N. (2014). Assessing Restoration Potential of Semi-natural Grasslands by Landscape Change Trajectories. Environ Manage, 53,739-756.

Ray D.K., Duckles J.M., Pijanowski B.C. (2010). The Impact of Future Land Use Scenarios on Runoff Volumes in the Muskegon River Watershed. Environ Manage, 46,351-366.

Rawls W.J., Brakensiek D.L., Miller N. (1983). Green-Ampt Infiltration Parameters from Soils Data. J Hydraul Eng-Asce, 109, 62-70.

Reaney S.M., Bracken L.J., Kirkby M.J. (2007). Use of the Connectivity of Runoff Model (CRUM) to investigate the influence of storm characteristics on runoff generation and connectivity in semi-arid areas. Hydrol Process, 21,894-906.

Reaney S.M., Bracken L.J., Kirkby M.J. (2014). The importance of surface controls on overland flow connectivity in semi-arid environments: results from a numerical experimental approach. Hydrol Process, 28, 2116-2128.

Rosindell J., & Cornell S.J. (2007). Species-area relationships from a spatially explicit neutral model in an infinite landscape. Ecol Lett, 10,586-595.

Ronfort C., Souchere V., Martin P., Sebillotte C., Castellazzi M.S., Barbottin A., Meynard J.M., Laignel B. (2011). Methodology for land use change scenario assessment for runoff impacts: A case study in a north-western European Loess belt region (Pays de Caux, France). Catena, 86, 36-48.

Rosch V., Tscharntke T., Scherber C., Batary P. (2013). Landscape composition, connectivity and fragment size drive effects of grassland fragmentation on insect communities. J Appl Ecol, 50,387-394.

Saura S., & Martinez-Millan J. (2000). Landscape patterns simulation with a modified random clusters method. Landscape Ecol, 15,661-678.

Saura S., & Martinez-Millan J. (2001). Sensitivity of landscape pattern metrics to map spatial extent. Photogramm Eng Rem S, 67, 1027-1036.

Saura S. (2002). Effects of minimum mapping unit on land cover data spatial configuration and composition. Int J Remote Sens, 23, 4853-4880.

Saura S. (2003). SimMAP 2.0 Landscape categorical spatial patterns simulation software: User's Manual. Madrid, Spain: Universidad Politecnica de Madrid.

Saura S. (2004). "Effects of remote sensor spatial resolution and data aggregation on selected fragmentation indices." Landscape Ecology, 19(2), 197-209.

Schroder B., & Seppelt R. (2006). Analysis of pattern-process interactions based on landscape models - Overview, general concepts, and methodological issues. Ecol Model, 199,505-516.

Schwarz W.L., Malanson G.P., Weirich F.H. (1996). Effect of landscape position on the sediment chemistry of abandoned-channel wetlands. Landscape Ecol, 11, 27-38.

Seto K.C., & Fragkias M. (2005). Quantifying spatiotemporal patterns of urban land-use change in four cities of China with time series landscape metrics. Landscape Ecol, 20,871-888.

Sharif H.O., Sparks L., Hassan A.A., Zeitler J., Xie H.J. (2010). Application of a Distributed Hydrologic Model to the November 17, 2004, Flood of Bull Creek Watershed, Austin, Texas. J Hydrol Eng, 15,651-657.

Smith T., Marshall L., McGlynn B., Jencso K. (2013). Using field data to inform and evaluate a new model of catchment hydrologic connectivity. Water Resour Res, 49, 6834-6846.

Summerville K.S., & Crist T.O. (2001). Effects of experimental habitat fragmentation on patch use by butterflies and skippers (Lepidoptera). Ecology, 82, 1360-1370.

Ty T.V., Sunada K., Ichikawa Y., Oishi S. (2012). Scenario-based Impact Assessment of Land Use/Cover and Climate Changes on Water Resources and Demand: A Case Study in the Srepok River Basin, Vietnam-Cambodia. Water Resour Manag, 26, 1387-1407.

Valtanen M., Sillanpaa N., Setala H. (2014). Effects of land use intensity on stormwater runoff and its temporal occurrence in cold climates. Hydrol Process, 28, 2639-2650.

Van Nieuwenhuyse B.H.J., Antoine M., Wyseure G., Govers G. (2011) .Pattern-process relationships in surface hydrology: hydrological connectivity expressed in landscape metrics. Hydrol Process, 25, 3760-3773.

Vaze J., Barnett P., Beale G., Dawes W., Evans R., Tuteja N.K., Murphy B., Geeves G., Miller M. (2004) Modelling the effects of land-use change on water and salt delivery from a catchment affected by dryland salinity in south-east Australia. Hydrol Process, 18, 1613-1637.

Venkatesh B., Lakshman N., Purandara B.K. (2014) Hydrological impacts of afforestation - A review of research in India. J Forestry Res, 25, 37-42.

White M.D., & Greer K.A. (2006). The effects of watershed urbanization on the stream hydrology and riparian vegetation of Los Penasquitos Creek, California. Landscape Urban Plan, 74,125-138.

Wu J.G., & Loucks O.L. (1995). From balance of nature to hierarchical patch dynamics: A paradigm shift in ecology. Q Rev Biol, 70,439-466.

Wu J.G., & David J.L. (2002). A spatially explicit hierarchical approach to modeling complex ecological systems: theory and applications. Ecol Model, 153, 7-26.

Yan H.X., & Edwards F.G. (2013). Effects of Land Use Change on Hydrologic Response at a Watershed Scale, Arkansas. J Hydrol Eng, 18, 1779-1785.

Yeo I.Y., & Guldmann J.M. (2006). Land-use optimization for controlling peak flow discharge and nonpoint source water pollution. Environ Plann B, 33,903-921.

Yeo I.Y., Guldmann J.M., Gordon S.I. (2007). A hierarchical optimization approach to watershed land use planning. Water Resour Res, 43.

Zhang G., Guhathakurta S., Dai G., Wu L.Y., Yan L.J. (2013). The Control of Land-Use Patterns for Stormwater Management at Multiple Spatial Scales. Environ Manage, 51,555-570.

Zhang G., Wu L.Y., Dai G., Lee S.S.L., Yan L.J. (2013). Landscape ecological approach to the ecological significance of cultural heritage sites. Life Science Journal, 10(2).

Zhang G., Guhathakurta S., Lee S, Moore A., Yan L.J. (2014). Grid-Based Land-Use Composition and Configuration Optimization for Watershed Stormwater Management. Water Resources Management, 28(10), 2867-2883.

Zhou T., Wu J.G., Peng S.L. (2012). Assessing the effects of landscape pattern on river water quality at multiple scales: A case study of the Dongjiang River watershed, China. Ecol Indic, 23,166-175.

Zhou F., Xu Y.P., Chen Y., Xu C.Y., Gao Y.Q., Du J.K. (2013). Hydrological response to urbanization at different spatio-temporal scales simulated by coupling of CLUE-S and the SWAT model in the Yangtze River Delta region. J Hydrol, 485, 113-125.