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Examining the Impact of Suburbanization on Surface Runoff using the SWAT

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ABSTRACT: This study examines the relationship between land use/land cover (LULC) changes and surface runoff generation empirically to reveal how urbanization has altered the hydrologic characteristics of a watershed. A hydrological model, the Soil and Water Assessment Tool (SWAT), is employed to estimate the watershed runoff generation for two LULC scenarios from 2002 to 2010. The Cypress Creek watershed was chosen for the investigation because of its recent development pressure resulting from the rapid growth of Houston, Texas. This watershed is located within Harris County, 37 km from Houston. Results indicate that the mean annual runoff change was high for most sub-basins that experienced significant urbanization. The correlation coefficients between low, medium, and high intensity developed lands and the amount of surface runoff were significantly positive with values ranging from 0.5 to 0.8, while the correlation coefficient of greenspaces with surface runoff was -0.6. These findings reveal the importance of land use changes and development densities in managing stormwater and suggest local planners and decision-makers on where and how to limit the future residential developments in rapidly growing suburbs.

Key words: SWAT,Stormwater management, Land cover, Simulation, Urbanization,Suburbs

INTRODUCTION

The influences of land cover changes, such as urbanization and deforestation, are the main cause of hydro-modification in a watershed (Chang andFranczyk, 2008). Increased impervious surfaces caused by urbanization can generate excessive runoff, lower soil porosity, decrease infiltration, and reduce aquifer recharge (Booth and Jackson, 1997; Brabec, 2009; Gearheart, 2007; Paul and Meyer, 2001; Schueler, 1994). In urban centers, impervious surfaces take more than 80 percent of the surface area, while suburban areas have an average of 20 to 50 percent impervious surfaces (Braden and Johnston, 2004). The hydrologic attributes greatly change when imperviousness exceeds 25 percent of a watershed (Schueler, 1994). For instance, generated runoff doubled when impervious surfaces increased by 10 to 20 percent (Arnold and Gibbons, 1996). Also, the increase of impervious surfaces had positive and strong correlation with the change of stream flow (Brody et al., 2007). The Natural Resources Conservation Service (NRCS, 1998) compared the runoff percentage of natural ground cover and urbanized areas and found that infiltration rate was reduced by 35 percent and runoff was increased by approximately more than 45 percent in urban areas. Moreover, studies from Hosseinzadeh (2005) and Sala (2003) show that stormwater runoff and flash floods in urbanized areas significantly increased as a result of the increase of impervious surfaces.

Considering the impacts of urbanization on the characteristics of a watershed, post development's peak flow time, the time of concentration, and baseflow can be decreased compared to the pre-development flow regime (Brabec, 2009; Cheng et al., 2013; Randolph, 2004; USEPA, 2009). The changes are mainly due to decreased infiltration and increased evapotranspiration functions. The increase of impervious surfaces and drainage pipelines expand the peak discharge from a certain storm (Arnold and Gibbons, 1996; Booth and Jackson, 1997; Randolph, 2004; Schueler, 1994). In particular, surface runoff is increased by the reduced infil-

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tration of water, and the hydrograph lag time is decreased by the increased rate of runoff accumulation (Randolph, 2004). In sum, a substantial body of research has proved that the increase of impervious surfaces triggered from rapid urbanization significantly increases runoff volume, degrades water quality, and facilitates flood risks.

Since the 1970s, populations increasingly have started to reside in suburbs of metropolitan areas rather than urban core in the United States, and most developed countries followed this trend (Levy, 2009). Accordingly, it led to the growth of numerous suburban and exurban communities. However, traditional development patterns did not reflect a suitable drainage system design. Conventional pipe-drainage systems designed to promptly drain surface runoff were insufficient and ineffective to manage the excessive overflow, which eventually caused downstream flooding and water degradation (Booth and Jackson, 1997; Ferguson, 1998; Yang and Li, 2011). In addition, urban sprawl accelerated the increase of impervious surfaces and affected negative influence on downstream hydrologic cycle (Carlson, 2004; Shuster et al., 2005; Sutton, 2003). Several studies assessed the impacts of land use/land cover change (LULC) on watershed response in a variety of fields by using the Soil and Water Assessment Tool (SWAT) and other hydrological modeling tools. Coutu and Vega) examined the relationship between the change of forest land uses and surface runoff in Chester County, Pennsylvania, by using the SWAT. They discovered that a significant negative correlation exists between forest areas and simulated runoff. Yang and Li (2011) applied the SWAT and the Kinematic Runoff and Erosion model (KINEROS) for their simulations in The Woodlands, Texas, and found that surface runoff conditions (e.g., runoff volume and sediment yields) could be affected by the development density. The high-density scenario could increase runoff by 35%, while the low-density one could cause 85% of runoff increased compared to the baseline condition. Kepner et al. (2004) employed the SWAT and the Automated Geospatial Watershed Assessment (AGWA) tool to assess how watershed characteristics (surface runoff, channel discharge, percolation, and sediment yield) change by simulating three future scenarios in Arizona and Mexico. The simulation results indicated that surface runoff in 2020 increased by 3.7 to 6.9% compared to baseline conditions in 2000. They concluded that urbanization and the increase of irrigated agriculture were the most significant factors that deteriorated future watershed conditions. Githui et al. (2009) investigated the impacts of agricultural land cover changes on runoff in Kenya by using SWAT and demonstrated that the increase of agricultural land cover significantly contributed to the increase of runoff while the climatic inputs were held constant.

Though the importance of minimizing the impervious surfaces is well understood in reducing surface runoff, only few studies to date have thoroughly assessed the impacts of different suburban land covers on runoff. This study addresses the gap by examining the correlation between developed land use/land cover (LULC) and runoff changes. Moreover, limited number of studies examined the impact of suburban development pattern on runoff generation. By looking at the detailed LULC classes, this study examines which types of residential development are preferable for the future growth within the rapidly urbanizing watershed.

MATERIALS & METHODS

SWAT, a hydrological model, was employed in this study to simulate the long-term surface runoff generation. SWAT has been long recognized as one of the best-known tools to examine water quality and quantity issues, particularly for estimating runoff in rural areas (Arnold andFohrer, 2005; Srinivasan and Arnold, 1994). Despite its original intent for rural watersheds, SWAT has been used for modelling urbanized watersheds as well (Arnold andFohrer, 2005; Coutu and Vega, 2007; Kepner et al., 2004; Yang and Li, 2011). SWAT is a continuous, computationally efficient, and physically based hydrologic model which requires variability of runoff controlling factors, such as weather, temperature, land uses, soils, and topography (Gassman et al., 2007). SWAT delineates the watershed boundaries, as well as sub-basins by using Hydrological Response Units (HRUs), and these HRUs are generated by different combination of land use and soil type (Arnold and Williams, 1995). The average runoff depths of sub-basins within the Cypress Creek watershed are simulated from 2002 to 2010, and the simulated streamflow was compared with the United States Geological Survey (USGS) measured gauge station data for calibration and validation process. The correlation between the change of LULC and runoff volume is quantified by testing Pearson product-moment correlation coefficient.

The study area is the Cypress Creek watershed, where the majority of land is located within Cypress, an unincorporated community of Harris County, Texas. The rapid economic growth and population expansion of Houston has catalyzed the suburban sprawl near the metro areas. Cypress (Cypress Creek watershed) is included as one of the fastest growing suburbs experiencing a number of single-family residential developments. As of 2010 U.S. Census, the population was 122,803 (zip codes labeled as Cypress) and it is estimated to increase continuously due to the sequence of residential developments. No physical boundary exists for this subdivision, but the 77429 and 77433 zip codes mostly represent outlining the subdivision's periphery. It is one of Houston area's largest suburban communities and located along U.S. Route 290, approximately 37 kilometers northwest of downtown Houston. The Cypress Creek watershed boundary was delineated using the USGS gauge station (no. 08068800) that is located near the confluence of Little Cypress Creek and Cypress Creek (Fig. 1). The watershed covers an area of 377 km2 and the main stream length from the outlet to headwater is 38.5 km. Stream flows from northwest to southeast direction with less than one percent of the average slope. Land cover within the southeast side of watershed has drastically changed between 2001 and 2011 as a result of suburbanization. Fig. 2 presents the change of developed land cover within this period. The

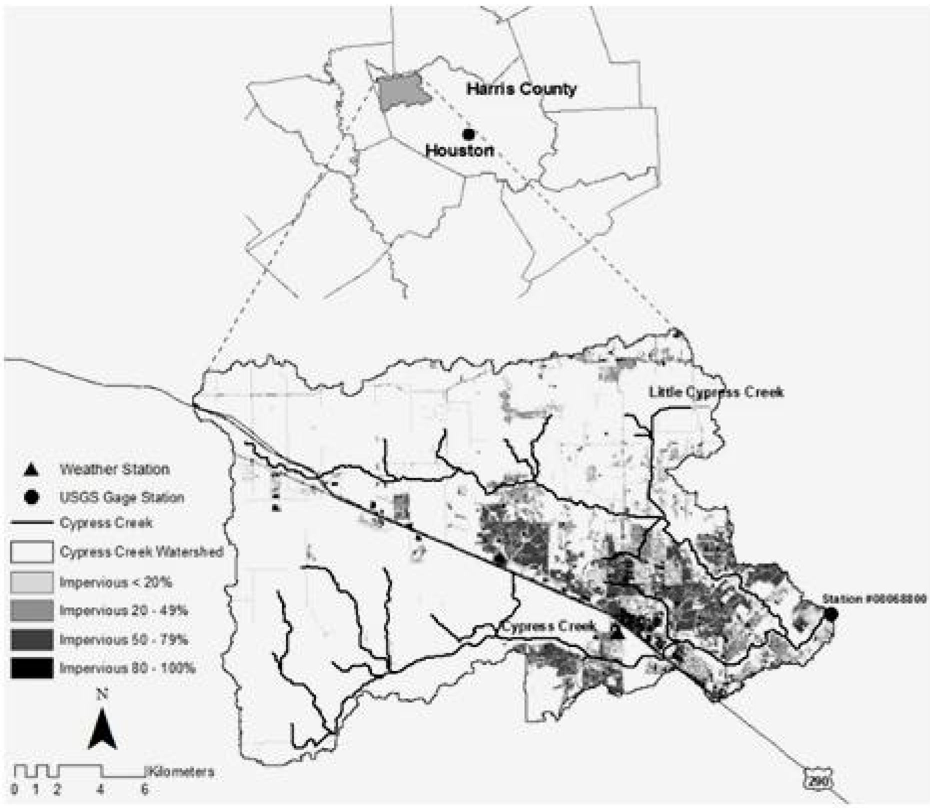

Fig. 1. Study area; The Cypress Creek watershed

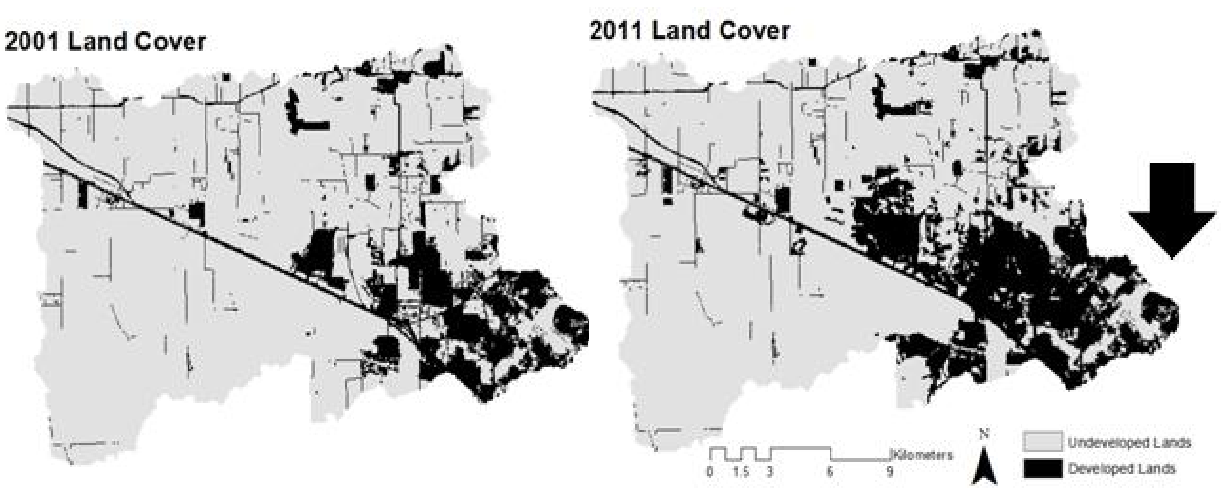

Fig. 2. Developed LULCs in 2001 and 2011

average annual precipitation in Cypress over the last 30 years is about 1,282 mm. The average evapotranspiration near the study site is 116 mm per month over the last 31 years (Texas A&MAgrilife Extension, 2015).

SWAT is a physically-based model that requires a variety of input parameters (Arnold et al., 2012; Coutu and Vega, 2007; Gassman et al., 2007). Datasets used in this study are: precipitation, weather, stream flow, topography, reach, soil, and land use. Historical daily precipitation data were obtained from the National Oceanic and Atmospheric Administration's (NOAA's) National Climatic Data Center (NCDC). Precipitation data from a weather station within the Cypress Creek were used for the analysis (GHCND: USC00412206). Stream flow data, which are required for model calibration and validation analysis, were downloaded from the USGS for the period of 2002 to 2010. Thirty meter resolution topography (Digital Elevation Models; DEMs) and reach (or flow lines) data were obtained from the USGS's National Hydrography Dataset Plus (NHDPlus) website. The Soil Survey Geographic Database (SSURGO) that is developed by the Natural Resources Conservation Service (NRCS), was used for the soil data. The 2001 and 2011 LULC data were obtained from the USGS National Land Cover Dataset (NLCD) at 30 meter resolution (Yang and Li, 2009). Landsat images were classified into eight major classes (water, developed, barren, forest, shrubland, herbaceous, planted/cultivated, and wetlands) with 20 specific LULC categories. In particular, developed land uses are categorized into four classes based on the percentage of impervious surfaces (<20%; 20-49%; 50-79%; 80-100%), and they were used to represent the development types (USGS, 2015). The current land cover coding system were consistently used starting from 2001.

The data were analyzed in three phases. First, the percentage change of the LULC between 2001 and 2011 was examined for 37 sub-basins within the Cypress Creek watershed. Specifically, eight major LULC classes were compared over this period by using ArcGIS 10.2 software and the Geospatial Modelling Environment (GME) (Beyer, 2010) extension. Second, SWAT hydrologic model (version 2012) was employed to estimate surface runoff regimes for two different land use scenarios from 2002 to 2010. In SWAT, we used the flow direction and accumulation method by using DEM data to calculate the stream network and delineate sub-basins. After generating the SWAT input files, SWAT model simulation was run by using the precipitation and weather data from 2002 to 2010 (9 years) in order to estimate the surface runoff volume of 37 sub-basins. To improve the model efficiency, calibration and validation analyses were conducted (Hernandez et al., 2000). Specifically, simulated streamflow was compared with the USGS measured data at the gauging station no. 08068800. The baseflow filter program (Arnold and Allen, 1999) was run to screen the runoff/baseflow fraction in streamflow. Sensitivity analysis, which assesses to identify parameters (model inputs) that may influence the predicted output of a runoff model (White andChaubey, 2005), was implemented. Based on the sensitive analysis of this research, three most sensitive parameters (curve number (CN2), soil evaporation compensation factor (ESCO), and base flow alpha factor (ALPHA-BF)) were adjusted. These key parameters were widely adjusted in previous SWAT watershed studies for estimating surface runoff process (Arnold et al., 2012). After these two processes, final calibrated models were chosen for the simulation. A warm-up period was established for two years (2000-2001) before running the simulation to examine the initial conditions. The model efficiency was measured by three criteria: the Nash and Sutcliffe efficiency (NSE) coefficient, the root mean square error (RSME)-observations standard deviation ratio (RSR), and R-square from the simple linear regression analysis. The NSE and RSR were calculated with the Equation (1) and (2), respectively.

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Q_m - Q_p\right)^2}{\sum_{i=1}^{n}\left(Q_m - Q_{avg}\right)^2} \quad (1)$$

$$RSR = \frac{RMSE}{STDEV_{Q_m}} = \frac{\sqrt{\sum_{i=1}^{n}\left(Q_m - Q_p\right)^2}}{\sqrt{\sum_{i=1}^{n}\left(Q_m - Q_{avg}\right)^2}} \quad (2)$$

where NSE is the coefficient of efficiency (ranging from: -∞ to 1); RSR is the RMSE-observations standard deviation ratio; Qm and Qp are the simulated and observed streamflow; and Qavg is the mean observed streamflow during the simulation period.

Finally, Pearson's correlation test was run to examine the degree of correlation between the percent change of developed LULC classes and the percent change in generated runoff. The Pearson Product-moment Correlation Coefficient supports the research hypothesis of this study. That is, as developed land cover increases, more surface runoff will be generated.

RESULTS & DISCUSSION

As presented in Table 1, the percentage of developed lands in Cypress increased significantly by 42.1%, while greenspaces (forest, shrubland, and planted/cultivated lands), which covered approximately 73% of the watershed in 2001 have been largely decreased by 12.9%. In addition, the percentage of water increased

Table 1. Land Use/Land Cover distribution in the Cypress Creek watershed

Land Use Land Cover (LULC)	2001 Area (%)	2011 Area (%)	Area Change between 2001 and 2011 (%)
Water	0.4	0.9	102.4
Developed	17.0	24.2	42.1
Barren	0.6	1.1	69.8
Forest	8.3	5.9	-28.5
Shrubland	3.4	2.2	-37.3
Herbaceous	2.3	2.4	3.4
Planted/Cultivated	61.4	55.6	-9.5
Wetlands	6.5	7.9	20.9

more than double. This may be due to the increase of retention ponds that have been installed from the new residential developments. Overall, the findings reveal that the study area has undergone a rapid urbanization between 2001 and 2011.

By using ArcHydro algorithm, SWAT can delineate the boundary of watershed as well as hydro-logically associated sub-basins, which classifies in a finer area (Coutu and Vega, 2007). Thrity-seven sub-basins within the Cypress Creek watershed were used to identify the land cover change patterns and the relationship between LULC classes and generated runoff (Fig. 3). Table 2 shows the size of each sub-basin and the percentage change of developed land covers (LULC code: 21 to 24). The average size of sub-basin was 10.2 km2.

Calibration and validation were conducted in SWAT. Specifically, the model was calibrated for the period of 2002 to 2006 and validated from 2007 to 2010 (Fig. 4). As shown in Table 3, simulated flow trend (yearly) fittingly followed the measured flow with the NSE greater than 0.75 and the RSR ranging from 0.31 to 0.40. Values of NSE higher or equal to 0.75 are recognized to be good simulation results for yearly data (Van LiewandGarbrecht, 2003). In addition, if RSR values lie in the range of 0.00 to 0.50, the model simulation performance is considered to be very good (Moriasi et al., 2007). Accordingly, the hydrological processes were realistically modelled.

SWAT generates the mean discharge rates for each sub-basin with the unit of cubic meter per second (cms). For this study, the flows were converted into total an-

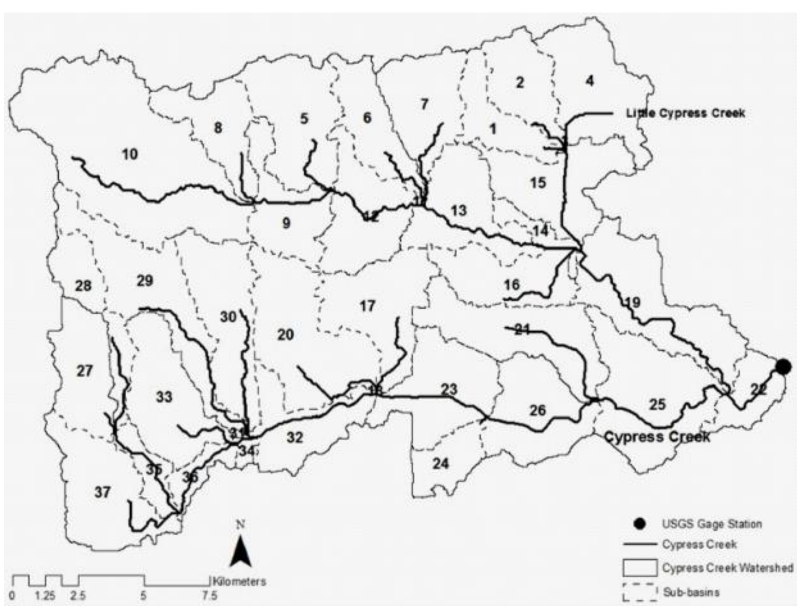

Fig. 3. Delineated sub-basins within the Cypress Creek watershed

Table 2. Developed land use/land cover change (%) between 2001 and 2011

Sub-basin	Area (km^2)	Developed, Open Space (Class: 21)	Developed, Low Intensity (Class: 22)	Developed, Medium Intensity (Class: 23)	Developed High Intensity (Class: 24)
1	6.79	-0.97	0.10	0.01	0.09
2	8.15	-0.96	0.03	0.33	0.18
3	0.08	0	0	0	0
4	13.96	-1.33	-0.87	0.19	0.28
5	14.01	-0.07	0.03	0.17	0.04
6	8.46	-0.11	0.02	0.02	0
7	10.88	2.27	0.16	-0.02	0.07
8	8.96	0.31	0.27	0	0
9	9.49	0.09	1.05	0.58	0.00
10	38.01	0.11	0.43	0.32	0.24
11	0.07	0	0	0	0
12	11.75	7.99	12.16	8.04	0.15
13	12.30	6.97	4.38	0.98	0.04
14	2.44	3.35	1.73	0.37	0.37
15	12.73	0.90	2.04	0.54	0.19
16	9.88	6.81	7.80	8.06	0.87
17	13.38	0.25	5.57	12.23	1.87
18	0.05	0	0	0	0
19	17.83	0.47	5.20	8.66	0.24
20	17.97	0.53	0.32	1.28	0.85
21	14.87	-0.01	6.80	17.16	3.23
22	5.32	-3.65	1.27	3.28	0.54
23	12.95	0.50	5.87	10.52	0.60
24	5.05	2.94	12.81	12.13	0.29
25	18.14	-4.52	1.73	11.40	1.55
26	12.39	-10.37	7.36	15.29	5.34
27	9.72	0	0	0	0
28	7.60	0	0	0	0
29	16.30	0.97	0.69	0.34	0.21
30	13.83	2.08	0.84	1.04	0.23
31	0.17	0	0	0	0
32	9.53	0	0	0	0
33	12.90	0.03	0	0	0
34	0.81	0	0	0	0
35	3.54	0	0	0	0
36	2.96	0	0	0	0
37	13.81	0	0	0	0
Average	10.19	0.39	2.10	3.05	0.47

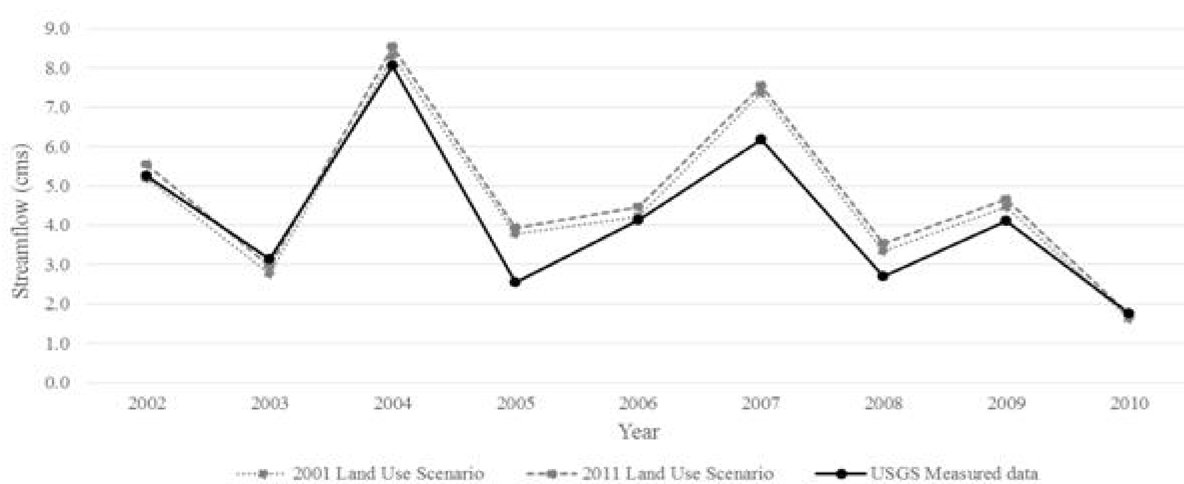

Fig. 4. Results for the annual mean simulated streamflow (calibration and validation)

Table 3. Model efficiency for the calibration and validation period

	Nash-Sutcliffe Coefficient		RSR	
	Calibration (yearly)	Validation (yearly)	Calibration (yearly)	Validation (yearly)
2001 Land Use Scenario	0.91	0.88	0.31	0.36
2011 Land Use Scenario	0.82	0.73	0.33	0.40

Table 4. Percent change of developed lands/greenspaces/runoff between 2001 and 2011

Sub-basin	Developed Land Cover (Class: 21-24)	Greenspaces (Forst+Shrubland+Planted/Cultivated) (Class: 41-43; 51; 81-82)	Average Runoff Change (%)
1	-0.76	-2.14	0
2	-0.42	-2.16	-20.03
3	0	0.00	<0.01
4	-1.73	0.00	0
5	0.17	-3.69	0.62
6	-0.06	-0.16	-38.80
7	2.47	-7.82	25.41
8	0.58	-1.15	0.96
9	1.73	-2.18	4.55
10	1.10	-5.01	2.73
11	0	0.00	115.66
12	28.33	-25.56	30.13
13	12.37	-11.66	31.60
14	5.82	-8.55	<0.01
15	3.68	-9.49	10.18
16	23.53	-24.18	166.12
17	19.92	-13.26	285.30
18	0	0.00	188.24
19	14.57	-14.63	89.18
20	2.98	-4.30	0.96
21	27.19	-28.54	227.22
22	1.44	-1.20	-16.25
23	17.49	-28.36	170.15
24	28.16	-33.17	80.53
25	10.16	-8.51	99.52
26	17.62	-23.98	267.02
27	0	-5.71	1.78
28	0	-3.26	-1.14
29	2.21	-5.63	4.24
30	4.18	-7.39	1.87
31	0	-6.49	51.89
32	0	-3.06	-2.72
33	0.03	-2.79	1.34
34	0	1.34	<0.01
35	0	-7.58	<0.01
36	0	9.95	-46.73
37	0	-5.63	-28.78

nual runoff depth (in centimeters). Due to the location of the city of Houston, urbanization of Cypress is expanding from the southeast side of the watershed to the northwest. Overall, mean annual runoff volume was increased when the simulation was run by the 2011 land use scenario. The trend shows that the mean annual runoff for most sub-basins located at the southeastern has drastically increased compared to other sub-basins. Seven sub-basins' (Sub-basin #2, 6, 22, 28, 32, 36, and 37) mean annual runoff has decreased. In specific, the percentage of developed land cover as well as greenspaces of those seven sub-basins did not change or slightly reduced between 2001 and 2011 (Table 4). Interestingly, although Sub-basin #22 was the outlet of the entire watershed and located where the development pressure was very strong, the runoff volume was not influenced by the nearby residential developments. Mean annual runoff for six sub-basins (Sub-basin #1, 3, 4, 14, 34, and 35) has changed less than 0.01% for both land use scenarios. Fig. 5 illus-

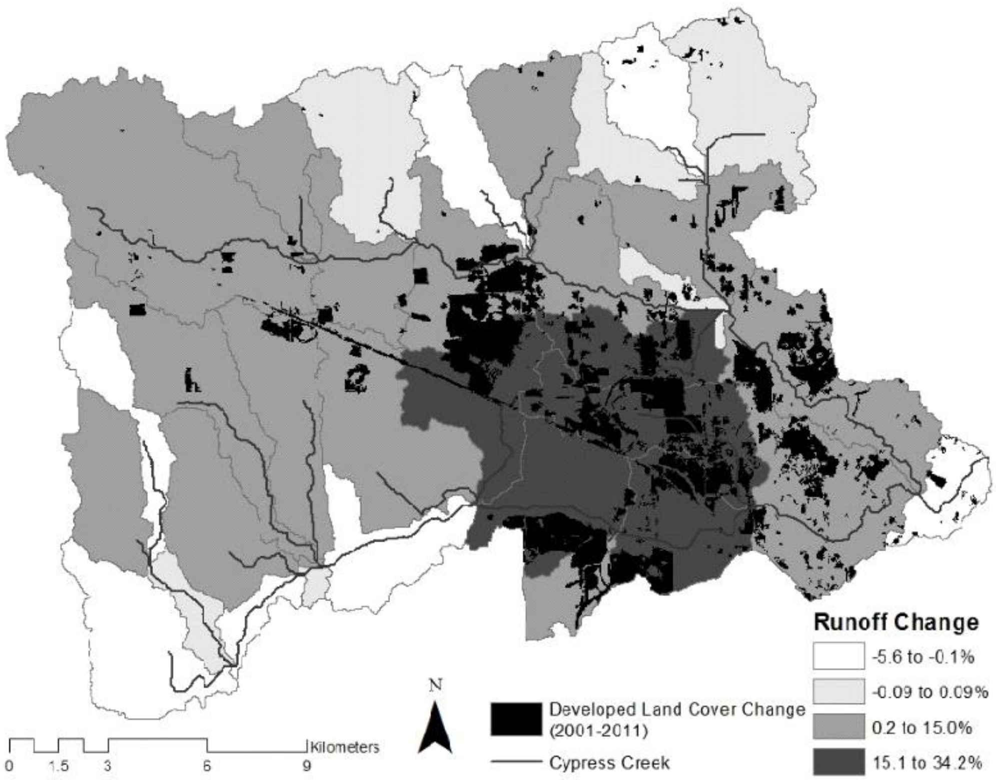

Fig. 5. Mean annual runoff change and developed LULC change by each sub-basin

Table 5. Correlation results for mean annual runoff change (y) and LULC change (xi) (N=37)

Variable	Coefficient	P-value
Developed, Open Space (Class: 21)	-0.182	0.281
Developed, Low Intensity (Class: 22)	0.557	0.000
Developed, Medium Intensity (Class: 23)	0.791	0.000
Developed High Intensity (Class: 24)	0.721	0.000
Developed Land Cover (Class: 21-24)	0.664	0.000
Greenspaces (Class: 41-43; 51; 81-82)	-0.621	0.000

trates the changes of mean annual runoff and developed land cover of each sub-basin. Most sub-basins' runoff was increased as urbanization occurred.

Table 5. Correlation results for mean annual runoff change (y) and LULC change (xi) (N=37)By employing the Pearson's Product-Moment Correlation Coefficients technique, we tested the degree of correlation between the dependent variable (y; mean annual runoff change) and independent variables (xi; developed land cover and greenspaces change). Five independent variables were significantly correlated with the dependent variable, where p<0.01 (Table 5). Developed LULC classes except Class 21 were positively correlated with the mean annual runoff change with correlation coefficients ranging from 0.56 to 0.79. In particular, 'medium density developed LULC (Class 23)' showed the highest correlation with the runoff change, following by 'high (Class 24) and low (Class 22) density developed LULCs.' However, statistically significant correlation did not exist with the 'developed, open space (Class: 21)' Overall 'developed LULCs (Class 21-24)' were positively correlated with the runoff change, which implies that as developed land areas increase, the volume of surface runoff may also increase. A correlation analysis was also conducted between the change of 'greenspaces (LULC Classes 41-43; 51; 81-82)' and mean annual runoff. This result indicates a significantly negative correlation between them, which is consistent with previous studies.

The findings have clearly indicated that development density has a strong correlation in the changes of generated surface runoff in the Cypress Creek watershed. The changes of 'medium and high density (Class 23 and 24) developed land covers' had a positive and relatively stronger association with the surface runoff change compared to the 'low density (Class 22) developed land cover.' This result coincides with the outcome of previous studies on the relationship between two variables (Blair et al., 2010; Booth and Jackson, 1997; OliveraandDeFee, 2007; Sriwongsitanon and Taesombat, 2011; Schueler, 1994; Yang and Li, 2011). However, the correlation result illustrates that medium and high density developments tend to generate greater mean annual runoff volume than other development density. As these areas mostly represent small-lot single-family residential and commercial areas, the finding supports different viewpoints with previous research (Anderson et al., 1976) by demonstrating that low density developments with large-lot single-family housing units may lead to less surface runoff. Thus, when land cover is solely considered, the compact residential developments should be formed with sufficient amounts and adequate locations of low-impact development (LID) techniques to minimize the surface runoff.

The protection of natural landscapes (green spaces), however, is more crucial than the indiscriminate expansion of residential developments in preserving the characteristics of hydrological regime. The 2011 land use map of the Cypress Creek watershed shows that about 12% of lands within the study area were used as residential purpose and approximately 99% of residential areas were built as single-family housings. Commercial land uses took only about 3% of the whole watershed. This prevailing trend demonstrates that conventional suburban sprawl is likely to continue within the study area. Hence, land use planning techniques, such as density bonuses, cluster zoning, purchase/transfer of development rights, urban growth boundaries, and conservation easements should be implemented at the local level to regulate the rapid sprawling within the watershed. Structural approaches, such as best management practices (BMPs) and LID techniques, are also recommended to be properly placed and designed to accommodate increased stormwater by using landscape features within a densely developed area (Cahill, 2012; Perez-Pediniet al., 2005). The concept of these structural tools is to maximize onsite storage and infiltration so as to protect and maintain downstream ecologically-sensitive areas and reduce the quantity of runoffs within the areas that are vulnerable from developments (Roseen et al., 2011).

Another finding shows that mean annual surface runoff of relatively small sub-basins (Sub-basin 11, 18, and 31; area size less than 0.1 km2), where no increment of developed LULC occurred, increased due to the impacts of upstream developments. These results correspond with the previous studies that the downstream hydrologic functions would be significantly influenced by the upstream conditions (Kaiser andBurby, 1987; Roy et al., 2008; Walsh et al., 2005). Planners should thus be conscious on permitting the future development locations in a way that ensures the protection of major stream segments (Brody et al., 2011).

The finding also shows that mean annual runoff of Sub-basin #22, which is the outlet of watershed, has been reduced even though it is surrounded in heavily developed areas. This consequence can be inferred from the unique condition of the study area, where retention basins predominantly exist in most residential subdivisions. Since these ponds have significant impacts on slowing down excessive runoff and reducing floods, further work needs to be conducted to provide insights on their functions in minimizing runoff volumes at the site-scale.

CONCLUSIONS

This study empirically investigated the impact of suburbanization development patterns on surface runoff. Two hydrologic modeling results showed that overall watershed runoff has increased by 4.3% due to adverse impacts of rapid residential developments. The entire watershed runoff did not increase as much as our initial expectation. This is perhaps because the large portion of the watershed is still undeveloped (approximately 75%) and still able to mitigate stormwater runoff. It should be noted that positive correlations exist between densely developed land areas and generated mean annual surface runoff. The correlation coefficients for developed land areas are up to 0.79, and negative association was discovered between greenspaces and runoff with the value of -0.62. The findings correspond with the previous studies (Coutu and Vega, 2007; Kepner et al., 2004) that urbanization disrupts the existing hydrologic regime and increases the risk of flood. However, this study has brought out that newly developing suburbs continue to have similar land development patterns as the previous ones, and this type of urban sprawl keeps exacerbating runoff volumes. Thus, the findings of this study suggest local governments, decision-makers, and planners increase their awareness of systematic stormwater management and to limit future developments that will impact the hydrologic regime. Watershed management plans need to be adopted at the regional level to facilitate the coordination of interconnected localities in managing runoff effectively and emphasize the value of greenspaces in mitigating potential urban floods. By integrating the large-scale goals and objectives of regional plans, specific planning strategies and policies of local municipalities, such as comprehensive plans and stormwater management plans, should be amended to reflect regional aims. Land use planning/regulation/incentive tools, such as clustering development, conservation easement, open space preservation, transfer of development right, overlay zoning, and density bonus, as well as continuous water quantity and quality monitoring programs could be employed for the implementation.

While this study re-confirms the impact of suburban developments, i.e., suburbanization of stormwater runoff, we suggest a continuation of this study will further the generalizability of the result. We recommend three areas for improvement. First, a large sample size will enhance the statistical validity and avoid external validity threats. Second, other modeling tools such as KINEROS and the HEC-Hydrologic Modeling System can be used to investigate extreme rainfall events and peak flows. Third, modeling the land use/land cover change in a longer term should be considered if rainfall and stream data are available.

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