Fourth Quarterly Report

Longitudinal Assessment of Development Composition and Spatial Patterns of Green Infrastructure for Effective Flood Control in Growing and Shrinking US Metropolitan Areas

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Executive summary

This study empirically assesses the longitudinal impacts of the development composition and spatial patterns of green infrastructure on urban runoff in two Midwestern regions: the Chicago-Naperville and Detroit-Warren-Ann Arbor combined statistical areas (CSAs). These two regions have demonstrated contradictory land development trends in response to population changes occurring in the last few decades. Local investments have focused more on infill housing development to accommodate population growth in the Chicago-Naperville CSA, while the constrained tax revenues in the shrinking Detroit-Warren-Ann Arbor CSA have led municipalities to focus on revitalizing blighted vacant lots, renovating them to be open green spaces for city beautification. Yet, due to climate change, increasing storm intensity and frequency are continuing to threaten both regions and exacerbate flood exposure more than ever before. This study hypothesizes that the contrasting trends in demographic transition and land development approaches in these areas have distinctively shaped the trajectory of flood risk over time. The major purposes of this study are to: 1) monitor the temporal and spatial patterns of floods and land use in association with demographic changes in both budding and depopulated regions, and 2) identify the longitudinal impacts of the quantity and quality of urban development and green infrastructure on runoff depth and peak flow. The research findings will be useful to policymakers, developers, water resource managers, and communities seeking to formulate strategies for future land development and green infrastructure plans in response to demographic changes, while also securing local flood storage capacity.

After successful completion of the third-quarter task of measuring the climate and biophysical conditions and running basic statistical models, the fourth-quarter task focused on developing advanced statistical models, such as quantile regression and panel data models, predicting the statistical relationship between key land use factors and runoff yields, and recommending adjusted land use policy orientations for future development.

1. Introduction

Issues related to flooding have become severe in the Chicago-Naperville and Detroit-Warren-Ann Arbor combined statistical areas (CSAs) in the Midwestern United States, though the two regions have demonstrated different land development trends in association with their contradictory population changes. The Chicago-Naperville CSA is a budding region, with a 3.8% population growth from 2000 to 2019 (US Census Bureau, 2021) and a predicted additional 25% growth by 2040 (Chicago Metropolitan Agency for Planning, 2010). The major plan for the region to accommodate its increasing housing and amenity needs is to redevelop vacant lots (Chicago Metropolitan Agency for Planning, 2010; Ramsey, 2012; US Census Bureau, 2020). Conversely, the Detroit-Warren-Ann Arbor CSA, a shrinking region, experienced a 2.4% population decline from 2000 to 2019, and the trend is ongoing (US Census Bureau, 2021). The number of vacant lots in this region is expected to increase in the future (Detroit Future City, 2016). Despite these opposite trajectories of population change and land development, both the Chicago-Naperville and Detroit-Warren-Ann Arbor CSAs have attempted to expand their quantity and quality of green infrastructure (GI) to mitigate the impact of urban flooding (City of Chicago, 2015; Detroit Future City, 2013, 2016). For example, the City of Chicago has put forward a gray-green combined infrastructure plan to control urban floods, mainly focusing on retrofits of existing developed areas (City of Chicago, 2015). Contrastingly, because of decreasing tax revenue, the City of Detroit has prioritized the revitalization of low-priced vacant lots into blue-green infrastructure (Detroit Future City, 2019; Nassauer et al., 2018; Steis-Thorsby et al., 2020).

Given these conditions, it is still unclear how varying GI and development compositions and configurations have longitudinally shaped the flooding response of cities. The major purposes of this study included: 1) exploring differences in land use quantity and quality in growing and shrinking regions, and 2) identifying their longitudinal and cross-sectional impacts on annual runoff depth and peak flow in response to long-term storm events.

This fourth-quarter task focused on developing advanced statistical models (i.e., panel data and quantile regression models) and analyzing the empirical relationship between land use factors and runoff yields; the results are earmarked for use in manuscript publications and conference presentations.

2. Method

2.1. GI pattern variables

In the final models, four FRAGSTATS indicators at a class level were selected to analyze the spatial and temporal trends of changes in the size and connectivity of development and GI patches: percentage of landscape (PLAND), largest patch index (LPI), radius of gyration (GYRATE), and patch cohesion index (COHESION). The size of each land use pattern was analyzed by PLAND and LPI (Mcgarigal, 2015). PLAND was used to measure the size proportion of land use types in watersheds. A higher PLAND value represented a much larger area of selected land use. LPI quantified the percentage of the largest patch in a watershed. Higher LPI values indicated patches in watersheds that had more dominant edges. The connectivity of land use was evaluated by GYRATE and COHESION (Mcgarigal, 2015). GYRATE, known as a correlation length, denoted the extent of each patch of a selected land use. COHESION represented the aggregation and clumpiness of patches. Higher GYRATE and COHESION jointly implied more elongated, connected, and clumped patterns of land use patches.

To test different contributions of GI patterns to runoff generation by geographic location and demographic characteristic, interaction terms with the Chicago-Naperville and Detroit-Warren-Ann Arbor

CSAs were added to model specification. By multiplying GI pattern indicators by the CSA dummy variable (0: Detroit-Warren-Ann Arbor CSA and 1: Chicago-Naperville CSA), the interaction effects were assessed.

The shape and isolation patterns of GI and developed areas at the class level, including edge density (ED), shape index (SHAPE), contiguity index (CONTIG), proximity index (PROX), Euclidean nearest neighbor distance (ENN), patch density (PD), and connectance index (CONNECT) were also measured and their impacts examined. They were dropped in the final models because of their non-significant associations with runoff yields and high multicollinearity. Finally, four indexes quantifying only the size and connectivity of the combined GI and developed area were calculated for 99 watersheds, using FRAGSTATS for the years 2001, 2006, 2011, and 2016.

2.2. Statistical analysis

Advanced econometric models such as panel data and quantile regression were developed after the basic pooled ordinary least squares (OLS) regression models were tested (in the previous task). To longitudinally explore the performance of land use patterns in modifying surface flow regimes, a random effects (RE) panel data model was used to enhance the validity of the results. However, the RE model assumed a constant impact of explanatory variables on runoff yield. Considering that land use impacts can be conditional based on the magnitude of runoff yield, an advanced statistical method was needed to better explain the data structure. Thus, quantile regression models were developed to estimate how the performance of GI and development quantity and quality affected each quantile of runoff depth and peak flow. The 0.05, 0.25, 0.50, 0.75, 0.95 quantiles of runoff yields were selected for this research.

Table 1. Construct variables, data sources, and analytical tools.

Construct	**Variable (acronym)**	**Description/Formula**	**Unit**	**Source**
Dependent variables				
	Runoff depth	Annual runoff depth per unit area in 2001, 2006, 2011, and 2016	mm	USGS
	Peak flow rate	Annual peak streamflow in 2001, 2006, 2011, and 2016	m^3/s	USGS
Independent variables				
Imperviousness variables				
	Impervious ratio (TIA)	Average impervious ratio in 2001, 2006, 2011, and 2016	%	USGS's NLCD
	Hydraulic connectivity (H conn)	$DCIA/_{TIA} \times (100)$	%	-
Land use pattern variables				
Size	Percentage of landscape (PLAND)	$\sum_{j=1}^{n} a_{ij}/A \times (100)$	%	USGS's NLCD
	Largest patch index (LPI)	$\max_{j=1}^{n} (a_{ij}) / A \times (100)$	%	USGS's NLCD
Connectivity	Radius of gyration (GYRATE)	$\sum_{r=1}^{z} \frac{h_{ijr}}{z}$	m	USGS's NLCD
	Connectance index (CONNECT)	$\left[\frac{\sum_{j\neq k}^{n} c_{ijk}}{\frac{n_i(n_i-1)}{2}}\right](100)$	%	USGS's NLCD
Control variables				
Climate variables				
	Annual precipitation (P)	Annual precipitation in 2001, 2006, 2011, and 2016	mm	PRISM Climate Data
	24-hour daily precipitation (P24h)	24-hour daily precipitation on the date of annual peak flow in 2001, 2006, 2011, and 2016	mm	PRISM Climate Data
	3-month antecedent wetness (P3m)	3-month wetness prior to the year of precipitation in 2001, 2006, 2011, and 2016	mm	PRISM Climate Data

Biophysical variables	5-day antecedent wetness (P5d)	5-day wetness prior to the date of annual peak flow in 2001, 2006, 2011, and 2016	mm	PRISM Climate Data
	Slope	Mean slope of the watershed	%	NHDPlus
	Saturated hydraulic conductivity (Ksat)	Mean saturated hydraulic conductivity of the watershed	μm/s	SSURGO
	Number of reservoirs	Number of reservoirs in 2001, 2006, 2011, and 2016	-	Google Earth
Location and time variables	Watershed area	Area of the watershed	km^2	USGS
	CSA	Detroit-Warren-Ann Arbor CSA (0) and Chicago-Naperville CSA (1)	0/1	-
	Year	2001, 2006, 2011, and 2016	0/1	-

GI land use patterns (including combined forest, grassland, shrub, and wetland classes) and developed areas were computed separately.

USGS's NLCD = United States Geological Survey's National Land Cover Dataset; TIA = Total impervious area; DCIA = Directly connected impervious area; PRISM = Parameter-elevation regressions on independent slopes model; NHDPlus = National hydrography dataset plus; SSURGO = Soil survey geographic database.

a_{ij} = Area (m^2) of patch ij; A = Total landscape area (m^2); h_{ijr} = Distance (m) between cell ijr and the centroid of patch ij, based on cell-center-to-cell-center distance; z = Total number of cells in the landscape; c_{jik} = Joining between patches j and k (0 = unjoined, 1 = joined) of the corresponding patch type (i), based on a user-specified threshold distance; n_i = Number of patches in the landscape of the corresponding patch type (class). FRAGSTATS Formula source: McGarigal (2015)

3. Results

3.1. Effects of impervious compositions on runoff depth

The effects of total impervious area (TIA) and hydraulic connectivity were examined in the pooled OLS, RE panel data, and quantile regression models (see Table 2). Both TIA and hydraulic connectivity were positively associated with runoff depth. Overall, the models explained about 38.4% to 68.9% of the variance in the relationship between impervious compositions and runoff depth. In general, the runoff depth in the Detroit-Warren-Ann Arbor CSA, a depopulating region with an increasing number of vacant lots, was significantly influenced by TIA rather than hydraulic connectivity. In contrast, hydraulic connectivity (instead of TIA) played a more important role in the Chicago-Naperville CSA, a growing city actively redeveloping vacant lands. With a 1% increase in TIA in the Detroit-Warren-Ann Arbor CSA, the runoff depth increased by 0.72% to 1.53%; every 1% increase in hydraulic connectivity in the Chicago-Naperville CSA resulted in a 0.38% to 0.69% increase in runoff depth.

In addition, in most models, annual precipitation and three-month antecedent wetness demonstrated a consistent, significantly positive association with runoff depth ($p < 0.001$) when controlling for all other variables.

Table 2. Results of the basic regression analyses predicting runoff depth (excluding land use patterns).

Index	OLS	RE	Q.05	Q.25	Q.50	Q.75	Q.95
Main effects							
Impervious ratio (TIA)	0.0072*** (0.0016)	0.0070** (0.0023)	0.0027 (0.0040)	0.0070* (0.0030)	0.0082** (0.0014)	0.0095*** (0.0019)	0.0153*** (0.0029)
Hydraulic connectivity (H_conn)	0.0013* (0.0007)	0.0015 (0.0009)	-0.0002 (0.0018)	0.0010 (0.0011)	0.0016* (0.0008)	0.0006 (0.0005)	0.0017 (0.0018)
Chicago interaction effects							
CSA(1)*TIA	0.0006 (0.0025)	0.0016 (0.0038)	0.0001 (0.0053)	-0.0015 (0.0040)	0.0029 (0.0026)	0.0014 (0.0022)	-0.0106* (0.0048)
CSA(1)*H_conn	0.0046*** (0.0012)	0.0044* (0.0018)	0.0069* (0.0030)	0.0041* (0.0018)	0.0038** (0.0015)	0.0051*** (0.0011)	0.0049 (0.0032)
Control variables							

Annual precipitation	0.0011*** (0.0002)	0.0014*** (0.0002)	0.0010 (0.0006)	0.0011*** (0.0003)	0.0009*** (0.0002)	0.0009*** (0.0002)	0.0010* (0.0004)
3-month antecedent wetness	0.0037*** (0.0005)	0.0035*** (0.0003)	0.0042*** (0.0009)	0.0040*** (0.0007)	0.0032*** (0.0006)	0.0033*** (0.0004)	0.0024*** (0.0005)
Mean slope	0.0136 (0.0217)	0.0025 (0.0350)	0.0150 (0.0396)	0.0013 (0.0287)	0.0162 (0.0212)	0.0058 (0.0125)	-0.0132 (0.0394)
K_{sat}	0.0033 (0.0020)	0.0046 (0.0029)	0.0030 (0.0076)	0.0052 (0.0048)	0.0026 (0.0026)	0.0035 (0.0027)	-0.0001 (0.0067)
Number of reservoirs	0.0018 (0.0025)	0.0041 (0.0040)	-0.0013 (0.0038)	0.0007 (0.0036)	0.0008 (0.0019)	0.0040 (0.0027)	0.0019 (0.0044)
CSA	0.1795*** (0.0384)	0.1825*** (0.0515)	0.1011 (0.1007)	0.0911 (0.0636)	0.1890*** (0.0357)	0.2935*** (0.0512)	0.3542*** (0.0965)
2001	0.2173*** (0.0557)	0.1999*** (0.0365)	0.2286* (0.0935)	0.2769*** (0.0707)	0.1580* (0.0660)	0.1521*** (0.0431)	0.1471 (0.1518)
2006	0.0559 (0.0716)	-0.0080 (0.0519)	0.0445 (0.1399)	0.0843 (0.1078)	0.0555 (0.0857)	0.0634 (0.0565)	0.0452 (0.0832)
2011	0.4000*** (0.0812)	0.3294*** (0.0553)	0.5648*** (0.1680)	0.4761*** (0.1213)	0.3335** (0.1034)	0.3303*** (0.0805)	0.2365 (0.1471)
Adj. R^2	0.587						
Within R^2		0.689					
Pseudo-R^2			0.461	0.384	0.397	0.454	0.424
Degree of freedom	267	267	267	267	267	267	267

OLS = Pooled OLS model; RE = Random effects panel data model; Q.05 = quantile regression model at level 0.05; Q.25 = quantile regression model at level 0.25; Q.50 = quantile regression model at level 0.50; Q.75 = quantile regression model at level 0.75; Q.95 = quantile regression model at level 0.95.
Notes: Non-standardized beta coefficients; standardized errors in parentheses.
Dependent variable: Logged runoff depth; CSA: Dummy variable (0: Detroit-Warren-Ann Arbor CSA; 1: Chicago-Naperville CSA)
* p<0.05, ** p<0.01, *** p<0.001

3.2. Effects of GI patterns on runoff depth

When examining the relationship between GI ***size*** and runoff depth (see Table 3), the percentage of GI area (i.e., PLAND) and LPI lost significance in all models ($p > 0.05$). Conversely, the ***connectivity*** of the GI demonstrated a significant association with runoff depth in the Chicago-Naperville CSA (see Table 4). A lower GYRATE and higher COHESION of the GI patches in the Chicago region led to a lower runoff depth ($p < 0.001$ in OLS). In the Detroit-Warren-Ann Arbor CSA, all connectivity variables lost significance except in the 0.5, 0.75, and 0.95 quantile regression models. The results showed that less clumped and aggregated GI patterns in the Detroit region contributed to a decreasing average or above runoff depth. Overall, as indicated by the R^2, the connectivity models outperformed the size models in accounting for variances in runoff depth.

Table 3. Results of the regression analyses predicting the effects of GI size on runoff depth.

Index	OLS	RE	Q.05	Q.25	Q.50	Q.75	Q.95
Main effects							
Percentage of area (PLAND)	0.0009 (0.0026)	0.0012 (0.0045)	0.0007 (0.0048)	-0.0009 (0.0038)	0.0006 (0.0022)	0.0044 (0.0025)	0.0047 (0.0063)
Largest patch (LPI)	-0.0016 (0.0149)	-0.0065 (0.0234)	0.0247 (0.0738)	-0.0079 (0.0270)	-0.0294 (0.0153)	-0.0046 (0.0101)	0.0250 (0.104)
Impervious ratio (TIA)	0.0081** (0.0029)	0.0083 (0.0046)	0.0096* (0.0043)	0.0056 (0.0041)	0.0079** (0.0026)	0.0155*** (0.0033)	0.0179 (0.0111)
Hydraulic connectivity (H_conn)	0.0014* (0.0007)	0.0016 (0.0011)	-0.0015 (0.0012)	0.0013 (0.0014)	0.0016** (0.0005)	0.0005 (0.0009)	0.0013 (0.0040)
Chicago interaction effects							
CSA(1)*PLAND	0.0062 (0.0029)	0.0047 (0.0042)	0.0052 (0.0098)	0.0054 (0.0044)	0.0038 (0.0026)	0.0036 (0.0037)	0.0076 (0.0091)

CSA(1)*LPI	-0.0029	0.0073	0.0090	0.0067	0.0320	-0.0196	-0.0802
	(0.0195)	(0.0293)	(0.0760)	(0.0332)	(0.0193)	(0.0184)	(0.107)
CSA(1)*TIA	0.0013	0.0013	-0.0070	0.0007	0.0051	-0.0026	-0.0044
	(0.0035)	(0.0053)	(0.0082)	(0.0049)	(0.0032)	(0.0039)	(0.0111)
CSA(1)*H_conn	0.0046***	0.0044*	0.0083***	0.0047*	0.0032*	0.0060***	0.0063
	(0.0013)	(0.0020)	(0.0023)	(0.0021)	(0.0013)	(0.0015)	(0.0048)
Control variables							
Annual precipitation	0.0010***	0.0014***	0.0012**	0.0011***	0.0008***	0.0006***	0.0006
	(0.0002)	(0.0002)	(0.0004)	(0.0003)	(0.0002)	(0.0002)	(0.0005)
3-month antecedent wetness	0.0037***	0.0035***	0.0037***	0.0038***	0.0033***	0.0035***	0.0035**
	(0.0005)	(0.0003)	(0.0009)	(0.0008)	(0.0005)	(0.0004)	(0.0012)
Mean slope	0.0014	-0.0009	-0.0217	0.0109	0.0499	-0.0112	-0.0634
	(0.0362)	(0.0636)	(0.0600)	(0.0490)	(0.0315)	(0.0253)	(0.0516)
K_{sat}	-0.0013	-0.0006	-0.0086	0.0006	0.0016	-0.0046	-0.0104*
	(0.0029)	(0.0029)	(0.0059)	(0.0039)	(0.0029)	(0.0033)	(0.0043)
Number of reservoirs	-0.0004	-0.0002	0.0002	-0.0021	-0.0031	0.0013	-0.0020
	(0.0023)	(0.0032)	(0.0067)	(0.0030)	(0.0021)	(0.0034)	(0.0041)
CSA	0.1403***	0.1318**	-0.0124	0.0696	0.1750***	0.2647***	0.2316*
	(0.0412)	(0.0494)	(0.1151)	(0.0680)	(0.0376)	(0.0499)	(0.0904)
2001	0.2154***	0.2010***	0.0707	0.2135*	0.1625***	0.1458**	0.3402*
	(0.0550)	(0.0368)	(0.0793)	(0.0913)	(0.0393)	(0.0542)	(0.1554)
2006	0.0516	-0.0147	-0.1614	0.0149	0.5749	0.1292*	0.1778
	(0.0705)	(0.0532)	(0.1245)	(0.1246)	(0.0685)	(0.0584)	(0.1683)
2011	0.3838***	0.3063***	0.3895*	0.3765**	0.3396***	0.3945***	0.3635
	(0.0840)	(0.0603)	(0.1742)	(0.1358)	(0.0761)	(0.0759)	(0.2015)
Adj. R^2	0.583						
Within R^2		0.673					
Pseudo-R^2			0.474	0.386	0.399	0.460	0.456
Degree of freedom	270	270	270	270	270	270	270

OLS = Pooled OLS model; RE = Random effects panel data model; Q.05 = quantile regression model at level 0.05; Q.25 = quantile regression model at level 0.25; Q.50 = Quantile regression model at level 0.50; Q.75 = Quantile regression model at level 0.75; Q.95 = Quantile regression model at level 0.95.
Notes: Non-standardized beta coefficients; standardized errors in parentheses.
Dependent variable: Logged runoff depth; CSA: Dummy variable (0: Detroit-Warren-Ann Arbor CSA; 1: Chicago-Naperville CSA)
$^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

Table 4. Results of the regression analyses predicting the effects of GI connectivity on runoff depth.

Index	**OLS**	**RE**	**Q.05**	**Q.25**	**Q.50**	**Q.75**	**Q.95**
Main effects							
Radius of gyration (GYRATE)	-0.0008*	-0.0008	-0.0017	-0.0009	-0.0006	-0.0004	-0.0006
	(0.0004)	(0.0005)	(0.0019)	(0.0005)	(0.0003)	(0.0002)	(0.0003)
Cohesion (COHESION)	0.0536*	0.0543	0.0898	0.0695	0.0396*	0.0518**	0.0759***
	(0.0225)	(0.0331)	(0.160)	(0.0497)	(0.0183)	(0.0158)	(0.0213)
Impervious ratio (TIA)	0.0054*	0.0049	-0.0015	0.0049	0.0075***	0.0110***	0.0146***
	(0.0022)	(0.0029)	(0.0110)	(0.0048)	(0.0019)	(0.0019)	(0.0025)
Hydraulic connectivity (H_conn)	0.0018*	0.0017	0.0012	0.0016	0.0016*	0.0022***	0.0028***
	(0.0008)	(0.0011)	(0.0041)	(0.0014)	(0.0008)	(0.0005)	(0.0007)
Chicago interaction effects							
CSA(1)*GYRATE	0.0021***	0.0021***	0.0019	0.0027***	0.0019***	0.0015***	0.0029***
	(0.0004)	(0.0006)	(0.0021)	(0.0008)	(0.0004)	(0.0003)	(0.0007)
CSA(1)*COHESION	-0.085***	-0.0856*	-0.0418	-0.119*	-0.076***	-0.078***	-0.134**
	(0.0235)	(0.0338)	(0.162)	(0.0558)	(0.0194)	(0.0172)	(0.0501)
CSA(1)*TIA	0.0055*	0.0062	0.0051	0.0076	0.0043	-0.0001	-0.0095*
	(0.0032)	(0.0040)	(0.0129)	(0.0059)	(0.0025)	(0.0029)	(0.0042)
CSA(1)*H_conn	0.0037**	0.0035*	-0.0001	0.0037	0.0027*	0.0030**	0.0036*
	(0.0012)	(0.0017)	(0.0046)	(0.0020)	(0.0013)	(0.0011)	(0.0014)
Control variables							
Annual precipitation	0.0014***	0.0016***	0.0017**	0.0012***	0.0010***	0.0010***	0.0015***
	(0.0002)	(0.0002)	(0.0006)	(0.0003)	(0.0002)	(0.0002)	(0.0003)
3-month antecedent	0.0035***	0.0035***	0.0040***	0.0038***	0.0032***	0.0030***	0.0023***

wetness	(0.0005)	(0.0003)	(0.0009)	(0.0007)	(0.0005)	(0.0003)	(0.0005)
Mean slope	0.0100 (0.0264)	0.0142 (0.0368)	0.0597 (0.0602)	-0.0055 (0.0408)	0.0227 (0.0173)	-0.0256 (0.0200)	-0.0541 (0.0355)
K_{sat}	0.0040 (0.0024)	0.0042* (0.0021)	0.0057 (0.0251)	0.0064 (0.0048)	0.0058* (0.0023)	0.0057 (0.0041)	0.0070 (0.0066)
Number of reservoirs	-0.0015 (0.0024)	-0.0021 (0.0028)	-0.0004 (0.0103)	-0.0037 (0.0027)	-0.0025 (0.0027)	0.0024 (0.0026)	0.0005 (0.0023)
CSA	0.2355*** (0.0475)	0.2200*** (0.0628)	0.0465 (0.2870)	0.2223* (0.0960)	0.2316*** (0.0435)	0.3397*** (0.0452)	0.5136*** (0.0768
2001	0.1635** (0.0551)	0.1736*** (0.0361)	0.1565 (0.1064)	0.2363** (0.0788)	0.1199* (0.0502)	0.0788* (0.0314)	0.0916 (0.0607)
2006	-0.0426 (0.0773)	-0.0652 (0.0587)	-0.1917 (0.1531)	0.0015 (0.1019)	0.0051 (0.0739)	0.0210 (0.0470)	0.0117 (0.0850)
2011	0.3027*** (0.0860)	0.2678*** (0.0624)	0.2268 (0.2066)	0.4037** (0.1295)	0.3016*** (0.0844)	0.2607*** (0.0658)	0.1238 (0.0999)
Adj. R^2	0.657						
Within R^2		0.686					
Pseudo-R^2			0.510	0.426	0.462	0.518	0.533
Degree of freedom	259	259	259	259	259	259	259

OLS = Pooled OLS model; RE = Random effects panel data model; Q.05 = Quantile regression model at level 0.05; Q.25 = Quantile regression model at level 0.25; Q.50 = Quantile regression model at level 0.50; Q.75 = Quantile regression model at level 0.75; Q.95 = Quantile regression model at level 0.95.
Notes: Non-standardized beta coefficients; standardized errors in parentheses.
Dependent variable: Logged runoff depth; CSA: Dummy variable (0: Detroit-Warren-Ann Arbor CSA; 1: Chicago-Naperville CSA)
$^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

3.3. Effects of development patterns on runoff depth

For the ***size*** effect of development patches (see Table 5), as expected in Table 2, the percentage of developed area (PLAND), as with TIA, was positively associated with runoff depth in the Detroit-Warren-Ann Arbor CSA ($p < 0.001$ in OLS), while the Chicago-Naperville CSA remained significantly influenced by hydraulic connectivity (rather than PLAND) ($p < 0.001$ in OLS). With a 1% increase in the percentage of developed area (PLAND) in the Detroit-Warren-Ann Arbor CSA, runoff depth increased by 0.38% to 0.77%. Regarding ***connectivity***, more connected patterns of development were found to significantly increase runoff depth in the basic OLS model ($p < 0.001$ for both GYRATE and COHESION; see Table 6). Similar to previous cases, the connectivity models outperformed the size models in accounting for the variance in runoff depth.

Table 5. Results of the regression analyses predicting the effects of development size on runoff depth.

Index	OLS	RE	Q.05	Q.25	Q.50	Q.75	Q.95
Main effects							
Percentage of area (PLAND)	0.0040*** (0.0009)	0.0039** (0.0013)	0.0017 (0.0021)	0.0038* (0.0018)	0.0046*** (0.0009)	0.0053** (0.0011)	0.0077*** (0.0017)
Hydraulic connectivity (H_conn)	0.0014* (0.0007)	0.0016 (0.0009)	-0.0001 (0.0014)	0.0011 (0.0012)	0.0015* (0.0007)	0.0013 (0.0007)	0.0021 (0.0033)
Chicago interaction effects							
CSA(1)*PLAND	-0.0003 (0.0014)	0.0002 (0.0021)	-0.0004 (0.0028)	-0.0006 (0.0022)	0.0006 (0.0014)	-0.0002 (0.0015)	-0.0050* (0.0024)
CSA(1)*H_conn	0.0046*** (0.0013)	0.0043* (0.0019)	0.0071** (0.0025)	0.0048* (0.0019)	0.0043** (0.0015)	0.0046*** (0.0013)	0.0039 (0.0041)
Control variables							
Annual precipitation	0.0011*** (0.0002)	0.0014*** (0.0002)	0.0010 (0.0005)	0.0011*** (0.0003)	0.0010*** (0.0002)	0.0008** (0.0002)	0.0008 (0.0006)
3-month antecedent	0.0037*** (0.0005)	0.0035*** (0.0003)	0.0041*** (0.0008)	0.0040*** (0.0007)	0.0032*** (0.0006)	0.0034*** (0.0005)	0.0023** (0.0008)

wetness							
Mean slope	0.0029 (0.0221)	-0.0109 (0.0366)	0.0157 (0.0308)	-0.0032 (0.0310)	0.0192 (0.0216)	-0.0047 (0.0159)	-0.0384 (0.0432)
K_{sat}	0.0031 (0.0021)	0.0044 (0.0032)	0.0027 (0.0062)	0.0047 (0.0051)	0.0018 (0.0025)	0.0032 (0.0027)	0.0033 (0.0047)
Number of reservoirs	0.0022 (0.0025)	0.0046 (0.0040)	-0.0013 (0.0031)	0.0003 (0.0035)	0.0009 (0.0017)	0.0052* (0.0026)	0.0040 (0.0089)
CSA	0.1686*** (0.0396)	0.1725** (0.0536)	0.0973 (0.0870)	0.0716 (0.0692)	0.1838*** (0.0398)	0.2891*** (0.0502)	0.3790*** (0.1109)
2001	0.2188*** (0.0560)	0.1984*** (0.0364)	0.2222** (0.0724)	0.2744*** (0.0745)	0.1748** (0.0582)	0.1707** (0.0514)	0.1392 (0.1581)
2006	0.0592 (0.0714)	-0.0077 (0.0517)	0.0258 (0.1405)	0.0910 (0.1145)	0.0678 (0.0719)	0.1054 (0.0664)	0.0512 (0.1786)
2011	0.4032*** (0.0802)	0.3304*** (0.0551)	0.5432** (0.1682)	0.4542*** (0.1214)	0.3270*** (0.0979)	0.3676*** (0.0838)	0.2705 (0.2077)
Adj. R^2	0.579						
Within R^2		0.689					
Pseudo-R^2			0.460	0.379	0.396	0.452	0.417
Degree of freedom	267	267	267	267	267	267	267

OLS = Pooled OLS model; RE = Random effects panel data model; Q.05 = Quantile regression model at level 0.05; Q.25 = Quantile regression model at level 0.25; Q.50 = Quantile regression model at level 0.50; Q.75 = Quantile regression model at level 0.75; Q.95 = Quantile regression model at level 0.95.
Notes: Non-standardized beta coefficients; standardized errors in parentheses.
Dependent variable: Logged runoff depth; CSA: Dummy variable (0: Detroit-Warren-Ann Arbor CSA; 1: Chicago-Naperville CSA)
*p < 0.05, **p < 0.01, ***p < 0.001

Table 6. Results of the regression analyses predicting the effects of development connectivity on runoff depth.

Index	OLS	RE	Q.05	Q.25	Q.50	Q.75	Q.95
Main effects							
Radius of gyration (GYRATE)	0.0000 (0.0000)	0.0000 (0.0000)	-0.0000 (0.0000)	0.0000* (0.0000)	0.0000 (0.0000)	0.0000 (0.0000)	-0.0000 (0.0000)
Cohesion (COHESION)	0.0139** (0.0050)	0.0119 (0.0076)	0.0105 (0.0117)	0.0082 (0.0059)	0.0088 (0.0050)	0.0124** (0.0045)	0.0238 (0.0170)
Impervious ratio (TIA)	0.0024 (0.0026)	0.0016 (0.0037)	0.0010 (0.0041)	0.0003 (0.0030)	0.0037 (0.0040)	0.0078*** (0.0017)	0.0066 (0.0055)
Hydraulic connectivity (H_conn)	0.0015 (0.0008)	0.0016 (0.0013)	0.0011 (0.0041)	0.0016 (0.0008)	0.0003 (0.0008)	0.0005 (0.0005)	-0.0000 (0.0034)
Chicago interaction effects							
CSA(1)*GYRATE	0.0001** (0.0000)	0.0000 (0.0000)	0.0001* (0.0000)	0.0000 (0.0000)	0.0001** (0.0000)	0.0000* (0.0000)	0.0000 (0.0000)
CSA(1)*COHESION	0.0697* (0.0302)	0.0700 (0.0417)	0.0606 (0.0657)	0.0603 (0.0433)	0.0413 (0.0276)	0.103*** (0.0287)	0.0285 (0.0671)
CSA(1)*TIA	-0.0030 (0.0033)	-0.0011 (0.0047)	-0.0050 (0.0058)	-0.0004 (0.0044)	-0.0015 (0.0046)	-0.009*** (0.0026)	-0.0089 (0.0053)
CSA(1)*H_conn	0.0064*** (0.0013)	0.0060** (0.0019)	0.0077 (0.0050)	0.0062*** (0.0014)	0.0065*** (0.0017)	0.0070*** (0.0013)	0.0073 (0.0042)
Control variables							
Annual precipitation	0.0011*** (0.0002)	0.0014*** (0.0002)	0.0011 (0.0007)	0.0009*** (0.0003)	0.0010*** (0.0002)	0.0009*** (0.0002)	0.0008* (0.0003)
3-month antecedent wetness	0.0037*** (0.0005)	0.0036*** (0.0003)	0.0036*** (0.0007)	0.0047*** (0.0007)	0.0041*** (0.0006)	0.0033*** (0.0004)	0.0026** (0.0009)
Mean slope	0.0189 (0.0232)	0.0169 (0.0366)	0.0037 (0.0313)	0.0068 (0.0265)	0.0345 (0.0240)	0.0187 (0.0163)	-0.0269 (0.0576)
K_{sat}	-0.0000 (0.0022)	0.0021 (0.0032)	0.0010 (0.0048)	-0.0000 (0.0031)	0.0029 (0.0033)	-0.0024 (0.0013)	-0.0024 (0.0073)
Number of reservoirs	-0.012*** (0.0026)	-0.0111** (0.0039)	-0.0132** (0.0051)	-0.012*** (0.0027)	-0.0107* (0.0042)	-0.007*** (0.0023)	-0.015*** (0.0030)
CSA	-0.0210 (0.0564)	-0.0070 (0.0761)	0.0091 (0.1305)	-0.0506 (0.0823)	0.0477 (0.0586)	0.0406 (0.0576)	0.2020 (0.1212)

2001	0.2149*** (0.0534)	0.2073*** (0.0342)	0.1757* (0.0714)	0.2984*** (0.0638)	0.1951* (0.0763)	0.1507*** (0.0230)	0.2100 (0.1073)
2006	0.0389 (0.0713)	0.0026 (0.0490)	-0.1074 (0.1316)	0.1681 (0.1044)	0.0915 (0.0959)	0.0596 (0.0510)	0.0955 (0.1510)
2011	0.3867*** (0.0777)	0.3398*** (0.0527)	0.4609* (0.2151)	0.5444*** (0.1050)	0.3911*** (0.1092)	0.3085*** (0.0692)	0.2859 (0.1659)
Adj. R^2	0.636						
Within R^2		0.694					
Pseudo-R^2			0.507	0.425	0.432	0.487	0.471
Degree of freedom	263	263	263	263	263	263	263

OLS = Pooled OLS model; RE = Random effects panel data model; Q.05 = Quantile regression model at level 0.05; Q.25 = Quantile regression model at level 0.25; Q.50 = Quantile regression model at level 0.50; Q.75 = Quantile regression model at level 0.75; Q.95 = Quantile regression model at level 0.95.
Notes: Non-standardized beta coefficients; standardized errors in parentheses.
Dependent variable: Logged runoff depth; CSA: Dummy variable (0: Detroit-Warren-Ann Arbor CSA; 1: Chicago-Naperville CSA)
*p < 0.05, **p < 0.01, ***p < 0.001

3.4. Effects of impervious composition on peak flow

The outcomes of the peak flow models demonstrated the significant impacts of watershed size and number of reservoirs (see Table 7). The size of the watershed was positively associated with peak flow, while the number of reservoirs negatively impacted peak flow ($p < 0.001$).

It is important to note that the peak flow models generally produced unexpected results. TIA in the Chicago region had an illogically negative association with peak flow ($p < 0.01$ in OLS). Similarly, hydraulic connectivity in both the Detroit and Chicago regions showed a negative impact on peak flow in all models. Considering that there was no scientific evidence supporting these results and the models explained a relatively lower variance in the dependent variable (compared to that of the runoff depth models), we concluded that the results for peak flow were unreliable and thus they are reported only in the Appendix.

Table 7. Results of the basic regression analyses predicting peak flow.

Index	OLS	RE	Q.05	Q.25	Q.50	Q.75	Q.95
Main effects							
Impervious ratio (TIA)	0.0195* (0.0083)	0.0182 (0.0124)	0.0187*** (0.0050)	0.0250*** (0.0071)	0.0147 (0.0081)	0.0133 (0.0089)	0.0081 (0.0167)
Hydraulic connectivity (H_conn)	-0.015*** (0.0039)	-0.0132* (0.0063)	-0.018*** (0.0043)	-0.0135** (0.0048)	-0.0121* (0.0054)	-0.0095 (0.0057)	0.0011 (0.0092)
Chicago interaction effects							
CSA(1)**TIA	-0.0319** (0.0109)	-0.0288 (0.0156)	-0.039*** (0.0074)	-0.037*** (0.0100)	-0.0259** (0.0097)	-0.0175 (0.0120)	-0.0081 (0.0178)
CSA(1)*H_conn	0.0122* (0.0049)	0.0105 (0.0075)	0.0209*** (0.0057)	0.0115 (0.0062)	0.0120 (0.0063)	0.0072 (0.0071)	-0.0027 (0.0112)
Control variables							
24-hour peak precipitation	0.0070** (0.0025)	0.0071*** (0.0019)	0.0042** (0.0013)	0.0043 (0.0026)	0.0054* (0.0022)	0.0099* (0.0032)	0.0149*** (0.0012)
5-day antecedent wetness	0.0046* (0.0022)	0.0059** (0.0021)	0.0090** (0.0027)	0.0051 (0.0031)	0.0069* (0.0028)	0.0054 (0.0029)	0.0016 (0.0042)
Size of watershed	0.0048*** (0.0005)	0.0047*** (0.0006)	0.0061*** (0.0005)	0.0053*** (0.0007)	0.0047*** (0.0007)	0.0051*** (0.0008)	0.0063*** (0.0012)
Mean slope	0.0416 (0.0751)	0.0243 (0.130)	0.0132 (0.0646)	0.0285 (0.0818)	0.0788 (0.0860)	0.107 (0.110)	-0.0041 (0.108)
K_{sat}	-0.0266 (0.0175)	-0.0239 (0.0246)	0.0391* (0.0166)	-0.0212 (0.0143)	-0.0160 (0.0157)	-0.0194 (0.0279)	-0.0170 (0.0368)
Number of reservoirs	-0.057*** (0.0142)	-0.0569** (0.0203)	-0.115*** (0.0085)	-0.087*** (0.0195)	-0.067*** (0.0193)	-0.0563** (0.0201)	-0.0411 (0.0428)

CSA	-0.3944*	-0.3681	0.1205	-0.3791*	-0.2740	-0.2133	-0.0642
	(0.1945)	(0.2821)	(0.2099)	(0.1567)	(0.1742)	(0.2033)	(0.3519)
2001	0.2801*	0.3224***	0.3005*	0.2223	0.2659	0.3176	0.6104*
	(0.1298)	(0.0919)	(0.1347)	(0.1976)	(0.1507)	(0.1766)	(0.2809)
2006	-0.0880	-0.0549	-0.4645***	-0.2207	-0.0784	0.0403	0.0688
	(0.1453)	(0.0864)	(0.0903)	(0.2007)	(0.1673)	(0.1757)	(0.2908)
2011	0.2969*	0.3084***	0.4702***	0.2912	0.2201	0.1735	0.2247
	(0.1351)	(0.0862)	(0.0737)	(0.1980)	(0.1729)	(0.1627)	(0.2808)
Adj. R^2	0.527						
Within R^2		0.399					
Pseudo-R^2			0.468	0.328	0.338	0.374	0.517
Degree of freedom	172	172	172	172	172	172	172

OLS = Pooled OLS model; RE = Random effects panel data model; Q.05 = Quantile regression model at level 0.05; Q.25 = Quantile regression model at level 0.25; Q.50 = Quantile regression model at level 0.50; Q.75 = Quantile regression model at level 0.75; Q.95 = Quantile regression model at level 0.95.

Notes: Non-standardized beta coefficients; standardized errors in parentheses.

Dependent variable: Logged peak flow; CSA: Dummy variable (0: Detroit-Warren-Ann Arbor CSA; 1: Chicago-Naperville CSA)

*p < 0.05, **p < 0.01, ***p < 0.001

4. Discussion

4.1. Impervious surface regulation for flood control

TIA and hydraulic connectivity were found to positively and significantly affect runoff depth. TIA was a better indicator than hydraulic connectivity in the Detroit-Warren-Ann Arbor CSA, a shrinking region with a decreasing population and increasing number of vacant lots. In contrast, hydraulic connectivity, the ratio of directly connected impervious area (DCIA) to TIA, was a better predictor of runoff depth in the Chicago-Naperville CSA, a growing city with an increasing population. Specifically, regulation of TIA was consistently effective in the majority of quantiles of runoff depth, except for the far below average runoff events in the Detroit-Warren-Ann Arbor CSA. Conversely, control of hydraulic connectivity or DCIA constantly outweighed that of TIA in the Chicago-Naperville CSA, except for during far above average flood events (see Table 2).

The findings of this will study assist policymakers with planning decision regarding what impervious surface measures should be prioritized for effective flood control in growing versus shrinking areas. For a shrinking region such as the Detroit-Warren-Ann Arbor CSA, TIA mitigation should be the primary consideration over hydraulic connectivity or DCIA for runoff volume control. However, TIA regulation plays a negligible role during far below average runoff events. One conceivable reason is that the small amount of runoff generated from TIA is absorbed by adjacent pervious areas, barely impacting the overall runoff volume of a watershed. Conversely, for a growing area such as the Chicago region, hydraulic connectivity or DCIA reduction should be a priority goal for reducing flood impacts. However, controlling hydraulic connectivity or DCIA is not significantly effective during far above average flood events. One possible reason is that excessive runoff may overwhelm pipelines and drown sewer systems in the short term, leaving a changing DCIA unimpactful.

4.2. Effectiveness of GI spatial patterns for flood control

This study examined the effectiveness of GI spatial patterns for runoff depth control. The results revealed that the ***size*** of the GI was not a significant determinant of runoff depth (see Table 3). Instead, regarding ***connectivity***, less clumped and aggregated GI patterns led to decrease average or above runoff depth in the Detroit-Warren-Ann Arbor CSA (see Table 4). Conversely, less connected but more aggregated GI patterns (i.e., lower GYRATE and higher COHESION) were likely to reduce greater runoff depth in the Chicago-Naperville CSA.

Based on the results mentioned above, policymakers and land-use planners should formulate corresponding strategies for the Detroit and Chicago regions to control intense flood events. It is important to note that the results for the Detroit-Warren-Ann Arbor CSA align with the current GI policy adopted by the Detroit Future City Plan of converting scattered neighborhood-scale low-priced vacant lots into GI patches. In contrast, the results for the Chicago-Naperville CSA imply that cities should invest in building or preserving aggregated forms of GIs as focal patches, and do so in a less connected manner across watersheds, allowing flood water from neighboring developed areas to be captured and retained more effectively.

Although this study provided insightful findings and policy implications for effective flood risk management, it had three limitations. First, because of limited data sources for land use, the GI and development patterns were computed only for the years 2001, 2006, 2011, and 2016. A dataset with a finer temporal resolution would have provided a better understanding of land use contributions to yearly flooding variations. Second, social variables such as demographic information were not accounted for in this study because their units of analysis (i.e., political jurisdictions) did not match with watershed boundaries. Third, linear statistical models (i.e., pooled OLS, panel data, and quantile regression models) were built to understand the statistical significance of key variables in this study. Future research should adopt advanced approaches such as machine learning or artificial intelligence to improve the performance of test sets, explore nonlinearity in data, and develop a predictive model that forecasts future changes in flooding patterns in response to changing climate and land development conditions.

5. Conclusion

This study analyzed the long-term effects of GI and development composition and arrangement on runoff yields in both budding and depopulating CSAs. Pooled OLS regression, panel data, and quantile regression models were developed while controlling for multiple climate and biophysical variables. The results revealed the significant effects of TIA and hydraulic connectivity on mitigating flood depth in shrinking and growing regions, respectively. Repurposing dispersed neighborhood-scale vacant lands to serve as GI should be a priority for the Detroit-Warren-Ann Arbor CSA, while a less connected and more aggregated pattern of GI should be designed and preserved in the Chicago-Naperville CSA. These research findings ultimately suggest that policymakers, land-use developers, and water resource managers should formulate more appropriate strategies and policies for mitigating flood volume according to the demographic trends of their city.

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Appendix

Table 1. Results of the regression analyses predicting the effects of GI size on peak flow.

Index	OLS	RE	Q.05	Q.25	Q.50	Q.75	Q.95
Main effects							
Percentage of area (PLAND)	0.0227 (0.0132)	0.0180 (0.0205)	-0.0008 (0.0113)	0.0121 (0.0158)	0.0134 (0.0148)	0.0364 (0.0231)	0.0483** (0.0177)
Largest patch (LPI)	-0.380*** (0.0658)	-0.337** (0.109)	-0.303*** (0.0561)	-0.303*** (0.0784)	-0.349*** (0.0736)	-0.434*** (0.115)	-0.445*** (0.0882)
Impervious ratio (TIA)	0.0115 (0.0132)	0.0086 (0.0201)	-0.0286* (0.0112)	0.0061 (0.0157)	-0.0007 (0.0148)	0.0181 (0.0230)	0.0367* (0.0177)
Hydraulic connectivity (H_conn)	0.0016 (0.0047)	-0.0000 (0.0071)	0.0072 (0.0040)	0.0010 (0.0056)	-0.0004 (0.0053)	0.0050 (0.0082)	0.0063 (0.0063)
Chicago interaction effects							
CSA(1)*PLAND	-0.0043 (0.0128)	0.0027 (0.0194)	0.0293** (0.0109)	0.0116 (0.0152)	-0.0039 (0.0143)	-0.238 (0.0223)	-0.0361* (0.0171)
CSA(1)*LPI	0.311*** (0.0726)	0.250* (0.118)	0.248*** (0.0619)	0.218* (0.0864)	0.281*** (0.0812)	0.402** (0.127)	0.365*** (0.0973)
CSA(1)*TIA	-0.0087 (0.0136)	-0.0038 (0.0207)	0.0382** (0.0116)	-0.0044 (0.0162)	0.0030 (0.0152)	-0.0105 (0.0237)	-0.0287 (0.0182)
CSA(1)*H_conn	-0.0051 (0.0057)	-0.0025 (0.0087)	-0.0068 (0.0049)	-0.0037 (0.0068)	-0.0004 (0.0064)	-0.0130 (0.0100)	-0.0174* (0.0076)
Control variables							
24-hour peak precipitation	0.0062** (0.0019)	0.0065*** (0.0015)	0.0029 (0.0017)	0.0057* (0.0023)	0.0055* (0.0022)	0.0088* (0.0034)	0.0139*** (0.0026)
5-day antecedent wetness	0.0044 (0.0023)	0.0057** (0.0018)	0.0029 (0.0020)	0.0039 (0.0028)	0.0044 (0.0026)	0.0052 (0.0041)	-0.0014 (0.0031)
Size of watershed	0.0061*** (0.0007)	0.0057*** (0.0011)	0.0065*** (0.0006)	0.0064*** (0.0009)	0.0055*** (0.0008)	0.0069*** (0.0013)	0.0065*** (0.0010)
Mean slope	0.167 (0.0931)	0.137 (0.157)	0.320*** (0.0793)	0.206 (0.111)	0.170 (0.104)	0.124 (0.163)	-0.137 (0.125)
K_{sat}	0.0090 (0.0109)	0.0095 (0.0166)	0.0162 (0.0093)	0.0022 (0.0130)	0.0198 (0.0122)	0.0254 (0.0191)	0.0248 (0.0146)
Number of reservoirs	-0.118*** (0.0180)	-0.108*** (0.0276)	-0.132*** (0.0153)	-0.137*** (0.0214)	-0.099*** (0.0201)	-0.139*** (0.0314)	-0.125*** (0.0241)
CSA	0.1233 (0.1353)	0.1250 (0.2143)	-0.0311 (0.1154)	0.0441 (0.1612)	0.2286 (0.1514)	0.3715 (0.2364)	0.2540 (0.1813)
2001	0.3170* (0.1244)	0.3355*** (0.0864)	0.4060*** (0.1060)	0.3858* (0.1481)	0.3051* (0.1392)	0.3148 (0.2173)	0.3690* (0.1667)
2006	-0.1182 (0.1230)	-0.0782 (0.0846)	-0.3252** (0.1048)	-0.1207 (0.1464)	-0.1624 (0.1376)	-0.0721 (0.2147)	0.0557 (0.1647)
2011	0.3461* (0.1339)	0.3309*** (0.0936)	0.6173*** (0.1142)	0.4170** (0.1595)	0.3710* (0.1499)	0.1827 (0.2339)	0.1911 (0.1765)
Adj. R^2	0.610						
Within R^2		0.401					
Pseudo-R^2			0.548	0.431	0.430	0.449	0.526
Degree of freedom	171	171	171	171	171	171	171

OLS = Pooled OLS model; RE = Random effects panel data model; Q.05 = Quantile regression model at level 0.05; Q.25 = Quantile regression model at level 0.25; Q.50 = Quantile regression model at level 0.50; Q.75 = Quantile regression model at level 0.75; Q.95 = Quantile regression model at level 0.95.
Notes: Non-standardized beta coefficients; standardized errors in parentheses.
Dependent variable: Logged peak flow; CSA: Dummy variable (0: Detroit-Warren-Ann Arbor CSA; 1: Chicago-Naperville CSA)
*p < 0.05, **p < 0.01, ***p < 0.001

Table 2. Results of the regression analyses predicting the effects of GI connectivity on peak flow.

Index	OLS	RE	Q.05	Q.25	Q.50	Q.75	Q.95
Main effects							

Radius of gyration (GYRATE)	-0.0029 (0.0019)	-0.0031 (0.0032)	-0.0010 (0.0014)	-0.0015 (0.0024)	-0.0026 (0.0025)	-0.0035 (0.0026)	-0.0021 (0.0010)
Cohesion (COHESION)	0.110 (0.123)	0.0995 (0.206)	0.0669 (0.0892)	0.0353 (0.156)	0.0558 (0.165)	0.211 (0.169)	0.0238 (0.0676)
Impervious ratio (TIA)	-0.0004 (0.0109)	-0.0047 (0.0181)	0.0223** (0.0079)	0.0102 (0.0138)	-0.0101 (0.0147)	0.0041 (0.0150)	-0.0080 (0.0060)
Hydraulic connectivity (H_conn)	-0.0131** (0.0048)	-0.0119 (0.0082)	-0.018*** (0.0035)	-0.0117 (0.0060)	-0.0125 (0.0064)	-0.0043 (0.0066)	0.0098*** (0.0026)
Chicago interaction effects							
CSA(1)*GYRATE	0.0025 (0.0020)	0.0019 (0.0034)	-0.0007 (0.0014)	-0.0003 (0.0025)	0.0021 (0.0026)	0.0050 (0.0027)	0.0056*** (0.0011)
CSA(1)*COHESION	-0.0860 (0.123)	-0.0635 (0.207)	-0.0261 (0.0897)	0.0339 (0.157)	-0.0036 (0.166)	-0.250 (0.170)	-0.0879 (0.0680)
CSA(1)*TIA	-0.0060 (0.0129)	-0.0004 (0.0216)	-0.0284** (0.0094)	-0.0200 (0.0163)	0.0022 (0.0173)	-0.0042 (0.0178)	0.0273*** (0.0071)
CSA(1)*H_conn	0.0109 (0.0059)	0.0105 (0.0100)	0.0221*** (0.0043)	0.0102 (0.0075)	0.0134 (0.0079)	-0.0009 (0.0081)	-0.014*** (0.0032)
Control variables							
24-hour peak precipitation	0.0063** (0.0022)	0.0065*** (0.0015)	0.0034* (0.0016)	0.0078** (0.0028)	0.0051 (0.0030)	0.0060 (0.0031)	0.0145*** (0.0012)
5-day antecedent wetness	0.0046 (0.0026)	0.0057** (0.0018)	0.0102*** (0.0019)	0.0037 (0.0033)	0.0052 (0.0035)	0.0026 (0.0036)	0.0038* (0.0015)
Size of watershed	0.0051*** (0.0007)	0.0052*** (0.0012)	0.0066*** (0.0005)	0.0059*** (0.0010)	0.0046*** (0.0010)	0.0057*** (0.0010)	0.0064*** (0.0004)
Mean slope	0.0661 (0.0874)	0.0730 (0.160)	0.0817 (0.0636)	0.0345 (0.111)	0.0351 (0.118)	-0.0178 (0.121)	-0.157** (0.0482)
K_{sat}	0.0169 (0.0117)	0.0235 (0.0181)	0.0433*** (0.0085)	0.0010 (0.0149)	0.0279 (0.0158)	0.0330* (0.0162)	0.0345*** (0.0065)
Number of reservoirs	-0.073*** (0.0172)	-0.0714* (0.0288)	-0.121*** (0.0125)	-0.095*** (0.0219)	-0.0729** (0.0232)	-0.0641** (0.0238)	-0.083*** (0.0095)
CSA	0.1795 (0.2080)	0.2460 (0.3588)	0.2268 (0.1513)	-0.1336 (0.2641)	0.2348 (0.2802)	0.3515 (0.2874)	0.1457 (0.1147)
2001	0.3051* (0.1402)	0.3221*** (0.0864)	0.3435*** (0.1020)	0.3274 (0.1780)	0.2177 (0.1889)	0.2104 (0.1937)	0.3326*** (0.0773)
2006	-0.1121 (0.1386)	-0.0732 (0.0843)	-0.4290*** (0.1008)	-0.1396 (0.1760)	-0.1484 (0.1867)	-0.0885 (0.1915)	-0.1217 (0.0764)
2011	0.3483* (0.1511)	0.3298*** (0.0933)	0.4782*** (0.1099)	0.3459 (0.1918)	0.3098 (0.2035)	0.3066 (0.2087)	0.1321 (0.0833)
Adj. R^2	0.506						
Within R^2		0.404					
Pseudo-R^2			0.517	0.343	0.333	0.382	0.506
Degree of freedom	171	171	171	171	171	171	171

OLS = Pooled OLS model; RE = Random effects panel data model; Q.05 = Quantile regression model at level 0.05; Q.25 = Quantile regression model at level 0.25; Q.50 = Quantile regression model at level 0.50; Q.75 = Quantile regression model at level 0.75; Q.95 = Quantile regression model at level 0.95.
Notes: Non-standardized beta coefficients; standardized errors in parentheses.
Dependent variable: Logged peak flow; CSA: Dummy variable (0: Detroit-Warren-Ann Arbor CSA; 1: Chicago-Naperville CSA)
*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

Table 3. Results of the regression analyses predicting the effects of development size on peak flow.

Index	OLS	RE	Q.05	Q.25	Q.50	Q.75	Q.95
Main effects							
Percentage of area (PLAND)	0.0107* (0.0043)	0.0101 (0.0077)	0.0106*** (0.0028)	0.0135* (0.0064)	0.0076 (0.0056)	0.0073 (0.0073)	0.0047 (0.0041)
Hydraulic connectivity (H_conn)	-0.015*** (0.0044)	-0.0134 (0.0074)	-0.017*** (0.0028)	-0.0143* (0.0065)	-0.0122* (0.0056)	-0.0097 (0.0074)	0.0009 (0.0041)
Chicago interaction effects							
CSA(1)*PLAND	-0.0166** (0.0056)	-0.0154 (0.0100)	-0.020*** (0.0036)	-0.0202* (0.0083)	-0.0124 (0.0072)	-0.0092 (0.0094)	-0.0047 (0.0053)

CSA(1)*H_conn	0.0121* (0.0055)	0.0106 (0.0093)	0.0222*** (0.0035)	0.0123 (0.0082)	0.0109 (0.0070)	0.0072 (00093)	-0.0025 (0.0052)
Control variables							
24-hour peak precipitation	0.0072*** (0.0021)	0.0071*** (0.0015)	0.0035* (0.0014)	0.0041 (0.0032)	0.0053 (0.0027)	0.0101** (0.0036)	0.0149*** (0.0020)
5-day antecedent wetness	0.0048 (0.0026)	0.0059** (0.0018)	0.0085*** (0.0017)	0.0046 (0.0039)	0.0070* (0.0034)	0.0056 (0.0044)	0.0017 (0.0025)
Size of watershed	0.0049*** (0.0007)	0.0047*** (0.0011)	0.0063*** (0.0004)	0.0052*** (0.0010)	0.0047*** (0.0009)	0.0050*** (0.0012)	0.0063*** (0.0006)
Mean slope	0.0570 (0.0743)	0.0368 (0.133)	0.0511 (0.0478)	0.0480 (0.110)	0.0835 (0.0952)	0.116 (0.126)	-0.0055 (0.0699)
K_{sat}	-0.0277 (0.0191)	-0.0259 (0.0342)	0.0404** (0.0123)	-0.0257 (0.0284)	-0.0164 (0.0245)	-0.0193 (0.0323)	-0.0181 (0.0180)
Number of reservoirs	-0.059*** (0.0172)	-0.0575* (0.0286)	-0.125*** (0.0111)	-0.088*** (0.0255)	-0.0667** (0.0220)	-0.0566 (0.0291)	-0.0402* (0.0162)
CSA	-0.4165* (0.1958)	-0.3938 (0.3526)	0.1745 (0.1259)	-0.3906 (0.2909)	-0.2895 (0.2510)	-0.2381 (0.3310)	-0.0808 (0.1843)
2001	0.2841* (0.1400)	0.3243*** (0.0869)	0.3259*** (0.0900)	0.2105 (0.2080)	0.2747 (0.1795)	0.3276 (0.2367)	0.6187*** (0.1318)
2006	-0.0881 (0.1371)	-0.0542 (0.0846)	-0.3879*** (0.0882)	-0.2253 (0.2037)	-0.0710 (0.1758)	0.0394 (0.2319)	0.0706 (0.1291)
2011	0.2922 (0.1490)	0.3081** (0.0938)	0.5020*** (0.0958)	0.3204 (0.2214)	0.2281 (0.1910)	0.1678 (0.2520)	0.2298 (0.1403)
Adj. R^2	0.524						
Within R^2		0.400					
Pseudo-R^2			0.466	0.324	0.334	0.372	0.517
Degree of freedom	172	172	172	172	172	172	172

OLS = Pooled OLS model; RE = Random effects panel data model; Q.05 = Quantile regression model at level 0.05; Q.25 = Quantile regression model at level 0.25; Q.50 = Quantile regression model at level 0.50; Q.75 = Quantile regression model at level 0.75; Q.95 = Quantile regression model at level 0.95.
Notes: Non-standardized beta coefficients; standardized errors in parentheses.
Dependent variable: Logged peak flow; CSA: Dummy variable (0: Detroit-Warren-Ann Arbor CSA; 1: Chicago-Naperville CSA)
*p < 0.05, **p < 0.01, ***p < 0.001

Table 4. Results of the regression analyses predicting the effects of development connectivity on peak flow.

Index	OLS	RE	Q.05	Q.25	Q.50	Q.75	Q.95
Main effects							
Radius of gyration (GYRATE)	0.0002*** (0.0001)	0.0002* (0.0001)	0.0003*** (0.0001)	0.0002 (0.0001)	0.0003** (0.0001)	0.0003*** (0.0001)	0.0001* (0.0001)
Cohesion (COHESION)	0.0243 (0.0220)	0.0216 (0.0395)	-0.0452* (0.0179)	0.0280 (0.0378)	0.0403 (0.0265)	0.0188 (0.0260)	0.0732*** (0.0185)
Impervious ratio (TIA)	-0.0091 (0.0096)	-0.0085 (0.0167)	0.0200* (0.0078)	-0.0017 (0.0165)	-0.0166 (0.0115)	-0.0198 (0.0113)	-0.029*** (0.0081)
Hydraulic connectivity (H_conn)	-0.015*** (0.0042)	-0.0142* (0.0070)	-0.018*** (0.0034)	-0.0144* (0.0072)	-0.0130* (0.0050)	-0.0153** (0.0049)	-0.013*** (0.0035)
Chicago interaction effects							
CSA(1)*GYRATE	-0.0001 (0.0001)	-0.0000 (0.0002)	-0.000*** (0.0001)	-0.0002 (0.0002)	-0.0000 (0.0001)	-0.0000 (0.0001)	0.0000 (0.0001)
CSA(1)*COHESION	-0.250* (0.113)	-0.249 (0.178)	0.0036 (0.0922)	-0.146 (0.195)	-0.384** (0.136)	-0.261 (0.134)	-0.315** (0.0954)
CSA(1)*TIA	0.0023 (0.0111)	0.0032 (0.0195)	-0.033*** (0.0090)	-0.0106 (0.0191)	0.0114 (0.0134)	0.0185 (0.0131)	0.0296** (0.0093)
CSA(1)*H_conn	0.0136** (0.0051)	0.0132 (0.0086)	0.0272*** (0.0041)	0.0123 (0.0087)	0.0089 (0.0061)	0.0121* (0.0060)	0.0099* (0.0043)
Control variables							
24-hour peak precipitation	0.0065** (0.0020)	0.0071*** (0.0015)	0.0015 (0.0016)	0.0042 (0.0034)	0.0053* (0.0024)	0.0070** (0.0023)	0.0146*** (0.0017)
5-day antecedent wetness	0.0047* (0.0024)	0.0059** (0.0018)	0.0070*** (0.0019)	0.0052 (0.0041)	0.0049 (0.0029)	0.0029 (0.0028)	0.0024 (0.0020)
Size of watershed	0.0046***	0.0044***	0.0066***	0.0047***	0.0047***	0.0051***	0.0038***

	(0.0008)	(0.0012)	(0.0006)	(0.0013)	(0.0009)	(0.0009)	(0.0007)
Mean slope	0.104 (0.0779)	0.0874 (0.139)	0.227*** (0.0635)	0.0764 (0.134)	0.0221 (0.0940)	0.171 (0.0922)	0.0793 (0.0657)
K_{sat}	-0.0467* (0.0189)	-0.0461 (0.0336)	0.0453** (0.0154)	-0.0743* (0.0325)	-0.0395 (0.0228)	-0.0268 (0.0223)	-0.0460** (0.0159)
Number of reservoirs	-0.087*** (0.0222)	-0.0802* (0.0359)	-0.144*** (0.0181)	-0.0701 (0.0381)	-0.094*** (0.0267)	-0.114*** (0.0262)	-0.067*** (0.0187)
CSA	-0.3110 (0.2288)	-0.2892 (0.4012)	0.2205 (0.1865)	-0.7513 (0.3937)	-0.1876 (0.2758)	-0.0055 (0.2707)	-0.1504 (0.1930)
2001	0.2788* (0.1273)	0.3118*** (0.0873)	0.3940*** (0.1038)	0.2837 (0.2190)	0.2765 (0.1534)	0.1966 (0.1506)	0.4528*** (0.1073)
2006	-0.0975 (0.1246)	-0.0643 (0.0846)	-0.4302*** (0.1015)	-0.2206 (0.2143)	-0.0906 (0.1502)	0.0748 (0.1474)	0.1805 (0.1051)
2011	0.3135* (0.1355)	0.3046** (0.0937)	0.5893*** (0.1105)	0.4664* (0.2332)	0.3150 (0.1634)	0.2995 (0.1604)	0.2594* (0.1143)
Adj. R^2	0.607						
Within R^2		0.404					
Pseudo-R^2			0.517	0.392	0.419	0.478	0.578
Degree of freedom	172	172	172	172	172	172	172

OLS = Pooled OLS model; RE = Random effects panel data model; Q.05 = Quantile regression model at level 0.05; Q.25 = Quantile regression model at level 0.25; Q.50 = Quantile regression model at level 0.50; Q.75 = Quantile regression model at level 0.75; Q.95 = Quantile regression model at level 0.95.

Notes: Non-standardized beta coefficients; standardized errors in parentheses.

Dependent variable: Logged peak flow; CSA: Dummy variable (0: Detroit-Warren-Ann Arbor CSA; 1: Chicago-Naperville CSA)

*p < 0.05, **p < 0.01, ***p < 0.001