Third 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 second quarterly task of quantifying the composition and configuration of green infrastructure and developed areas at consistent intervals from 2001 to 2016, the third quarterly task focused on measuring the climate and biophysical conditions and running statistical models; geospatial and statistic tools such as ArcGIS and STATA were used to accomplish this goal.

1. Introduction

Precipitation and antecedent wetness are the two direct and significant determinants of runoff depth and peak flow (Olivera & DeFee, 2007; Penna et al., 2011; Thomas et al., 2016). The runoff yield is subject to the increase during intensive, large rainfall events (Penna et al., 2011). A prolonged wet condition prior to major events saturates soil, escalating the potential for flooding during both frequent and infrequent storm events (Penna et al., 2011; Thomas et al., 2016).

Hydraulic conductivity, K_{sat}, which represents the dynamic transportation of water across diverse landscapes, is a hydrological concept defining the vertical movement of runoff that affects surface flow patterns and flood outcomes (Appels et al., 2016; Bracken & Croke, 2007; dos Santos et al., 2021). Bracken & Croke (2007) longitudinally explored the impact of hydraulic conductivity on runoff and concluded that on a flat terrain, near-saturated soil's hydraulic conductivity was one of the decisive factors generating surface runoff. Humberto Blanco-Canqui et al. (2002) explored the influence of hydraulic conductivity on runoff, and their Water Erosion Prediction Project (WEPP) hillslope model revealed that the higher K_{sat} had a negative association with runoff depth. Dos Santos (2021) specified that peak discharge rate was also strongly impacted by saturated hydraulic conductivity and antecedent soil water content.

This third quarterly task focused on measuring the control variables including the climate and biophysical conditions in the Chicago-Naperville and Detroit-Warren-Ann Arbor CSAs. The mean slope was analyzed as an additional control variable in the prediction model since the slope gradient is known to have a positive impact on runoff depth (El Kateb et al., 2013). Yet, the slope over one percent is found to have a negligible impact on both runoff depth and peak flow (Mumford & Neal, 1938). Reservoirs and dams, designed to control flooding, were also set as control variables in the models. As baseline regression models, the pooled ordinary least square (OLS) models were built to examine the longitudinal effects of green infrastructure and development's composition and configuration on runoff yields in both CSAs.

2. Method

2.1. Data construct and analysis

Control variables, including precipitation, antecedent wetness, slope, saturated hydraulic conductivity, and number of dams and reservoirs, were measured in this third quarterly task. To predict annual runoff depth, annual precipitation depth and 3-month depth prior to a given year (as an antecedent wetness factor) were computed. Meantime, for predicting annual peak discharge rate, 24-hour storm depth on the day that the peak flow took place in a given year as well as 5-day prior depth were measured. The Parameter-elevation Regressions on Independent Slopes Model (PRISM)'s climate data were used to extract and compute the corresponding daily, monthly, and annual storm depths at five-year intervals from 2001 to 2016 in ArcGIS.

As a biophysical variable, the mean slope was calculated based on the 30-m resolution national elevation dataset derived from the National Hydrography Dataset Plus (NHDPlus). The mean saturated hydraulic conductivity of soils, K_{sat}, was also computed for each watershed from the data retrieved from the Soil Survey Geographic Database (SSURGO). Finally, the number of dams was extracted from the National Inventory of Dams (NID). Based on the location of each dam, the number of reservoirs was visually monitored on the Google Earth's historical imageries and counted for the years 2001, 2006, 2011, and 2016 (see Table 1).

Table 1. Construct variables and data sources.

Variable	Description	Unit	Data Source
Annual Precipitation	Annual precipitation in the years 2001, 2006, 2011, and 2016	mm	PRISM Climate Data
24h precipitation	The 24-hour daily precipitation on the date of annual peak flow in the years 2001, 2006, 2011, and 2016	mm	PRISM Climate Data
3-month antecedent wetness	The 3-month wetness prior to the year of precipitation in the years 2001, 2006, 2011, and 2016	mm	PRISM Climate Data
5-day antecedent wetness	5-day wetness prior to the date of annual peak flow in the years 2001, 2006, 2011, and 2016	mm	PRISM Climate Data
slope	The mean slope of a watershed	%	NHDPlus
Saturated hydraulic conductivity (K_{sat})	The mean saturated hydraulic conductivity of a watershed	Micrometers per second	SSURGO
Number of dams	The number of dams in the years 2001, 2006, 2011, and 2016	-	NID
Number of reservoirs	The number of reservoirs in the years 2001, 2006, 2011, and 2016	-	Google Earth

PRISM = Parameter-elevation Regressions on Independent Slopes Model; NHDPlus = National Hydrography Dataset Plus; SSURGO = Soil Survey Geographic Database; NID = National Inventory of Dams.

2.2. Statistical analysis

The pooled OLS regression models were then built to analyze how the changes in the quantity and quality of green infrastructure, imperviousness, and urban development affect the two dependent variables: annual runoff depth and peak flow. The independent variables in the models are the mean total impervious area (TIA), hydraulic connectivity (the ratio of DCIA to TIA), and spatial patterns of green infrastructure and developed areas. Other variables affecting annual runoff depth and peak flow, such as precipitation, antecedent wetness, slope, saturated hydraulic conductivity, and number of dams and reservoirs, were also specified in the models as control variables. To test the different contributions of TIA and land use patterns to runoff generation by geographic location, interaction terms with the Chicago-Naperville and Detroit-Warren-Ann Arbor CSAs were particularly added in the models.

Some land use pattern variables were found to be highly interrelated each other through pairwise correlation tests. Thus, in this study, respective models were developed by the pre-determined criteria of land use patterns (i.e., size, shape, isolation/fragmentation, and connectivity) for both green infrastructure and development, in order to avoid multicollinearity issues. To increase the validity of results, outliers were excluded from the sample during the model specification process, and the OLS assumptions such as homoskedasticity and normality of residuals were completely checked. Finally, it is important to note that all dependent variables were log transformed to approximate the normality.

3. Results

The outcomes of the pooled OLS models (see Tables 2-5) specify the significant impacts of green infrastructure and development's composition and configuration on runoff depth and peak flow. Overall, TIA, hydraulic connectivity, annual precipitation, and 5-month antecedent wetness are consistently the most significant factors with the high standardized beta coefficients in the runoff depth models. Conversely, land-use patterns and hydraulic connectivity play more important roles in the peak flow models. Interaction terms in both models revealed different dominant factors by CSA. The runoff depth and peak flow in the Chicago-Naperville CSA, a budding region redeveloping vacant lots, are significantly influenced by the green infrastructure and development patterning. In contrast, either TIA or hydraulic connectivity serves a more dominant factor in the Detroit-Warren-Ann Arbor CSA, a shrinking region with growing vacant lands.

Table 2. Results of the pooled OLS regression analysis predicting runoff depth by green infrastructure pattern.

Index	Size model	Shape model	Isolation/Fragmentation model	Connectivity model
Main effects				
Percentage of area (PLAND)	0.001 (0.046)			
Largest patch (LPI)	0.003 (0.014)			
Shape (SHAPE)		0.106 (0.024)		
Contiguity (CONTIG)		0.139 (0.021)		
Proximity (PROX)			0.000 (0.023)	
Cohesion (COHESION)				0.007 (0.046)
Connectance (CONNECT)				-0.000 (-0.000)
Impervious ratio (TIA)	0.009** (0.294)	0.007*** (0.236)	0.008** (0.249)	0.007** (0.245)
Hydraulic connectivity (H_conn)	0.002* (0.118)	0.002** (0.120)	0.002** (0.128)	0.002 (0.123)
Interaction effects				
1.CSA*PLAND	0.009** (0.190)			
1.CSA*LPI	-0.036 (-0.154)			
1.CSA*SHAPE		-0.134 (-0.024)		
1.CSA*CONTIG		-0.162 (-0.019)		
1.CSA*PROX			0.001*** (0.182)	
1.CSA*COHESION				0.002 (0.013)
1.CSA*CONNECT				-0.030* (-0.194)
1.CSA*TIA	0.004 (0.093)	0.001 (0.035)	0.003 (0.078)	0.006 (0.148)
1.CSA*H_conn	0.004** (0.175)	0.004** (0.166)	0.003** (0.145)	0.004** (0.198)
Control variables				
Annual precipitation	0.001*** (0.308)	0.001*** (0.345)	0.001*** (0.298)	0.001*** (0.342)
3-month antecedent wetness	0.004*** (0.516)	0.003*** (0.503)	0.003*** (0.505)	0.004*** (0.514)
Mean slope	-0.020 (-0.037)	0.005 (0.010)	-0.019 (-0.036)	0.002 (0.003)
K_{sat}	-0.004	0.001	-0.001	-0.000

	(-0.064)	(0.020)	(-0.020)	(-0.006)
Number of reservoirs	-0.000 (-0.006)	0.001 (0.010)	-0.001 (-0.010)	-0.002 (-0.039)
Adj. R^2	0.619	0.595	0.627	0.622
Degree of freedom	288	288	288	288

Notes: Non-standardized beta coefficients; Standardized beta coefficients;
Dependent variable: Logged runoff depth; CSA: dummy variable (0: DWAA CSA; 1: CN CSA)
* p<0.05, ** p<0.01, *** p<0.001

Table 3. Results of the pooled OLS regression analysis predicting peak flow by green infrastructure pattern.

Index	Size model	Shape model	Isolation/Fragmentation model	Connectivity model
Main effects				
Percentage of area (PLAND)	-0.026*** (-0.363)			
Contiguity (CONTIG)		6.402*** (0.439)		
Proximity (PROX)			-0.003** (-0.299)	
Radius of gyration (GYRATE)				-0.002* (-0.249)
Impervious ratio (TIA)	(omitted)	0.017* (0.230)	(omitted)	(omitted)
Hydraulic connectivity (H_conn)	-0.025*** (-0.556)	-0.022*** (-0.507)	-0.027*** (-0.606)	-0.028*** (-0.629)
Interaction effects				
1.CSA*PLAND	0.029** (0.291)			
1.CSA*CONTIG		-3.562 (-0.200)		
1.CSA*PROX			0.006*** (0.447)	
1.CSA*GYRATE				0.003*** (0.401)
1.CSA*TIA	(omitted)	-0.041*** (-0.463)	(omitted)	(omitted)
1.CSA*H_conn	0.016** (0.307)	0.016** (0.307)	0.018** (0.346)	0.020** (0.375)
Control variables				
24-hour peak precipitation	0.005* (0.153)	0.005* (0.155)	0.006* (0.175)	0.005* (0.160)
5-day antecedent wetness	0.011** (0.254)	0.005 (0.124)	0.010** (0.241)	0.010** (0.231)
Mean slope	-0.025 (-0.020)	-0.126 (-0.098)	-0.092 (-0.072)	-0.130 (-0.101)
K_{sat}	0.019 (0.121)	0.006 (0.037)	0.007 (0.046)	0.021 (0.136)
Number of reservoirs	0.032** (0.162)	0.037*** (0.186)	0.035*** (0.176)	0.030** (0.150)
Adj. R^2	0.284	0.395	0.330	0.301
Degree of freedom	194	194	194	194

Notes: Non-standardized beta coefficients; Standardized beta coefficients;
Dependent variable: Logged peak flow; CSA: dummy variable (0: DWAA CSA; 1: CN CSA)
* p<0.05, ** p<0.01, *** p<0.001

Table 4. Results of the pooled OLS regression analysis predicting runoff depth by development pattern.

Index	Size model	Shape model	Isolation/Fragmentation model	Connectivity model
Main effects				
Percentage of area (PLAND)	0.004*** (0.235)			
Contiguity (CONTIG)		0.225 (0.015)		
Proximity (PROX)			0.000	

			(0.036)	
Patch density (PD)			-0.001***	
			(-0.155)	
Radius of gyration				0.000
(GYRATE)				(0.027)
Cohesion				0.012
(COHESION)				(0.102)
Impervious ratio (TIA)	(omitted)	0.006*	(omitted)	0.001
		(0.214)		(0.046)
Hydraulic connectivity	0.002**	0.002	0.002	0.002
(H_conn)	(0.115)	(0.108)	(0.083)	(0.121)
Interaction effects				
1.CSA*PLAND	0.000			
	(0.009)			
1.CSA*CONTIG		-0.511		
		(-0.030)		
1.CSA*PROX			0.000**	
			(0.243)	
1.CSA*PD			-0.000	
			(-0.004)	
1.CSA*GYRATE				0.000***
				(0.283)
1.CSA*COHESION				0.025
				(0.069)
1.CSA*TIA	(omitted)	0.002	(omitted)	0.003
		(0.043)		(0.068)
1.CSA*H_conn	0.003**	0.004*	0.005***	0.004*
	(0.156)	(0.157)	(0.221)	(0.165)
Control variables				
Annual precipitation	0.001***	0.001***	0.001***	0.001***
	(0.308)	(0.307)	(0.292)	(0.314)
3-month antecedent	0.004***	0.004***	0.004***	0.004***
wetness	(0.560)	(0.556)	(0.561)	(0.541)
Mean slope	0.016	0.023	0.025	0.022
	(0.030)	(0.043)	(0.046)	(0.042)
K_{sat}	0.001	0.002	0.001	0.001
	(0.022)	(0.028)	(0.011)	(0.022)
Number of reservoirs	-0.000	-0.000	-0.007***	-0.010***
	(-0.007)	(-0.009)	(-0.133)	(-0.207)
Adj. R^2	0.573	0.577	0.628	0.642
Degree of freedom	301	301	301	301

Notes: Non-standardized beta coefficients; Standardized beta coefficients;
Dependent variable: Logged runoff depth; CSA: dummy variable (0: DWAA CSA; 1: CN CSA)
* $p<0.05$, ** $p<0.01$, *** $p<0.001$

Table 5. Results of the pooled OLS regression analysis predicting peak flow by development pattern.

Index	Size model	Shape model	Isolation/Fragmentation model	Connectivity model
Main effects				
Percentage of area	0.003			
(PLAND)	(0.075)			
Shape (SHAPE)		-0.084		
		(-0.007)		
Proximity (PROX)			0.000	
			(0.225)	
Patch density (PD)			0.003	
			(0.172)	
Radius of gyration				0.000
(GYRATE)				(0.208)
Cohesion				-0.030
(COHESION)				(-0.123)
Hydraulic connectivity	-0.023***	-0.022***	-0.020***	-0.023***
(H_conn)	(-0.533)	(-0.508)	(-0.462)	(-0.540)
Interaction effects				
1.CSA*PLAND	-0.016**			
	(-0.364)			

1.CSA*SHAPE		-5.316**		
		(-0.396)		
1.CSA*PROX			0.000	
			(0.147)	
1.CSA*PD			0.018***	
			(0.503)	
1.CSA*GYRATE				0.000**
				(0.279)
1.CSA*COHESION				-0.525***
				(-0.577)
1.CSA*H_conn	0.020**	0.012	0.016**	0.021***
	(0.383)	(0.234)	(0.300)	(0.410)
Control variables				
24-hour peak	0.004	0.004	0.004	0.004
precipitation	(0.119)	(0.104)	(0.113)	(0.122)
5-day antecedent	0.005	0.004	0.005*	0.004
wetness	(0.118)	(0.104)	(0.123)	(0.100)
Mean slope	-0.103	-0.170	-0.051	-0.037
	(-0.081)	(-0.133)	(-0.040)	(-0.029)
K_{sat}	0.013	0.030**	0.026*	0.023*
	(0.094)	(0.217)	(0.184)	(0.167)
Number of reservoirs	0.025**	0.033**	0.021	-0.002
	(0.130)	(0.173)	(0.108)	(-0.010)
Adj. R^2	0.279	0.360	0.465	0.442
Degree of freedom	206	206	206	206

Notes: Non-standardized beta coefficients; Standardized beta coefficients;
Dependent variable: Logged peak flow; CSA: dummy variable (0: DWAA CSA; 1: CN CSA)
* p<0.05, ** p<0.01, *** p<0.001

When examining different characteristics of green infrastructure and development patterns, regarding the ***size***, a higher percentage of the green infrastructure area (PLAND) helps reduce peak flow in the Detroit region ($p < 0.001$). The ***shape*** of land uses generally does not demonstrate a significant association with runoff yields except in the runoff depth model; the shape (SHAPE) and contiguity (CONTIG) of green infrastructure patches are positively related with runoff depth. Regarding the ***isolation/fragmentation and connectivity***, a less isolated land-use pattern with higher proximity (PROX), cohesion (COHESION), and radius of gyration (GYRATE) tend to increase runoff depth.

It is important to note that some results in the pooled OLS models are counterintuitive, mostly in the peak flow models. The coefficients of shape (SHAPE), proximity (PROX), cohesion (COHESION), and radius of gyration (GYRATE) show unexpected signs. Counterintuitively, the percentage of the green infrastructure area (PLAND) in the Chicago region also demonstrates a significant positive association with runoff yields in the pooled OLS models ($p < 0.1$). To longitudinally explore the performance of land use patterns in modifying surface flow regimes while controlling for all potential time-invariant regressors and estimate their specific impacts on different quantiles of runoff depth and peak flow, advanced econometric models such as panel data and quantile regression models will be further used in the next task to enhance the validity of results.

4. Next tasks

The next tasks for the fourth quarterly report will focus on developing advanced statistical models such as quantile regression and/or panel data models and preparing for a manuscript publication as well as a conference presentation based on the complete results. It is important to note that a PhD student named Zhicheng Xu, a research assistant on this project, submitted a conference abstract to the Council of Educators in Landscape Architecture (CELA) in September 2021 under the supervision of the investigator, Dr. Wonmin Sohn, with the preliminary results of this project. The abstract was accepted in November 2021 after a peer review, and the project outcome will be presented at the CELA annual conference in March 2022.

Task	Major Activities	2021										2022	
		Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb
Task 1: Watershed delineation	Activity 1 – Watershed delineation	■											
	Activity 2 – Verification	■	■										
Task 2: Variables measurement	Activity 3 – Measurement of hydrologic variables			■	■								
	Activity 4 – Measurement of imperviousness variables				■	■	■						
	Activity 5 – Measurement of GI pattern variables						■	■					
	Activity 6 – Measurement of climate and geophysical variables							■					
Task 3: Data analysis	Activity 7 – Statistical modeling								■	■	■		
Task 4: Documentation and dissemination	Activity 8 – Report writing, manuscript publication, and conference presentation											■	■

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