Environment, Development and Sustainability
https://doi.org/10.1007/s10668-018-0210-3

A panel data analysis of a spatial measurement of green infrastructure and its potential effectiveness on peak streamflow

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Received: 18 October 2017 / Accepted: 24 June 2018

Abstract
Research on the possible benefits of green infrastructure as a hazard mitigation strategy has been limited by the lack of effective tools for the identification and measurement of the specific dimensions of green infrastructure particularly within highly developed urban environments. Consequently, there has been little empirical research conducted on the potential benefits of green infrastructure for reducing streamflow, an indicator of runoff and potential flooding mitigation. This study seeks to further research green infrastructure as a potential tool for hazard mitigation by examining its consequences for streamflow over a 2-year period in 2004 and 2010 for two key urban areas subject to flooding in Texas, USA (Austin and Houston Metropolitan areas) in panel models to assess the effectiveness of green infrastructure for reducing runoff as assessed by using streamflow gage data predicting annual peak flow. The statistical models suggested that green infrastructure contributes to reduce annual peak flow in urbanized watersheds. The effect in the fixed effects model suggests that with every percent increase in green infrastructure within the 100-year floodplain, peak annual flow decreased by 7.7% ($R^2=0.6985$). The effects of green infrastructure outside the floodplain appeared to be significant, and its magnitude in the fixed effects model was −7.1% ($R^2=0.6447$). These differences suggest slightly greater consequences for preserving green infrastructure within floodplains when it comes to peak annual flows. Moreover, the analyses explained that green infrastructure in Austin appears to be more effective on peak annual flow when, compared to Houston, suggesting that green infrastructure has elevated consequences in areas with greater topographical diversity. The effectiveness of green infrastructure in critical places will help make a guideline for the balanced urban development with implementation of green infrastructure.

Keywords Green infrastructure · Streamflow · Hazard mitigation · Runoff

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Published online: 29 June 2018

1 Introduction

Since green infrastructure is being touted as a potential hazard mitigation tool, it is important to study the relationship between green infrastructure and streamflow. Green infrastructure has been identified as a strategy to increase water infiltration and minimize surface runoff (Armson et al. 2013; Gill et al. 2007), to improve urban air quality (Jayasooriya et al. 2017), and to moderate urban heat island effect (Connors et al. 2013; Armson et al. 2012). Also, the effects of green infrastructure as a climate change adaptation strategy, especially for mitigating flooding hazard, have been identified (Cheng et al. 2017). However, research on the possible benefits of green infrastructure as a hazard mitigation strategy has been limited by the lack of effective tools for the identification and measurement of the specific dimensions of green infrastructure and the balance between green infrastructure and urban development particularly within highly developed urban environments. Consequently, there has been little empirical research conducted on the potential benefits of green infrastructure for stabilizing streamflow not to contribute to peak streamflow within a short lag time, an indicator of potential urban flooding mitigation.

Green infrastructure generally refers to an interconnected network of wetlands, forests, and green space that conserves ecosystem function and services (Beatley 2009; Benedict and McMahon 2002). Green infrastructure has diverse benefits which include streamflow stabilization, reduction of surface runoff volume, intensive stormwater runoff management (Gill et al. 2007), enhancement of stormwater quality, and maintenance of base flows (Ahern 2007; Dietz 2007; Dietz and Cluasen 2008). Also, there is less development impact on the flow regime with green infrastructure design when compared to the conventional drainage design (Yang and Li 2013). Depending on the discipline or the scale at which green infrastructure is implemented, green infrastructure has been defined diversely (Allen 2012). Green infrastructure at regional scale specifically includes strategic land acquisition and conservation easements, open-space preservation policy, and incentives and regulation for protection of floodplain, wetlands, and other natural green space that help reduce flooding (Allen 2012). In addition to natural green infrastructure, engineered strategies to promote low impact development such as rain gardens, bioretentions, constructed wetlands, and green roofs have been implemented at site scale. However, green infrastructure has been studied primarily at the community scale, utilizing very coarse measurements. At the site scale, green infrastructure has been applied with very site-specific details and characteristics. What has been missing is a more broadly based assessment employing refined measures that will allow for the examination of the particular forms and place-specific integration of green infrastructure within a community (Young 2011). For example, previous research has considered pervious surfaces, such as different types of wetlands and undeveloped land use/land cover, to examine the impact on flood losses at the county level (Brody et al. 2012, 2014). Additionally, the adverse hazard impacts from rapid urban development have been studied, specifically the effects of urbanization on runoff and impacts of development patterns on flooding (Baloch et al. 2015; Brody et al. 2013; Kim et al. 2017; Olivera and DeFee 2007). It may not simply be the amount of green infrastructure that functions as an important factor to reduce streamflow, but also the location, spatial characteristics, and qualities of green infrastructure. However, there is a research gap that the consequences of specific green infrastructure patterns and forms within urban areas especially along the 100-year floodplains for streamflow reduction have not been studied. The 100-year floodplain is considered as an approach to delineate areas of high flood risk, which is designated by a standardized statistical measure for the area with 1% chance of flooding in a year (Prasad 2016). As the 100-year floodplain is a demarcated area of high risk, it is important to study how green infrastructure along the 100-year floodplain affects stabilized streamflow, resulting in a contribution to urban flooding reduction. Also, research has not been conducted employing green infrastructure measurement from 1-m high-resolution imagery which allows to differentiate diverse green infrastructure in dense urban area such as significant amount of lawn space on residential land use. The measurements of previous studies were Coastal Change Analysis Program (C-CAP) land cover classification derived from Landsat Thematic Mapper data at 30-m resolution or National Land Cover Database (NLCD) at the same resolution, which were coarse to capture detailed green infrastructure information in urban areas, and these datasets do not consider green areas besides those in green-related categories (Brody et al. 2014; Ritters et al. 2009; Lee 2018).

This study seeks to further research green infrastructure as a potential tool for hazard mitigation by examining its consequences for streamflow over a 2-year period in 2004 and 2010 for two key urban areas subject to flooding in Texas, USA (the Austin and Houston Metropolitan areas) by (1) utilizing high-resolution (1-m) imagery to assess the amount, form, type, and placement of green infrastructure in dense urban environments and then (2) utilizing these measures in panel models to assess the effectiveness of green infrastructure for reducing runoff as assessed by using streamflow gage data predicting annual peak flow. As population and urban development increase rapidly in Texas, conversion of open-space and added imperviousness is closely related to adverse hazard impacts, such as stormwater runoff and flooding, resulting in increases in potential economic damage. This study for the effectiveness of green infrastructure in critical places will help make a guideline for the balanced urban development with implementation of green infrastructure.

2 Methods

2.1 Study area and sample selection

For this study, the metropolitan areas of Houston and Austin in Texas in the USA were considered as the study area. Although these metropolitan areas are located in geographically different environments, these two areas both have stormwater runoff and flooding issues due to urban development and imperviousness and they are both located in the Gulf region of Texas (Brody et al. 2011; Zahran et al. 2008). The Houston metropolitan area is an ideal area to analyze the relationship between green infrastructure and streamflow, which is one of the indicators for flooding. The number of fatalities from floods in Harris County, Texas (the county in which Houston is located), between 1960 and 2008 is the largest among all coastal counties in Texas (Brody et al. 2011). From 1996 to 2001, this county was one of the top 10 jurisdictions in the nation in approving land conversion for development (Brody et al. 2013). With the aim of strategically implementing green infrastructure dealing with open-space conversion and rapid urban development, Harris County is an ideal urban area to study. The terrain characteristic of Harris County is very flat; for example, the stream channel slopes of Houston metropolitan area in Harris County are 1–8 feet per mile. These flat slopes, clay soils, and intense rainfall patterns are closely linked to stormwater and flooding (Bedient et al. 2002).

The Austin metropolitan area is located approximately 150 miles northwest of the Gulf of Mexico in south-central Texas (Veenhuis and Gannett 1986). Travis County, Texas (the county in which Austin is located), is among the top 10% of flood-prone communities as

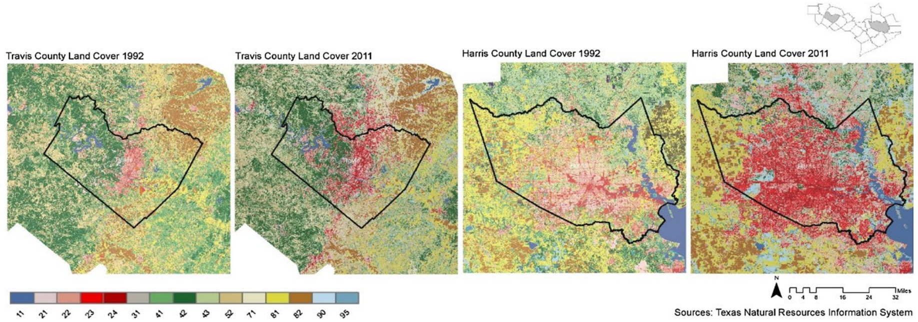

Fig. 1 National land cover change between 1992 and 2011—Travis county and Harris County. (NLCD legends: 11 open water, 21 developed, open space, 22 developed, low intensity, 23 developed, medium intensity, 24 developed, high intensity, 31 barren land, 41 deciduous forest, 42 evergreen forest, 43 mixed forest, 52 shrub/scrub, 71 grassland/herbaceous, 81 pasture/hay, 82 cultivated crops, 90 woody wetlands, 95 emergent herbaceous wetlands)

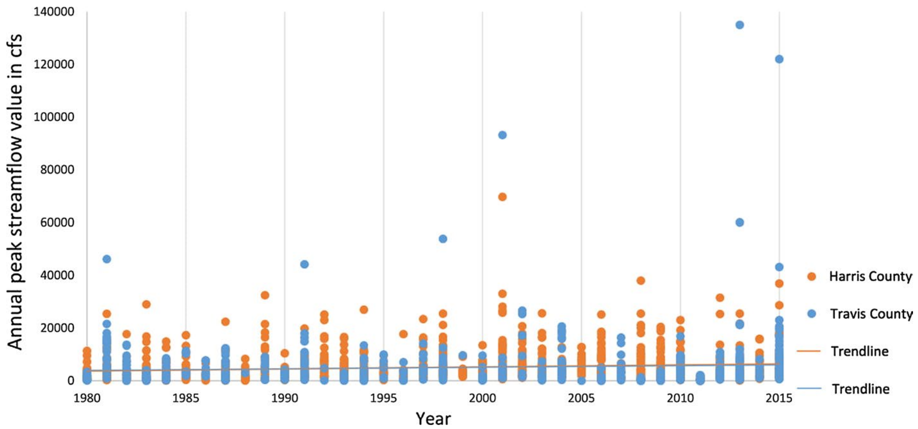

Fig. 2 Annual peak streamflow data in Travis and Harris Counties between 1980 and 2015

reported by the Federal Emergency Management Agency (FEMA). Travis County was among the top 20 Texas counties with the highest flood causalities between 1997 and 2001 (Zahran et al. 2008). The rainfall and terrain characteristics of Travis County make the region vulnerable to stormwater and flooding. As it is located near the Gulf Coast of Texas, heavy precipitation from tropical storms can be produced. Additionally, steep topography with rapid urban development patterns is linked to flash flooding (Looper and Vieus 2012). These two metropolitan areas have different regional characteristics, and these two regions have a wide variation of environmental conditions such as slope and soil type. These variations help analyze the effectiveness of green infrastructure on streamflow for those rapidly urbanizing areas in Texas. Figure 1 shows rapid urbanization and intensive land cover change between 1992 and 2011 in Travis and Harris Counties. Historical annual peak streamflow data from the US Geological Survey (USGS) for the stream gage stations in the two counties between 1980 and 2015 are plotted in Fig. 2, and the trendlines indicate that annual peak streamflow had increased over 35 years. Several studies have explained

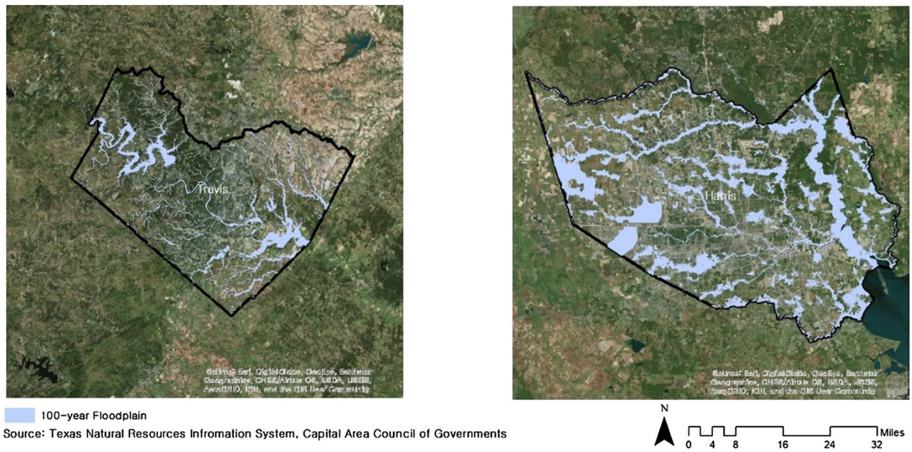

Fig. 3 Distribution of 100-year floodplain in Travis County and Harris County

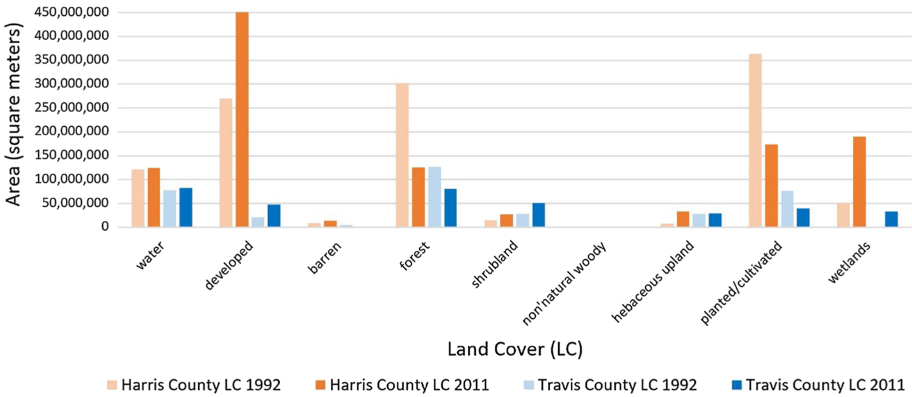

Fig. 4 Land cover change in floodplains in Travis and Harris Counties between 1992 and 2011

that the runoff volume (Jennings and Jarnagin 2002) and peak flow rates (Leopold 1968; Chen et al. 2017; Muñoz et al. 2018) increased due to urbanization, and rapid land cover changes in the study area may have contributed to increased streamflow. Figure 3 identifies 100-year floodplain in the two counties, and Fig. 4 shows how much land cover change has happened on the floodplain between 1992 and 2011. For these 20 years, in Travis County, developed land cover had increased by 123%, whereas forest land cover had decreased by 36%. Similar pattern in Harris County has also been identified. Developed land cover had increased by 66%, whereas forest land cover had decreased by 58%.

For this study, intra-jurisdictional data at the watershed level were employed instead of using jurisdictional-level, community-, or county-level data. Specifically, watersheds were delineated based on locations of stream gage stations as a unit of analysis because ecological boundaries were more appropriate in analyzing the effectiveness of green infrastructure for streamflow reduction. To select stream gage stations to delineate watersheds, this study first considered all stream gage stations in the Austin and Houston metropolitan areas including 23 counties. Second, this study considered the stream gage stations that were not located at the outlet of a dam or reservoir. Finally, stream gage stations providing peak streamflow for the study period for 2004 and 2010 were considered. The first year that the National Agriculture Imagery Program (NAIP) was available for the study area was 2004, provided in the proper format for Normalized Difference Vegetation Index (NDVI) measurement (1-m high resolution and color infrared) to measure green infrastructure in the study area. The most recent year was 2010, available in the same resolution and format. Due to the difficulty acquiring proper NAIP imagery gathered in more recent years, only the time period between 2004 and 2010 was considered for this study. The above selection parameters resulted in a set of 66 stream gage stations available for the analysis of peak streamflow. Since this study conducted data analysis for two-time period panel data analysis, the total number of data points collected was 132 for peak flow analysis.

2.2 Unit of analysis

To delineate watersheds based on the selected stream gage stations, hydrologic analysis by the ArcGIS spatial tool was used with the digital elevation model (DEM) downloaded from the National Hydrography Dataset (NHD) Plus version 2. Once each watershed was delineated, watersheds with enough streamflow measurement data for the study period (2004 and 2010) were selected. Using the NHD Plus dataset based on the available stream gage stations, 66 watersheds across the two metropolitan areas were delineated (see Fig. 5). Ideally, it was best to have continuous watersheds as units of analysis. However, due to the lack of historical stream gage data for the study area in 2004 and 2010, it was not available to delineate watersheds continuously.

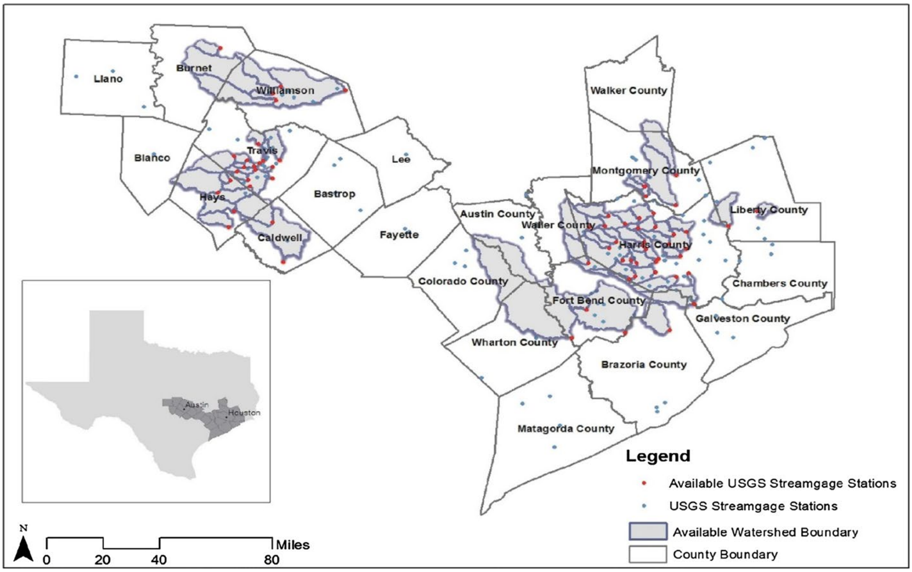

Fig. 5 Available USGS streamgage stations and watershed delineation

2.3 Concept measurement

2.3.1 Dependent variable

The dependent variable in the conceptual model was annual peak flow. Streamflow peak was developed by collecting daily stream discharge data for 2004 and 2010 for each gage station. Annual peak flow was the maximum discharge recorded each water year at each individual gage station, and it represented the high flow event for each year at each individual gage station. As the dependent variable should be normally distributed for data analysis, log transformation was conducted.

2.3.2 Independent variables

2.3.2.1 Overall green infrastructure First, overall green infrastructure was defined as the percentages of green infrastructure captured from the National Agriculture Imagery Program (NAIP) at watershed scale. Highly detailed measurements of green infrastructure which was utilized for this study, particularly within complex urban environments, were also expected to have a negative effect on annual peak flow.

Normalized Difference Vegetation Index (NDVI) values range from −1 to 1. This calculation is based on the fact that chlorophyll absorbs red, whereas the mesophyll leaf structure scatters near-infrared (Pettorelli et al. 2005). The National Aeronautics and Space Administration (NASA) explains that very low values of NDVI (0.1 and below) correspond to barren areas of rock, sand, or snow. Moderate values represent shrub and grasslands (0.2–0.3), while high values indicate temperate and tropical rainforests (0.6–0.8). To measure the overall green infrastructure in the delineated watersheds, the reclassification of NDVI values was conducted to assign values of either "0" or "1." Each cell with an NDVI value less than 0.1 was reclassified as "0," whereas cells with an NDVI value greater than 0.1 were reclassified as "1." The NDVI was analyzed based on 1-m high-resolution NAIP imagery, provided by the US Department of Agriculture (USDA). For example, it allows to capture and identify more types of green infrastructure such as a significant amount of lawn on residential land uses in dense urban environments, while the National Land Cover Data (NLCD) are not able to provide green infrastructure information on residential land cover. Lee (2018) explains that the high-resolution NAIP imagery is suggested to capture detailed green infrastructure as a different approach compared to the NLCD. The total green infrastructure based on this high resolution in Harris County, TX, is 61.5% of the area, compared to the 51.5% calculated from the NLCD.

2.3.2.2 Green infrastructure location measures It may not simply be the amount of green infrastructure within a watershed that is key, but also the location. For example, previous studies suggest that green infrastructure has the ecological capability to absorb, store, and slowly release water, thus decreasing runoff and streamflow (Brody et al. 2008). Green infrastructure implementation such as setbacks from or buffers around waterways in the 100-year floodplains reduces adverse impacts from flooding. Saleh et al. (2017) showed that the vegetative buffer strips are effective for reducing the runoff volume by 35–90% using their experimental plots.

In light of these findings, a number of locational dimensions of green infrastructure were considered. Specifically, three measures capturing the location of green infrastructure relative to the 100-year floodplain boundary were considered. These measures were:

the percentage of green infrastructure in the 100-year floodplains in each watershed, the percentage of green infrastructure outside the 100-year floodplains, and the percentage of green infrastructure in the 60-m buffer around the floodplain (see Fig. 6).

2.3.2.3 Green infrastructure spatial pattern measures Landscape metrics have emerged as an important method of quantifying landscape patterns in order to gain a better understanding of the relationships and changes in landscapes through time and space (Park et al. 2014). Landscape metrics measure spatial patterns of the different landscape types such as landscape composition, number, size, distribution, connectivity, and configuration (Leitão et al. 2006; Brody et al. 2013; Olivera and Defee 2007; Hepcan 2013). In order to measure spatial distribution of green infrastructure and how the composition changes, patch density (PD) was used as one of the green infrastructure's spatial pattern variables. As land use patterns have changed as a result of rapid urban development, distribution of green infrastructure across land use types has also been altered. To further help analyze landscape configuration, correlation length (GYRATE_AM), a variable that explains patch extensiveness, was included for this study (Leitão et al. 2006). Including these landscape metrics may help capture how particular forms of spatial patterns of green infrastructure can have consequences on reducing streamflow. Independent variables of landscape metrics were measured by utilizing the FRAGSTATS program, a spatial pattern analysis program for quantifying landscape structure (McGarigal and Marks 1994), with the reclassified green infrastructure data gathered using the NDVI.

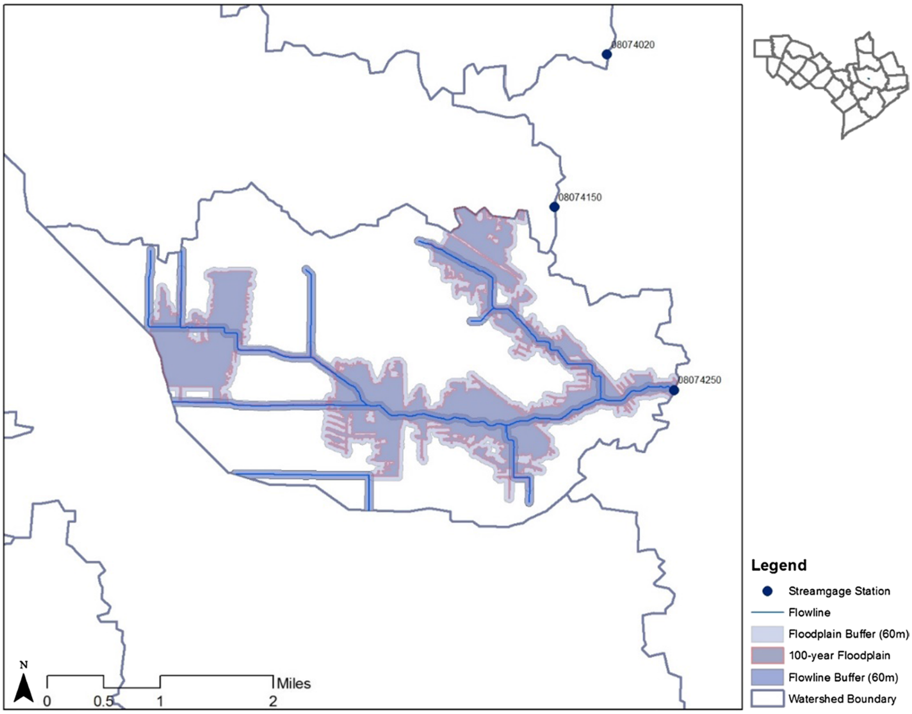

Fig. 6 Green infrastructure location measures

2.3.3 Control variables

To analyze the relationship between green infrastructure and streamflow measurements, several control variables that are related to the effect on streamflow were considered. These variables were considered based on previous research showing significant relationship between each variable and streamflow measurements. The general sets of control measure included area related to (1) natural environmental variables (watershed area, drainage area, floodplain area, stream density, slopes, precipitation, and soils) and (2) impervious surface measures. Table 1 summarizes conceptual measurement and hypothesized effects of this study.

3 Data analysis

Primary analysis strategy of this study was broken into two phases of analyses performed. Phase 1 focused on a series of fixed and random effect panel models that tested the consequences of (1) overall green infrastructure described as the percentage of green infrastructure in watershed, (2) locational dimensions of green infrastructure (i.e., green infrastructure in the 100-year floodplains, outside of the 100-year floodplains, or in 60-m buffer zones from floodplains), and (3) landscape metrics for green infrastructure spatial pattern—patch density and correlation length. Throughout both fixed and random effects models were employed, allowing for some or all (time variant and invariant) control measures to be included in the models.

In Phase 2, the models for both phases were reanalyzed testing for statistically significant difference across the two urban areas included in this analysis: the Austin and the Houston metropolitan areas. This phase was to assess whether or not there might be important regional variations in the consequences of green infrastructure across the two urban areas. These two areas vary considerably with the terrain characteristics such as slope and soil types (Bedient et al. 2002; Looper and Vieus 2012) which may have consequences for the effectiveness of green infrastructure (GI) when addressing annual peak flow. For Phase 2, first a regional or metropolitan dummy variable was included in each of the models previously estimated in Phase 1, along with a set of interactions between the dummy variable and each of the key GI variables included in the model. Specifically, a regional dummy variable labeled Houston was included along with interactions between this variable and each of the key GI measures included in a specific model. The dummy was tested for "level" differences between the two areas, while the interactions were tested for incremental variations in the effects for each GI measure. Statistical testing was performed to test for improvements in the models (implying metropolitan variations) and for incremental and net effects for each GI measure.

It should be noted that for all of the above analyses, diagnostics for cross-sectional dependence, heteroskedasticity, and spatial autocorrelation test were performed. Friedman's test for cross-sectional dependence showed that there was no cross-sectional dependence. The result of heteroskedasticity test recommended the use of robust for robust standard errors; hence, robust standard errors were utilized and are presented in all tables. Global Moran's I test for regression residual showed that there was no spatial autocorrelation. The regression residual of peak annual flow had a Moran's I value of 0.194 ($p=0.194$). As the data for this study were for only 2 years with gaps, the serial correlation test was not

Table 1 Conceptual measurement and hypothesized effects

	Variable	Type	Measurement	Hypothesized effects	Source
Streamflow	Annual peak flow	Dependent variable	Maximum annual flow at each stream gage station		USGS
	Mean annual flow	Dependent variable	Average discharge of the water year at each stream gage station		USGS
Overall green infrastructure (GI)	% of GI in the watershed	Independent variable	Area of GI/area of watershed	–	USDA
Green infrastructure location measures	% of GI in the 100-year floodplain	Independent variable	Area of GI outside of the 100-year floodplain/area of outside of the 100-year floodplain	–	USDA
	% of GI outside of the 100-year floodplain	Independent variable	Area of GI outside of the 100-year floodplain/area of outside of the 100-year floodplain	–	USDA
	% of GI in the 60-m buffer around floodplain	Independent variable	Area of GI in the 60-m buffer around floodplain/area of 60-m buffer around floodplain	–	USDA
Green infrastructure spatial pattern measures	Patch density (PD)	Independent variable	Number of patches per 100 hectare	–	USDA
	GYRATE_AM (correlation length)	Independent variable	Mean distance between each cell in a patch and the patch's centroid cells	–	USDA
Natural environmental factors	Watershed area	Control variable	Area of watershed	+	
	Drainage area	Control variable	Area of contributing drainage area	+	
	Floodplain area	Control variable	Percentage of area within the FEMA-defined 100-year floodplain	+	HGAC
	Stream density	Control variable	Total length of stream/area of watershed	+	NHD
	Slopes	Control variable	Average percent slope	+	USGS DEMs
	Precipitation	Control variable	Annual average rainfall	+	PRISM dataset
	Soils	Control variable	Average soil permeability	–	STATGO
Built environmental factor	Impervious surface	Control variable	Percent of impervious surface	+	NLCD

USGS US Geological Survey, *USDA* US Department of Agriculture, *HGAC* Houston–Galveston Area Council, *NHD* National Hydrography Dataset, *DEMs* digital elevation models, *PRISM* parameter elevation regression on independent slopes model, *STATAGO* State Soil Geographic, *NLCD* National Land Cover Data necessary. The multicollinearity issue was tested by running variance inflation factor (VIF) after conducting the least squares dummy variable model with the same variables.

Finally, Hausman test was conducted throughout the analysis to assess whether or not there were significant variations in the fixed and random effect estimates for time-variant variables. Such test was always significant with Prob (χ^2) < 0.05. For those predisposed to only focusing on within observation differences, these results are interpreted to mean that fixed effect model should be preferred. In this context, time-invariant control variables such as watershed area, drainage area, floodplain percentages, soil permeability, slope percentages, and stream density which are important factors for predicting streamflow should be excluded from the models. However, since random effect panel models allow for the inclusion of time-invariant variables as explanatory variable and allow for a more theoretically appropriate model specification when considering both within and between observation variations, random effect models were presented as well. When considering the overall results, particular attention was paid to assessments of green infrastructure that were significant across both types of models, since they were much more likely to be robust.

4 Result

4.1 Overall green infrastructure and peak annual flow

Table 2 presents a series of fixed and random effect panel models assessing the consequences of green infrastructure on peak annual flow, focusing on the overall percentage of green infrastructure within a watershed and with respect to the location of green infrastructure relative to the floodplain. Unfortunately, due to multicollinearity problems between total green infrastructure and its locational measures, separate sets of models were analyzed. Focusing first on the baseline set of models (1A Models), the control variables worked as expected. In the fixed effect model, the two time-variant indicators of precipitation and imperviousness had significant effects on peak annual flow. Specifically, precipitation had a significant positive effect on peak annual flow, suggesting that every millimeter of precipitation increased peak annual flow by 0.54%. Also, every percentage point of impervious surface in a watershed also increased peak annual flow by 36%. The random effects model suggests that watershed and drainage area also had significant positive effects while soil permeability significantly reduced peak annual flow across watersheds through time. Every square mile of watershed area increased peak flow by 0.27%, while every square mile of drainage area increased peak flow by 0.006%. On the whole, these patterns of findings with respect to the baseline control measures hold across all other model sets, with the exception of soil permeability and slope. Soil permeability tended to become insignificant once green infrastructure measures were introduced into the model while the watershed's slope tended to become positively albeit only marginally (0.1) significant after green infrastructure measures were introduced into the model.

The 2A Models added to the baseline models the percentage of watershed area associated with green infrastructure, and in both cases, adding overall green infrastructure significantly increased the respective R^2's of the models, in comparison to the appropriate base model. Whether considering the fixed or random effects model, in each case the consequences of green infrastructure were statistically significant and negative, having controlled for the baseline factors. These findings are consistent with the first hypothesis that overall green infrastructure should significantly reduce peak annual flow. However,

Table 2 Fixed and random effect panel model predicting peak annual flow 1

	1A Models		2A Models		3A Models						4A Models	
	Fixed	Random	Fixed	Random	Fixed	Random	Fixed	Random	Fixed	Random	Fixed	Random
Baseline control variables												
Watershed area		0.0026*** (0.0009)		0.0023*** (0.0009)		0.0027*** (0.0009)		0.0022** (0.0009)		0.0027*** (0.0008)		0.0025** (0.0010)
Drainage area		0.00005*** (0.00001)		0.00006*** (0.00001)		0.00006*** (0.00001)		0.00006*** (0.00001)		0.00006*** (0.00001)		0.00006*** (0.00001)
Floodplain %		0.0146 (0.0116)		0.0183 (0.0119)		0.0117 (0.0124)		0.0161 (0.0115)		0.0107 (0.0121)		0.0129 (0.0125)
Precipitation	0.0054*** (0.0007)	0.0040*** (0.0004)	0.0055*** (0.0007)	0.0043*** (0.0005)	0.0052*** (0.0006)	0.0041*** (0.0004)	0.0056*** (0.0007)	0.0043*** (0.0005)	0.0053*** (0.0006)	0.0041*** (0.0005)	0.0049*** (0.0008)	0.0042*** (0.0004)
Soil permeability		−0.0110** (0.0045)		−0.0056 (0.0051)		−0.0077 (0.0047)		−0.0063 (0.0052)		−0.0083* (0.0049)		−0.0066 (0.0053)
Impervious %	0.3576*** (0.1127)	0.2072*** (0.0046)	0.2202* (0.1105)	0.0137** (0.0056)	0.2179** (0.1048)	0.0163*** (0.0051)	0.2314** (0.1105)	0.0147*** (0.0055)	0.1928* (0.1051)	0.0174*** (0.0055)	0.2605** (0.1039)	0.0150*** (0.0056)
Slope %		0.0567 (0.0578)		0.1216* (0.0654)		0.1058* (0.0614)		0.1113* (0.0640)		0.0872 (0.0670)		0.1161* (0.0643)
Stream density		0.2773 (0.2403)		0.0940 (0.2452)		0.1042 (0.2562)		0.1347 (0.2356)		0.2214 (0.2473)		0.0867 (0.2495)
Overall GI variable												
Percentages of GI												
in the watershed			−0.0745*** (0.0220)	−0.0292** (0.0122)								
GI location variables												
Percentages of GI												
in the 100-year floodplain					−0.0799*** (0.0188)	−0.0214** (0.0092)					−0.1148*** (0.0377)	−0.0169 (0.0127)

Table 2 (continued)

	1A Models		2A Models		3A Models						4A Models	
	Fixed	Random	Fixed	Random	Fixed	Random	Fixed	Random	Fixed	Random	Fixed	Random
outside the 100-year flood-plain							−0.0737** (0.0239)	−0.0253** (0.0123)			0.0604 (0.0501)	−0.0096 (0.0171)
60-m buffer around flood-plain									−0.0931*** (0.0211)	−0.0155 (0.0145)		
Constant	−8.5670* (4.3842)	3.2013*** (0.7053)	0.4280 (4.7297)	4.9967*** (0.9407)	1.7720 (4.5300)	4.9270*** (0.9493)	−0.1997 (4.7144)	4.6975*** (0.9106)	2.8627 (4.4093)	4.2186*** (1.1320)	−0.5778 (4.51093)	5.1300*** (0.9492)
N	132	132	132	132	132	132	132	132	132	132	132	132
R-squared												
within	0.6057	0.5633	0.6519	0.6035	0.6985	0.6148	0.6447	0.5943	0.6865	0.5940	0.7071	0.6151
between		0.5665		0.5351		0.5151		0.5384		0.5259		0.5165
overall		0.5644		0.5785		0.5787		0.5745		0.5697		0.5795
Hausman test: Prob (χ^2)	0.0308		0.0069		0.0000		0.0085		0.0000		0.0000	

Standard errors are in parentheses

***$p < 0.01$; **$p < 0.05$; *$p < 0.1$

the magnitudes of the effects of green infrastructure differed considerably between the two models. In the fixed effect model, the results suggest that the peak annual flow decreased by 7.2% for every percent increase in overall green infrastructure, while in the random effects model there was a 2.9% decrease for every percent increase in overall green infrastructure. Both cases represent rather significant reductions in peak flow for the period under consideration.

4.2 Green infrastructure location and peak annual flow

The 3A Models assessed the consequences of the specific locations of green infrastructure within the watershed location variables on annual peak flow. In light of multicollinearity issues, three sets with only one of the locational variables in the model were presented, then a set with two of the locational measures. The first model set in 3A included only the percent of green infrastructure in the 100-year floodplain. This measure was negative and statistically significant, in both the fixed and random effects model. The effect in the fixed effects model suggests that with every percent increase in GI within the 100-year floodplain, peak annual flow decreased by 7.7%. Controlling for time-invariant measures reduced the effect to 2.1%. As can be seen in the next set of models, the effects of GI outside the floodplain appeared to be quite comparable, in that both measures were significant, have negative effects, and their magnitudes in the fixed (−7.1%) and the random (−2.5%) were similar to those for GI in the floodplain.

The final set of models in this series included measures of green infrastructure in the 60-m buffer around the floodplain. In the fixed effects model, the percent of GI in the 60-m buffer around the floodplain had a significant negative effect, as anticipated, and the coefficient's magnitude suggests that with every percentage point increase in GI in this buffer, peak annual flows decreased by 8.9%. However, when other time-invariant measures are controlled for, this effect became insignificant.

4.3 Green infrastructure spatial patterns and peak annual flow

Table 3 presents a series of fixed and random effect panel models assessing the consequences of green infrastructure on peak annual flow, focusing on the overall percentage of green infrastructure within a watershed and with respect to the location of green infrastructure relative to the floodplain, and also considering one of the spatial patterns of green infrastructure, patch density. Due to multicollinearity issues already explained for Table 2, separate sets of models were analyzed. Specifically, three sets of models are presented in Table 3 in that each set of models with the measure of %GI overall or with respect to location includes the associated patch density measures—hence, each model assessed not only the percentage of GI overall or with respect to particular locations within the watershed, but also the patch density of that percentage of GI. In general, the larger the patch density measure, the more contiguously clustered the %GI.

Table 4 presents a series of fixed and random effect panel models assessing the consequences of green infrastructure on peak annual flow, focusing on the overall percentage of green infrastructure within a watershed and with respect to the location of green infrastructure relative to the floodplain, and one of the spatial patterns of green infrastructure, GYRATE_AM.

Particularly, the 3C models assessed the consequences of the specific locations of green infrastructure within the watershed location variables and GYRATE_AM as

Table 3 Fixed and random effect panel model predicting peak annual flow 2

	2B Models		3B Models						4B Models	
	Fixed	Random	Fixed	Random	Fixed	Random	Fixed	Random	Fixed	Random
Baseline control variables										
Watershed area		0.0104*** (0.0032)		0.0027 (0.0024)		0.0062** (0.0029)		0.0023 (0.0023)		0.0072** (0.0028)
Drainage area		0.00008*** (0.00002)		0.00006*** (0.00001)		0.00005*** (0.00001)		0.00006*** (0.00001)		0.00005*** (0.00001)
Floodplain %		0.0129 (0.0126)		0.0114 (0.0126)		0.0074 (0.0127)		0.0107 (0.0122)		0.0029 (0.0138)
Precipitation	0.0040*** (0.0008)	0.0034*** (0.0005)	0.0052*** (0.0008)	0.0043*** (0.0005)	0.0039*** (0.0008)	0.0036*** (0.0005)	0.0048*** (0.0007)	0.0041*** (0.0005)	0.0039*** (0.0009)	0.0036*** (0.0005)
Soil permeability		−0.0085** (0.0037)		−0.0066 (0.0047)		−0.0073 (0.0048)		−0.0085* (0.0050)		−0.0060 (0.0050)
Impervious %	0.2546** (0.1221)	0.0147** (0.0061)	0.2289** (0.1106)	0.0172*** (0.0048)	0.2644** (0.1185)	0.0149** (0.0062)	0.2094* (0.1057)	0.0170*** (0.0055)	0.2846** (0.1157)	0.0175*** (0.0059)
Slope %		0.1494** (0.0746)		0.0984 (0.0607)		0.1244* (0.0708)		0.0853 (0.0724)		0.1206* (0.0689)
Stream density		0.0796 (0.2870)		0.1564 (0.2523)		0.2061 (0.2664)		0.2283 (0.2499)		0.2747 (0.2692)
Overall GI variable										
Percentages of GI										
in the watershed	−0.1302*** (0.0262)	−0.0574** (0.0226)								
GI location variables										
Percentages of GI										
in the 100-year floodplain			−0.0832** (0.0416)	−0.0067 (0.0135)					−0.0993 (0.0606)	0.0080 (0.0209)

Table 3 (continued)

	2B Models		3B Models						4B Models	
	Fixed	Random	Fixed	Random	Fixed	Random	Fixed	Random	Fixed	Random
outside the 100-year floodplain					−0.1348*** (0.0251)	−0.0510** (0.0206)			0.0208 (0.0568)	−0.04040* (0.0217)
60-m buffer around floodplain							−0.1033*** (0.0213)	−0.0152 (0.0147)		
GI spatial patterns variables										
PD (patch density)										
in the watershed	−0.0042*** (0.0014)	−0.0019* (0.0010)								
in the 100-year floodplain			−0.0002 (0.0020)	0.0010 (0.0007)					0.0007 (0.0021)	0.0018 (0.0011)
outside the 100-year floodplain					−0.0043*** (0.0013)	−0.0016* (0.0008)			−0.0028** (0.0014)	−0.0023** (0.0009)
60 m buffer around floodplain							−0.0008* (0.0005)	−0.00001 (0.00035)		
Constant	4.8992 (5.3019)	7.8787*** (1.9558)	1.5469 (6.2753)	3.2166* (1.3227)	5.0704 (4.9833)	7.2884*** (1.7456)	4.4306 (4.6506)	4.2567*** (1.4729)	1.1351 (6.2023)	5.4752*** (2.0175)
N	122	122	130	130	126	126	130	130	126	126
R-squared										
within	0.6637	0.6058	0.6977	0.6160	0.6794	0.6110	0.7052	0.5914	0.7292	0.6465
between		0.5529		0.5130		0.5446		0.5197		0.5276
overall		0.5870		0.5788		0.5870		0.5659		0.6029
Hausman test: Prob (χ^2)	0.0101		0.0001		0.0021		0.0000		0.0002	

Standard errors are in parentheses

***$p<0.01$; **$p<0.05$; *$p<0.1$

Table 4 Fixed and random effect panel model predicting peak annual flow 3

	2C Models		3C Models						4C Models	
	Fixed	Random	Fixed	Random	Fixed	Random	Fixed	Random	Fixed	Random
Baseline control variables										
Watershed area		0.0077** (0.0032)		0.0032 (0.0028)		0.0038 (0.0025)		0.0023 (0.0025)		0.0071** (0.0032)
Drainage area		0.00009*** (0.00002)		0.00007*** (0.00001)		0.00006*** (0.00001)		0.00006*** (0.00001)		0.00007*** (0.00001)
Floodplain %		0.0153 (0.0120)		0.0205 (0.0146)		0.0118 (0.0117)		0.0106 (0.0115)		0.0290** (0.0140)
Precipitation	0.0058*** (0.0008)	0.0042*** (0.0005)	0.0049*** (0.0008)	0.0040*** (0.0004)	0.0056*** (0.0008)	0.0042*** (0.0005)	0.0054*** (0.0007)	0.0041*** (0.0005)	0.0046*** (0.0009)	0.0040*** (0.0005)
Soil permeability		−0.0078** (0.0038)		−0.0062 (0.0050)		−0.0063 (0.0046)		−0.0084* (0.0050)		−0.0020 (0.0051)
Impervious %	0.2351** (0.1167)	0.0181*** (0.0062)	0.1985 (0.1235)	0.0137** (0.0059)	0.2112* (0.1217)	0.0217*** (0.0062)	0.2013* (0.1077)	0.0171*** (0.0056)	0.2396* (0.1233)	0.0182*** (0.0062)
Slope %		0.1233* (0.0682)		0.0953 (0.0608)		0.0969 (0.0729)		0.0838 (0.0664)		0.0906 (0.0719)
Stream Density		0.0814 (0.2544)		0.1452 (0.2517)		0.2313 (0.2578)		0.2289 (0.2488)		0.2605 (0.2626)
Overall GI variable										
Percentages of GI										
in the watershed	−0.1022*** (0.0327)	−0.0326** (0.0134)								
GI location variables										
Percentages of GI										
in the 100-year floodplain			−0.0604** (0.0241)	−0.0131 (0.0115)					−0.1179** (0.0458)	0.0041 (0.0148)

Table 4 (continued)

	2C Models		3C Models						4C Models	
	Fixed	Random	Fixed	Random	Fixed	Random	Fixed	Random	Fixed	Random
outside the 100-year floodplain					−0.1065*** (0.0358)	−0.0437*** (0.0145)			0.0550 (0.0600)	−0.0394** (0.0193)
60 m buffer around floodplain							−0.1070*** (0.0248)	−0.0155 (0.0170)		
GI spatial patterns variables										
GYRATE_AM (correlation length)										
in the watershed	0.0012 (0.0008)	0.0002 (0.0002)								
in the 100-year floodplain			−0.0013 (0.0012)	−0.0006 (0.0005)					−0.0005 (0.0013)	−0.0013** (0.0006)
outside the 100-year floodplain					0.0027* (0.0021)	0.0013** (0.0006)			0.0015 (0.0020)	0.0018*** (0.0007)
60 m buffer around floodplain							0.0027 (0.0028)	0.00006 (0.00187)		
Constant	−0.4107 (5.3174)	4.8126*** (0.9393)	1.9915 (5.2306)	4.5608*** (0.9481)	0.6648 (5.4379)	4.6803*** (0.9405)	2.7198 (4.6475)	4.2251*** (1.1260)	−0.0532 (5.5106)	4.3418*** (1.0663)
N	122	122	130	130	126	126	130	130	126	126
R-squared										
within	0.6309	0.5771	0.7067	0.6206	0.6454	0.5963	0.7168	0.5912	0.6913	0.6383
between		0.5598		0.5050		0.5612		0.5201		0.5782
overall		0.5709		0.5791		0.5855		0.5659		0.6145
Hausman test: Prob (χ^2)	0.0348		0.0000		0.0383		0.0000		0.0009	

Standard errors are in parentheses

***$p < 0.01$; **$p < 0.05$; *$p < 0.1$

one of the spatial pattern variables of green infrastructure on annual peak flow. The first model set in 3C included only the percent of green infrastructure in the 100-year floodplain and GYRATE_AM in the 100-year floodplain. Only the percentage of green infrastructure in the 100-year floodplain was negative and statistically significant in the fixed effect model ($p < 0.05$), suggesting that every percent increase in green infrastructure within the 100-year floodplain, peak annual flow decreased by 5.9%. However, it was not significant in the random effects model. Furthermore, and most importantly for these models, the spatial pattern variables (GYRATE_AM) were not statistically significant in either model. As can be seen in the next set of models, the effect of green infrastructure outside the floodplain again was statistically significant and negative in both the fixed and random effects models. The effect in the fixed effects model suggests that with every percent increase in green infrastructure outside the 100-year floodplain decreased 10.1%. The peak annual flow decreased by 0.27% for every 1-m-distance increase in GI patch between each cell in a patch and the patch's centroid. Controlling for time-invariant measures reduced the effect to 4.3 and 0.13%, respectively. Most interestingly, and perhaps disconcertingly, the spatial effects of GYRATE_AM were statistically significant in these models, albeit only marginally significant in the fixed effect model, but their effects were positive. The final set in this series included measures of green infrastructure within a 60-m buffer around the floodplain. In this set, the coefficient for green infrastructure was only significant in the fixed effects model. In that model, the percent of GI in the 60-m buffer around the floodplain had a significant negative effect, as anticipated, and the coefficient's magnitude suggests that with every percentage point increase in GI in this buffer, peak annual flows decreased by 10.2%. However, when other time-invariant measures were controlled for in the random effects model, the GI within the 60-m buffer became insignificant.

4.4 Summary of effectiveness of green infrastructure on peak annual flow

The series of fixed and random effect panel models assessing the consequences of green infrastructure on annual peak flow suggests that the percent of green infrastructure in the watershed was a significant negative determinant of annual peak flow. Furthermore, there was evidence that its locational features with respect to the floodplain may well have consequences, and spatial attribute related to patch density was significant as well. However, the GRYATE_AM measure did not seem to have much consequence in the majority of the models predicting annual peak flow.

4.5 Regional variations in green infrastructure effects on peak annual flow

Random effect panel models assessing regional variations in green infrastructure effects on annual peak flow suggest that while there did not appear to be differences in the consequences of %GI in the overall watersheds between Austin and Houston areas, in that green infrastructure significantly reduced peak annual flows in both areas, there were some variations with respect to GI's locational features (see Appendices A, B, C). In particular, the %GI in the floodplain and in the buffer around the floodplain appeared to be more effective in watersheds located in the Austin region in comparison with the Houston region. Specifically, these findings suggest that the consequences of green infrastructure whether considering the percent in the entire watershed or with respect to specific locations remained significant and negative—reducing annual peak flow for watersheds within the Austin area. Furthermore, increasing the patch density of GI, at least outside the floodplain could have added benefits. With respect to Houston watershed however, the result, after controlling for patch density, brought into question the benefits of GI both within the whole watershed and for specific locations, for reducing peak annual flow level. Furthermore, patch density did not help reducing peak annual flow. Also, spatial pattern related to GYRATE_AM did not show statistically significant results on reducing annual peak flow for both the Austin and Houston areas.

5 Discussion

When controlling for other control variables, the series of models assessing the consequences of green infrastructure indicated that green infrastructure had an important effect on streamflow. Based on the results of this study, it can be concluded that green infrastructure contributes to reduced annual peak flow in urbanized watersheds. The results of the various fixed and random effects models to test the consequences of the percent of green infrastructure for reducing annual peak flow showed that green infrastructure in the watershed, in the 100-year floodplain, and outside the 100-year floodplain was statistically significant for annual peak flow reduction. It can be interpreted that the effects of green infrastructure exist regardless of the locations; however, the slight differences are identified. In the fixed effect model, the peak annual flow decreased by 7.2% for every percent increase in overall green infrastructure, while in the random effects model there was a 2.9% decrease. As expected, the higher the percentages of green infrastructure in a watershed, the lower the annual peak flow. The effect in the fixed effects model suggests that with every percent increase in GI within the 100-year floodplain, peak annual flow decreased by 7.7%. Controlling for time-invariant measures reduced the effect to 2.1%. The effects of GI outside the floodplain appeared to be quite comparable, in that both measures were significant, had negative effects, and their magnitudes in the fixed (−7.1%) and the random (−2.5%) were similar to those for GI in the floodplain. The only differences between these two sets were with respect to the R^2 values where they were slightly higher in the models including the percent GI within the floodplain (fixed = 0.6985; random = 0.5787), as opposed to the percent GI outside the floodplain (fixed = 0.6447, random = 0.5745). Not only the amount of green infrastructure in a watershed functions as an important factor, but also the location of green infrastructure relative to the 100-year floodplain functions differently. While these differences were slight, particularly with respect to the random effects models, they perhaps suggest slightly greater consequences for preserving GI within floodplains when it comes to peak annual flows. In the fixed effects model, the percent of GI in the 60-m buffer around the floodplain had a significant negative effect, and the coefficient's magnitude suggests that with every percentage point increase in GI in this buffer, peak annual flows decreased by 8.9%. However, when other time-invariant measures were controlled for, this effect became insignificant. The result of the 4A models including both green infrastructures in the 100-year floodplain and outside of the 100-year floodplain variables perhaps gave some weight to the relative importance for retaining or expanding GI within the floodplain, but again the findings were mixed. Based on these consequences of green infrastructure in the watershed as well as in different locations relative to the 100-year floodplain, it could be suggested that preserving and implementing green infrastructure in the 100-year floodplains are most useful to reduce peak annual flow.

This study also tested a series of fixed and random effect panel models assessing the consequences of green infrastructure on streamflow, focusing on the overall percentage of green infrastructure within a watershed and with respect to the location of green infrastructure relative to the floodplain, and also considering the spatial patterns of green infrastructure, patch density, and correlation length. The results also point to the effectiveness of green infrastructure on annual peak flow reduction. Specifically, the percent of a watersheds green infrastructure as well as the density of the patches of green infrastructure had consequences on peak annual flow. Increasing the percent of GI within the watershed reduced peak flow, and increasing the density also had mitigative consequences, reducing the peak flow as well. These findings suggest that while there were substantial and significant reductions in peak flow with increase of GI within a watershed, but these reductions could be enhanced by increasing their density.

When just examining the percent of GI in the watershed, it appeared that increasing GI both in and outside the floodplain had negative consequences (see Table 3). However, just based on the consistency of results between the fixed and random effect models, it appeared that both the percent of GI and its patch density of GI outside the floodplain consistently had negative and significant consequences on annual peak flow. This implies that percent of a green infrastructure as well as the density of the patches of green infrastructure had consequences on peak annual flow outside the floodplain. From a planning perspective, this means that not only the percent of green infrastructure, and also the spatial patterns of green infrastructure are important factors that should be considered for strategical green infrastructure implementation for outside of the 100-year floodplain.

In comparison with the consequence of patch density, GYRATE_AM as one of green infrastructure's spatial pattern measures did not seem to have much consequence in the majority of the models predicting peak annual flow. Specifically, they showed no effect when focusing on total GI as a percent of the entire watershed, within the floodplain, as well as within a 60-m buffer. GYRATE_AM measures how far across a landscape a patch extends, either the patch shape is elongated with a higher GYRATE value, or it is comprised of compact patch shapes of the same size. Therefore, GYRATE_AM provides insights into the average distance that a streamflow can move across a landscape. However, since this measure does not explain the direction of the patch shape, (e.g., whether a patch is located perpendicular or parallel to a waterway), this spatial pattern may not have a strong statistical relationship with streamflow.

Our sample of watersheds was drawn from two major metropolitan areas in Texas that are subject to flooding, the Austin and Houston metropolitan areas. Since these two areas vary considerably with the terrain characteristics, the consequences for the effectiveness of GI may vary across these two areas. The random effects models assessing these regional variations in the consequences for green infrastructure on annual peak flow suggest that while there appeared to be no differences in the consequences of %GI in the overall watersheds between Austin and Houston areas, in that green infrastructure significantly reduced annual flows in both areas, there were some variations with respect to GI's locational features. In particular, the %GI in the floodplain and in the buffer around the floodplain appeared to be more effective in watersheds located in the Austin region in comparison with the Houston region. However, these findings must be tempered by the results when controlling for spatial features as well. The regional variation analysis showed that the consequences of green infrastructure whether considering the percent in the entire watershed or with respect to specific locations remained significant and negative—reducing peak annual flow for watersheds within the Austin area. Furthermore, increasing the patch density of GI at least outside the floodplain can have added benefits. The results of the random effects models assessing variations in the consequences for green infrastructure on streamflow imply that the geographic characteristics of the Austin metropolitan area (such as its steep slope, as compared to the flat slope of the Houston metropolitan area) are one of the reasons green infrastructure works better to reduce peak annual flow. Furthermore, GYRATE_AM, a variable that explains patch extensiveness, did not show statistically significant results on reducing annual peak flow for both the Austin and Houston areas. This again emphasizes that this measurement is not significant enough to capture the relationship between the green infrastructure spatial pattern and streamflow.

6 Policy implications

The results of this study indicate that green infrastructure implementation in urban areas has important influences on streamflow, especially annual peak flow. This conclusion underscores the importance of protecting and implementing green infrastructure in order to maintain existing ecosystem functions, as well as to attenuate streamflow in urban areas.

Even though green infrastructure has a significant effect on streamflow, it is both difficult and expensive to preserve the existing green infrastructure and implement green infrastructure in urban areas such as the Austin and Houston metropolitan areas. Therefore, several policy approaches should be followed to acquire green infrastructure in critical places vulnerable to runoff. These strategies include conservation easements, overlay zones, the transfer of development rights, and density bonuses (Brody and Highfield 2013). For example, Austin has proposed the use of green infrastructure to protect environmentally sensitive areas and integrate nature into the city. The city of Austin has been purchasing property to create the Water Quality Protection Lands, and they applied some of these strategies in their efforts to acquire new green infrastructure. In addition to this approach to implement green infrastructure, several other policy implications will be helpful for preserving existing green infrastructure and balancing urban development and green infrastructure implementation. Integrated, stakeholder-driven approach for a Green Infrastructure Spatial Planning (GISP) model to maximize ecosystem services can be applied to cities planning future green infrastructure (Meerow and Newell 2017). The spatial distribution of climate justice in green infrastructure planning can also support decision making in community planning not only to prioritize green infrastructure, but also to address equity in climate change adaptation (Cheng 2016). Also, for significant implementation, green infrastructure on private property, appropriate education programs and incentives for green infrastructure implementation should be provided. Policy implication to provide free green infrastructure or to accrue a savings with implementation will increase citizen's willingness (Baptiste et al. 2015).

The results of this study also indicate that the spatial pattern of the green infrastructure significantly affects the amount of streamflow, even when controlling for multiple variables. The results emphasize that not only floodplain management itself, but also management outside of the floodplain should be planned. Also, high patch density across different locations appears to contribute to reduced streamflow. For example, a series of panel models of overall green infrastructure and different locational aspects of green infrastructure showed that preserving green infrastructure in the 100-year floodplain would be most useful for reducing peak annual flow. As greater proportion of 100-year floodplain within a watershed has significantly positive effect on flood damage (Brody et al. 2017), policy for preserving green infrastructure in the 100-year floodplain is important. To preserve existing green infrastructure, different policy options to encourage the development out of the 100-year floodplain can be suggested. These options are regulatory approaches, incentive-based approaches—density bonuses, transfer of development rights, clustering and conservation easements (Brody et al. 2013; Bengston et al. 2004). Also, to increase green infrastructure in the 100-year floodplains, zoning ordinance for regulating land use including tree canopy cover can be suggested. For example, Chesapeake, Virginia, required through its zoning ordinance the maintenance of different percentages of canopy cover (Hartel 2003). This canopy requirements included 10, 15, and 20% mature canopy for non-residential, multi-family residential, and single-family/duplex residential uses, respectively. Similar strategy for zoning ordinance for the 100-year floodplains will be helpful to implement green infrastructure.

7 Limitation and future research

One of the major constraints of this study was sample size due to the limited amount of available streamflow data and its consequences for the analysis strategy. Issues of multicollinearity also have been compounded leading to larger standard errors and less reliable estimates. In addition to the limited streamflow data and lack of stream gage stations, watershed delineation was not possible in some parts of the study area.

One limitation of this study is the potential for internal validity threats such as history threat and selection bias (Babbie 2011). This study analyzed the relationship between green infrastructure and streamflow by using a longitudinal analysis to reduce the history threat. However, as this study considered only two time periods, water years 2004 and 2010, it did not include data generated between 2004 and 2010. Therefore, there is a potential internal history threat. Another limitation of this study is a potential external validity threat due to the fact the effectiveness of green infrastructure for streamflow reduction had only been observed in the Austin and Houston metropolitan urban areas. In order to generalize the effect of green infrastructure, further research in different urban settings should be pursued.

Although this study provides important information about the relationship between green infrastructure and streamflow, future studies should endeavor to understand this relationship more fully. This study analyzed only two landscape metrics for green infrastructure spatial patters. Further research focused on testing additional green infrastructure spatial patterns will provide a better understanding of the effectiveness of green infrastructure on streamflow reduction. Also, how local jurisdictions implement green infrastructure as a mean of effective non-structural mitigation for streamflow reduction is suggested for future research that will be analyzed by considering green infrastructure-related Community Rating System (CRS) activities as a control variable. In this same way, CRS activities can be analyzed for their relationship to green infrastructure implementation. More detailed analysis of spatial distribution of curve number (CN) and potential infiltration and streamflow is suggested for future research, since high-resolution dataset for green infrastructure measurement employed for this research is available to differentiate green infrastructure in dense urban environments.

This research examined only a two-year time frame in 2004 and 2010. Future investigations should include a broader time frame by incorporating more recent year's green infrastructure and streamflow data. Also, new measurement of green infrastructure using 1-m high-resolution imagery should be analyzed with regard to different types of green infrastructure and land use information. As different land uses have different development patterns, variation in green infrastructure exists across land use types (Hill et al. 2010). In order to measure these variations across different land uses, an empirical study based on higher resolution data should be undertaken. Such future work will provide essential information about the usefulness of green infrastructure in urban areas, and how green infrastructure distribution across different land use types affects effectiveness of green infrastructure on reducing streamflow and flooding in urban areas.

This study has several contributions to the research on green infrastructure and streamflow. This study empirically evaluated the impacts of green infrastructure within a watershed and with respect to the location of green infrastructure relative to the floodplain on peak annual flow. In terms of locational aspects, it may not simply consider the amount of green infrastructure, but also locational measurements and spatial patterns. The result of this study will contribute to establish guidelines for appropriate amount and spatial patterns of green infrastructure. The findings of this study will also help provide additional decision support tools for urban planners, policy makers, and community residents, as they evaluate the existing green infrastructure in communities and make decisions regarding the implementation of new green infrastructure to contribute reduced peak annual flow in urbanized watersheds.

Appendix A

See Table 5.

Table 5 Random effect panel model with a dummy variable predicting peak annual flow Phase 1

	2A Model	3A Models			4A Model
Baseline control variables					
Watershed area	0.0023** (0.0009)	0.0023** (0.0011)	0.0022** (0.0010)	0.0030*** (0.0008)	0.0021* (0.0012)
Drainage area	0.00006*** (0.00001)	0.00006*** (0.00001)	0.00006*** (0.00001)	0.00006*** (0.00001)	0.00006*** (0.00001)
Floodplain %	0.0249* (0.0127)	0.0248** (0.0121)	0.0214* (0.0124)	0.0256** (0.0108)	0.0234* (0.0124)
Precipitation	0.0042*** (0.0005)	0.0036*** (0.0004)	0.0043*** (0.0005)	0.0038*** (0.0005)	0.0036*** (0.0005)
Soil permeability	−0.0068 (0.0059)	−0.0104* (0.0054)	−0.0062 (0.0061)	−0.0110* (0.0057)	−0.0078 (0.0067)
Impervious %	0.0151*** (0.0058)	0.0212*** (0.0055)	0.0156*** (0.0058)	0.0221*** (0.0055)	0.02180*** (0.0061)
Slope %	0.1384 (0.0892)	0.1248* (0.0699)	0.1118 (0.0904)	0.1380* (0.0813)	0.0754 (0.0861)
Stream density	0.0424 (0.2317)	0.1916 (0.2166)	0.0961 (0.2300)	0.2133 (0.2109)	0.3116 (0.2353)
Regional dummy variable					
Houston	−2.2339 (1.4629)	−6.3230*** (1.8484)	−1.1326 (1.5462)	−5.5780*** (1.9897)	−5.2707*** (2.0368)
Overall GI variable					
GI % in watershed	−0.0554** (0.0233)				
GI % in watershed*Houston	0.0361 (0.0278)				
GI location variables					
GI % in floodplain		−0.0901*** (0.0242)			−0.1033*** (0.0350)
GI % in floodplain*Houston		0.0906*** (0.0262)			0.1141*** (0.0356)
GI % out of floodplain			−0.0378 (0.0248)		0.0317 (0.0352)
GI % out of floodplain*Houston			0.0167 (0.02880)		−0.0493 (0.0394)
GI % in floodplain buffer				−0.0808*** (0.0281)	
GI % in floodplain buffer*Houston				0.0859*** (0.0319)	
Constant	6.6494*** (1.6064)	9.6250*** (1.9279)	5.5217*** (1.6258)	8.3490*** (2.1334)	8.5800*** (1.9524)
N	132	132	132	132	132
R-squared					
within	0.5991	0.6750	0.5904	0.6225	0.6953
between	0.5569	0.5218	0.5503	0.5561	0.5041
overall	0.5842	0.6185	0.5763	0.5987	0.6245
Test for joint effect: Prob (χ^2)	0.2752	0.0023	0.7032	0.0195	0.0101

This model includes a dummy variable (Houston), regional dummy variable. It equals one for Houston and zero for Austin. Test for joint effect is for testing joint effect of a regional dummy variable and a dummy interaction. Standard errors are in parentheses

***$p<0.01$; **$p<0.05$; *$p<0.1$

Appendix B

See Table 6.

Table 6 Random effect panel model with a dummy variable predicting peak annual flow Phase 2

	2B Model	3B Models			4B Model
Baseline control variables					
watershed area	0.0088** (0.0038)	−0.0010 (0.0024)	0.0059* (0.0027)	0.0021 (0.0023)	0.0051* (0.0029)
Drainage area	0.00007*** (0.00002)	0.00007*** (0.000008)	0.00005*** (0.00001)	0.00005*** (0.000007)	0.00006*** (0.00002)
Floodplain %	0.0109 (0.0128)	0.0235* (0.0135)	0.0100 (0.014)	0.0289** (0.0126)	0.0143 (0.0131)
Precipitation	0.0039*** (0.0005)	0.0039*** (0.0005)	0.0040*** (0.0005)	0.0041*** (0.0005)	0.0034*** (0.0005)
Soil permeability	−0.0109** (0.0047)	−0.0076 (0.0065)	−0.0098** (0.0048)	−0.0130*** (0.0050)	−0.0111** (0.0055)
Impervious %	0.0155** (0.0069)	0.0207*** (0.0056)	0.0150** (0.0067)	0.0232*** (0.0055)	0.0196*** (0.0062)
Slope %	0.1871** (0.0931)	0.0907 (0.0680)	0.1657* (0.0885)	0.1537** (0.0752)	0.1168 (0.0781)
Stream density	0.1366 (0.2507)	0.3497 (0.2482)	0.1837 (0.2319)	0.2711 (0.2279)	0.2767 (0.2503)
Regional dummy variable					
Houston	−13.2989*** (1.6017)	−13.7455*** (4.2832)	−13.1407*** (1.6420)	−9.0939*** (2.0210)	−19.3203*** (3.9244)
Overall GI variable					
GI % in watershed	−0.1401*** (0.0247)				
GI % in watershed*Houston	0.1649*** (0.0235)				
GI location variables					
GI % in floodplain		−0.1263** (0.0519)			−0.1484*** (0.0556)
GI % in floodplain*Houston		0.1655*** (0.0497)			0.1571*** (0.0572)
GI % out of floodplain			−0.1349*** (0.0244)		−0.0484 (0.0422)
GI % out of floodplain*Houston			0.1616*** (0.0242)		0.0705 (0.0444)
GI % in floodplain Buffer				−0.0757*** (0.0286)	
GI % in floodplain buffer*Houston				0.0899*** (0.0304)	
GI spatial patterns variables					
PD (patch density)					
PD in watershed	−0.0047*** (0.0009)				
PD in watershed*Houston	0.0073*** (0.0010)				

Table 6 (continued)

	2B Model	3B Models			4B Model
PD in Floodplain		−0.0029 (0.0025)			−0.0038 (0.0025)
PD in floodplain*Houston		0.0054** (0.0025)			0.0038 (0.0028)
PD out of floodplain			−0.0044*** (0.0008)		−0.0028*** (0.0009)
PD out of floodplain*Houston			0.0071*** (0.0009)		0.0049*** (0.0014)
PD in floodplain buffer				−0.0008 (0.0005)	
PD in floodplain buffer*Houston				0.0019*** (0.0005)	
Constant	14.1482*** (2.0408)	13.0892*** (4.8342)	13.7661*** (1.976)	9.2951*** (2.1111)	20.0120*** (4.2493)
N	122	130	126	130	126
R-squared					
within	0.7736	0.7431	0.7788	0.7002	0.8190
between	0.5967	0.4823	0.6061	0.5590	0.6099
overall	0.7127	0.6442	0.7181	0.6485	0.7463
Test for joint effect: Prob (χ^2)	0.0000	0.0058	0.0000	0.0000	0.0000

This model includes a dummy variable (Houston), regional dummy variable. It equals one for Houston and zero for Austin. Test for joint effect is for testing joint effect of a regional dummy variable and a dummy interaction. Standard errors are in parentheses

***$p < 0.01$; **$p < 0.05$; *$p < 0.1$

Appendix C

See Table 7.

Table 7 Random effect panel model with a dummy variable predicting peak annual flow Phase 3

	2C Model	3C Models			4C Model
Baseline control variables					
Watershed area	0.0064** (0.0032)	0.0023 (0.0028)	0.0030 (0.0023)	0.0018 (0.0025)	0.0056 (0.0034)
Drainage area	0.00008*** (0.00002)	0.00006*** (0.00001)	0.00005*** (0.00001)	0.00006*** (0.00001)	0.00006*** (0.00002)
Floodplain %	0.0227* (0.0124)	0.0267* (0.0137)	0.0286** (0.0126)	0.02382** (0.0104)	0.0380*** (0.0133)
Precipitation	0.0042*** (0.0005)	0.0036*** (0.0005)	0.0042*** (0.0005)	0.0038*** (0.0005)	0.0034*** (0.0005)
Soil permeability	−0.0092** (0.0046)	−0.0094* (0.0057)	−0.0054 (0.0055)	−0.0102* (0.0058)	−0.0050 (0.0059)
Impervious %	0.0202*** (0.0070)	0.0200*** (0.0063)	0.0256*** (0.0065)	0.0235*** (0.0056)	0.02884*** (0.0073)
Slope %	0.1331 (0.0915)	0.1169 (0.0771)	0.0737 (0.0890)	0.1096 (0.0783)	0.0446 (0.0843)
Stream density	0.0490 (0.2483)	0.2040 (0.2262)	0.1529 (0.2363)	0.2121 (0.2174)	0.3636 (0.2590)
Regional dummy variable					
Houston	−2.5088 (1.6707)	−5.6693*** (1.7006)	−3.3195** (1.5702)	−6.3287*** (2.3447)	−6.9082*** (1.6429)
Overall GI variable					
GI % in watershed	−0.0647** (0.0269)				
GI % in watershed*Houston	0.04040 (0.0321)				
GI location variables					

Table 7 (continued)

	2C Model	3C Models			4C Model
GI % in floodplain		−0.0731*** (0.0257)			−0.0947** (0.0371)
GI % in floodplain*Houston		0.0723*** (0.0276)			0.1086*** (0.0389)
GI % out of floodplain			−0.08415*** (0.0260)		−0.0043 (0.0420)
GI % out of floodplain*Houston			0.0472 (0.0322)		−0.0284 (0.0460)
GI % in floodplain buffer				−0.0995*** (0.0361)	
GI % in floodplain buffer*Houston				0.0887** (0.0441)	
GI spatial patterns variables					
GYRATE_AM (correlation length)					
GYRATE_AM in watershed	0.0003 (0.0003)				
GYRATE_AM in watershed*Houston	−0.00002 (0.0003)				
GYRATE_AM in floodplain		−0.0010 (0.0012)			−0.0013 (0.0011)
GYRATE_AM in floodplain*Houston		0.0010 (00012)			0.0007 (0.0010)
GYRATE_AM out of floodplain			0.0017** (0.0008)		0.0017 (0.0011)
GYRATE_AM out of floodplain*Houston			−0.0001 (0.0008)		0.00003 (0.0012)
GYRATE_AM in floodplain buffer				0.0020 (0.0023)	

Table 7 (continued)

	2C Model	3C Models			4C Model
GYRATE_AM in Floodplain buffer*Houston				0.0021 (0.0032)	
Constant	6.7254*** (1.6999)	9.0222*** (1.6588)	7.0917*** (1.6725)	9.3630*** (2.4208)	9.5642*** (1.8425)
N	122	130	126	130	126
R-squared					
within	0.5701	0.6944	0.5900	0.6297	0.7321
between	0.5926	0.5031	0.6362	0.5524	0.5781
overall	0.5775	0.6241	0.6056	0.6020	0.6738
Test for joint effect: Prob (χ^2)	0.4538	0.0003	0.0626	0.0067	0.0000

This model includes a dummy variable (Houston), regional dummy variable. It equals one for Houston and zero for Austin. Test for joint effect is for testing joint effect of a regional dummy variable and a dummy interaction. Standard errors are in parentheses

***$p<0.01$; **$p<0.05$; *$p<0.1$

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