First 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: Chicago-Naperville and Detroit-Warren-Ann Arbor combined statistical areas (CSAs). In association with population changes over the last few decades, the two regions have demonstrated contradictory land development trends. 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 put more effort into revitalizing blighted vacant lots, renovating them to be open green spaces for city beautification. Yet, in the face of climate change, increasing storm intensity and frequency are continuing to threaten both regions and exacerbating 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 purpose of this study is 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 contribute 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.

The first quarterly task focused on delineating watersheds in the study area based on topographic characteristics and computing hydrologic variables such as annual runoff depth and peak flow at consistent intervals from 2001 to 2016.

1. Introduction

In the last several decades, the Chicago-Naperville and Detroit-Warren-Ann Arbor combined statistical areas (CSAs) in the Midwest have experienced contrasting trends in socio-demographic transition. The Chicago-Naperville CSA is a budding region, recording a 3.8% population growth from 2000 to 2019 (US Census Bureau, 2021); the population in Chicago-Naperville-Elgin metropolitan statistical area (MSA) is expected to have an additional 25% growth (2.4 million people) by 2040 (Chicago Metropolitan Agency for Planning, 2010). The metropolitan area had the third-highest gross domestic product (GDP) among all US metropolitan regions in 2014, with $50,690 per capita personal income (ProximityOne, 2018a; Statista, 2020). Conversely, the Detroit-Warren-Ann Arbor CSA is a rapidly shrinking region. Its population declined by approximately 2.4% from 2000 to 2019 (US Census Bureau, 2021), and this trend will continue, particularly in the city of Detroit (Detroit Future City, 2013). Based on 2014 GDP data, the Detroit-Warren-Dearborn MSA ranked only 14th, with a $44,500 per capita personal income (ProximityOne, 2018b; Statista, 2020). Detroit, one of the poorest cities in the US, had the highest poverty rate of 16.2% in 2014, higher than the national average poverty rate (Bouffard, 2015).

The Chicago and Detroit regions demonstrated different land development trends in association with their contradictory population changes. The gross vacancy rate in the Chicago-Naperville-Elgin MSA has shown a downward trend since 2015, since vacant lots have been redeveloped to accommodate the approximately 1.2 million in population growth expected by 2040 (Chicago Metropolitan Agency for Planning, 2010; Ramsey, 2012; US Census Bureau, 2020). Conversion of vacant lots into urban agriculture, community gardens, parks, and bus shelters has also been planned as ways of bringing communities and residents together (Chicago Metropolitan Agency for Planning, 2010). Conversely, due to the decreasing population, the number of vacant lands will continue to grow in the Detroit area (Detroit Future City, 2016). In 2014, Detroit had approximately 120,000 vacant lots totaling more than 20 square miles, and that number is forecast to exceed 40 square miles in the future (Detroit Future City, 2013, 2016). The gross vacancy rate in the Detroit-Warren-Dearborn MSA continued to hover around 9% through 2018 (US Census Bureau, 2020). Unlike the Chicago area, only a limited number of vacant lots have been redeveloped for new housing construction in the Detroit area because of the immense amount of vacant land (Detroit Future City, 2016). More than 60% of the current vacant lots in Detroit are suitable for open green space development (Detroit Future City, 2016).

Even with these varying development trajectories pertaining to population gain and loss, the flooding issue has increased in severity in both CSAs. According to the National Land Cover Dataset from 2001 to 2016 provided by the United States Geological Survey (USGS), the Chicago-Naperville CSA experienced a 20% increase in impervious surfaces, while the Detroit-Warren-Ann Arbor CSA remained almost unchanged. In the Chicago region, urbanization has been one of the major drivers of flooding. Infill and sprawl development in the Chicago region has increased impervious coverage and modified environmental conditions, resulting in the expansion of floodplains, loss of vegetation, and deterioration of retention properties of soils, increasing runoff yields and the risk of flooding (Chicago Metropolitan Agency for Planning, 2010, 2017, 2018; City of Chicago, 2014). In the Detroit area, a degraded gray infrastructure and large amount of vacant land contribute to flooding (Detroit Future City, 2013). The capacity of current stormwater management systems is not enough to manage the overwhelming amount of stormwater during extreme events, threatening human safety (The City of Detroit Water and

Sewerage Department, 2018). Moreover, climate shifts are bringing additional challenges to controlling flooding in both the Chicago and Detroit regions. The intensity and frequency of extreme storm events are projected to continue to grow in the next few decades (Chicago Metropolitan Agency for Planning, 2017; City of Detroit, 2019; The City of Detroit Water and Sewerage Department, 2018).

Green infrastructure is a promising, cost-effective strategy for managing stormwater (Chicago Metropolitan Agency for Planning, 2010, 2017). However, a lack of green infrastructure poses a significant threat to both the Chicago and Detroit regions. Along with urbanization, many natural areas and habitats have been destroyed in the Chicago region, jeopardizing indigenous species (Chicago Mayor's Nature & Wildlife Advisory Committee, 2011). By 1980, in the Detroit region, over 500,000 trees had disappeared due to disease, urbanization, and economic constraints (American Forests, 2012). Urban forests were severely injured, even if Detroit was known as the "city of trees" (Austin & Kaplan, 2003).

Considering land development trends and socioeconomic statuses, current municipalities in the Chicago and Detroit regions have attempted to expand their green infrastructure in a variety of ways. Based on local community funding and government budgets, the Chicago region has developed a multi-year green infrastructure plan to manage stormwater (City of Chicago, 2015). The plan emphasizes retrofits of existing developed areas with green infrastructure, particuarly focusing on the neighborhood scale, in order to control basement flooding (Chicago Metropolitan Agency for Planning, 2010; City of Chicago, 2015; Steele, 2017). A combination of gray and green infrastructure has also been suggested to control intense flood events. Unlike the Chicago region, cost-effective approaches are more preferred in the Detroit region, due to decreasing tax revenues and recovery from bankruptcy (Steis-Thorsby et al., 2020). The Detroit metropolitan area has plentiful low-price vacant lots, of which conversion into green infrastructure would be both feasible and effective (Detroit Future City, 2019; Nassauer et al., 2018). A combination of blue and green infrastructure systems has been put forward in Detroit to replace aging and costly gray infrastructure and manage stormwater runoff (Detroit Future City, 2013, 2016).

Given these conditions, it is unclear how different land use approaches, in association with population gain or loss, shape the resilience of metropolitan regions and protect them from current and future natural disasters, or how changes in the quantity and quality of imperviousness and green infrastructure longitudinally affect the flooding response of cities. In the face of increasing flood risks accelerated by climate change, it is important to develop a comprehensive understanding of urban flooding mechanisms in both growing and shrinking communities. The purpose of this research is to cross-sectionally and longitudinally examine the composition and configuration of development and green infrastructure on urban runoff in the selected Midwestern CSAs: Chicago-Naperville and Detroit-Warren-Ann Arbor. This first quarter task was to delineate watersheds using Arc Hydro, a hydrologic model in ArcGIS (Maidment, 2002), and estimate the annual runoff depths and peak flow rates of watersheds at five-year intervals from 2001 to 2016.

2. Methods

2.1. Study area

This study selected 99 watersheds intersecting with the Chicago-Naperville and Detroit-Warren-Ann Arbor CSAs (see Figure 1). The study area has a humid continental climate (Kottek et al., 2006). In the Chicago-Naperville CSA, the average annual precipitation from 1871 to 2020 was 937 mm (National Weather Service, 2020). The annual temperature fluctuates between -5.55°C and 28.3°C (Weather Spark, 2020). Similar to the climate in the Chicago region, the average annual precipitation in the Detroit-Warren-Ann Arbor CSA is 835.41 mm, with the mean temperature ranging from -4.12°C in January to 23.06°C in July (National Centers for Environmental Prediction, 2014).

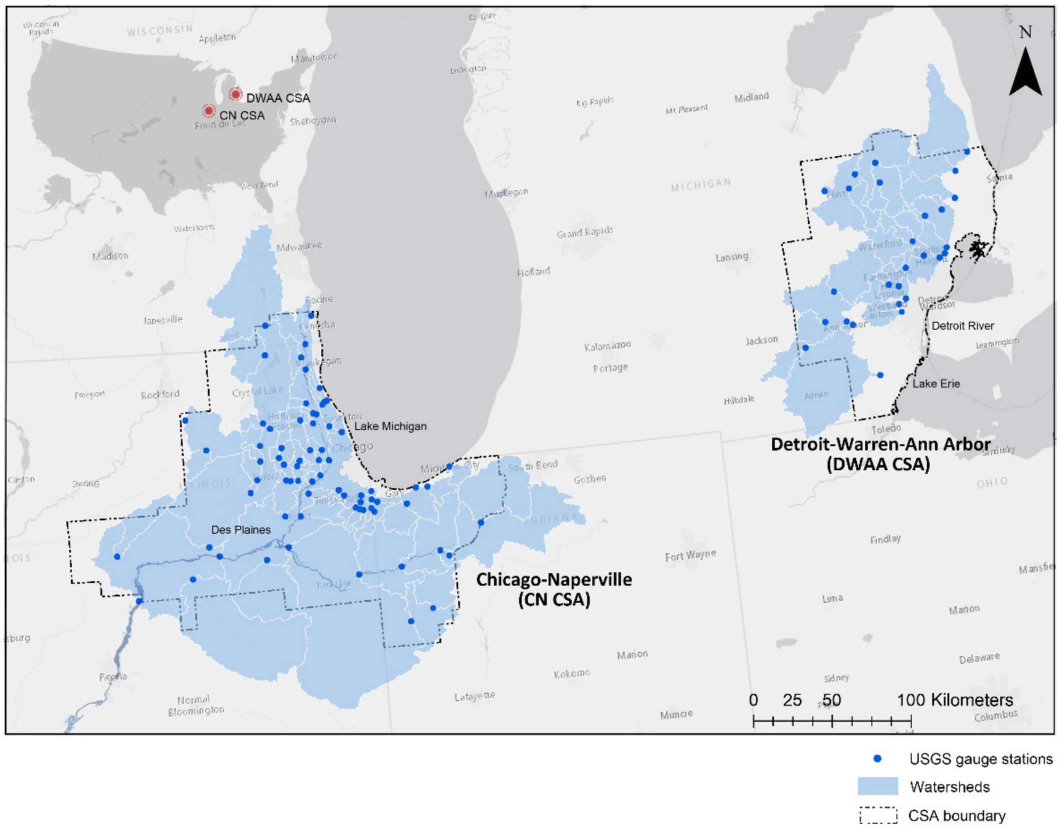

Figure 1. Ninety-nine watersheds located in the Chicago-Naperville and Detroit-Warren-Ann Arbor CSAs.

The surface drainage patterns of both regions are determined by their unique topographies. Along with the construction of the Chicago Sanitary and Ship Canal, the sewer systems of most watersheds in the Chicago-Naperville CSA were designed to flow into the Des Plaines and Mississippi Rivers to the southwest, away from Lake Michigan (Chicago Metropolitan Agency for Planning, 2014; Chrzastowski, 2009). The stormwater sewer system in the Detroit-Warren-Ann Arbor CSA is combined with wastewater sewage and flows eastward to the Rouge and Detroit Rivers, and finally to Lake Erie (The City of Detroit Water and Sewerage Department, 2018).

2.2. Data construct and analysis

This first quarter task was to measure the annual runoff depths and peak flow rates of watersheds in both CSAs at five-year intervals from 2001 to 2016. Data regarding streamflow, monitored every 15 minutes, were retrieved from the USGS and converted into annual parameters (see Table 1).

Table 1. Construct variables and data source.

Variable	Description	Unit	Data Source
Runoff depth	Annual runoff depth per unit area in the years 2001, 2006, 2011, and 2016	mm	USGS
Peak flow rate	Annual peak streamflow in the years 2001, 2006, 2011, and 2016	m^3/s	USGS

USGS = United States Geological Survey.

2.2.1. Watershed delineation

Using Arc Hydro, the research team delineated watersheds based on the 30m resolution National Elevation Dataset and 2001 to 2016 streamflow data obtained from USGS gauging stations. The flow direction grid and surface flow accumulation network were first produced and forced into the modeling of the stream network. To ensure measurement validity, the simulated stream network was verified using measured data extracted from the National Hydrography Dataset (NHD Plus). The drainage line and watershed delineation then proceeded using the verified stream network. As a result, 72 watersheds for the Chicago-Naperville CSA and 27 watersheds for the Detroit-Warren-Ann Arbor CSA were delineated and analyzed in this study.

2.2.2. Hydrologic variables measurement

Two hydrologic parameters, annual runoff depth per unit watershed area and peak flow, were computed as dependent variables for each watershed, based on USGS streamflow data collected every 15 minutes from 2001 to 2016. The impacts of upstream watersheds on target watersheds were factored out by subtracting the influx streamflow from the outflow. Out of the total 99 watersheds, only head watersheds in which streams of the highest order were positioned were selected for peak flow computation. The peak flow of downstream watersheds was excluded from the sampling because the duration of runoff and time to peak were not consistent across all watersheds.

3. Results

Except in 2006, the average annual runoff depth in the Chicago-Naperville CSA was much greater than that of the Detroit-Warren-Ann Arbor CSA (see Tables 2 and 3). Overall, the Chicago region experienced a more substantial variation in peak flow and runoff depth than the Detroit region, even when the mean annual peak flows in the Chicago and Detroit regions were comparable. The Chicago region had the highest mean annual runoff depth in 2016, while the Detroit region had the highest value in 2011. For peak flow, the Chicago region demonstrated the highest mean annual peak flow in 2011, while the Detroit region was highest in 2001.

It is important to note that some potential errors and/or outliers in the runoff depth estimation were identified in the Chicago-Naperville CSA. Possible reasons for negative values include technical or measurement errors in the USGS's gauging method and an excessive withdrawal of freshwater for agricultural, industry, and municipal uses.

Table 2. Annual runoff depth and peak flow in the Chicago-Naperville CSA.

Variable	Year	Mean	Std.	Range
Runoff depth (mm)	2001	379.54	178.02	-158.24-844.70
	2006	278.66	199.53	-453.70-877.13
	2011	444.73	235.19	-547.24-1,173.43
	2016	511.13	338.29	-451.23-2,737.21
Peak flow rate (m^3/s)	2001	46.52	92.93	3.26-515.37
	2006	30.71	40.86	1.87-220.59
	2011	48.24	60.86	2.72-319.98
	2016	36.85	62.63	2.22-325.64

Table 3. Annual runoff depth and peak flow in the Detroit-Warren-Ann Arbor CSA.

Variable	Year	Mean	Std.	Range
Runoff depth (mm)	2001	281.25	56.08	199.35-429.87
	2006	304.83	74.62	203.00-483.41
	2011	372.87	76.35	277.03-550.67
	2016	250.93	53.71	161.37-365.88
Peak flow rate (m^3/s)	2001	47.29	61.59	5.95-253.72
	2006	33.60	52.99	2.58-223.70
	2011	43.65	49.94	5.10-208.98
	2016	24.00	40.11	2.24-170.47

As shown in Figures 2 and 3, the middle region of the Chicago-Naperville CSA recorded the highest runoff depth throughout the entire study period, most predominantly in the city of Chicago, Grundy County, and Kendall County, and partially in Will County. Livingston County, located in the southwest of the Chicago-Naperville CSA, also had the highest peak flow rate in this region. In the Detroit-Warren-Ann Arbor CSA, watersheds in the southeast and Wayne County were exposed to more flooding risk with higher runoff depths (see Figure 4). The watershed with the highest peak flow rate was in the northwest of the Detroit-Warren-Ann Arbor CSA: Sanilac County (see Figure 5).

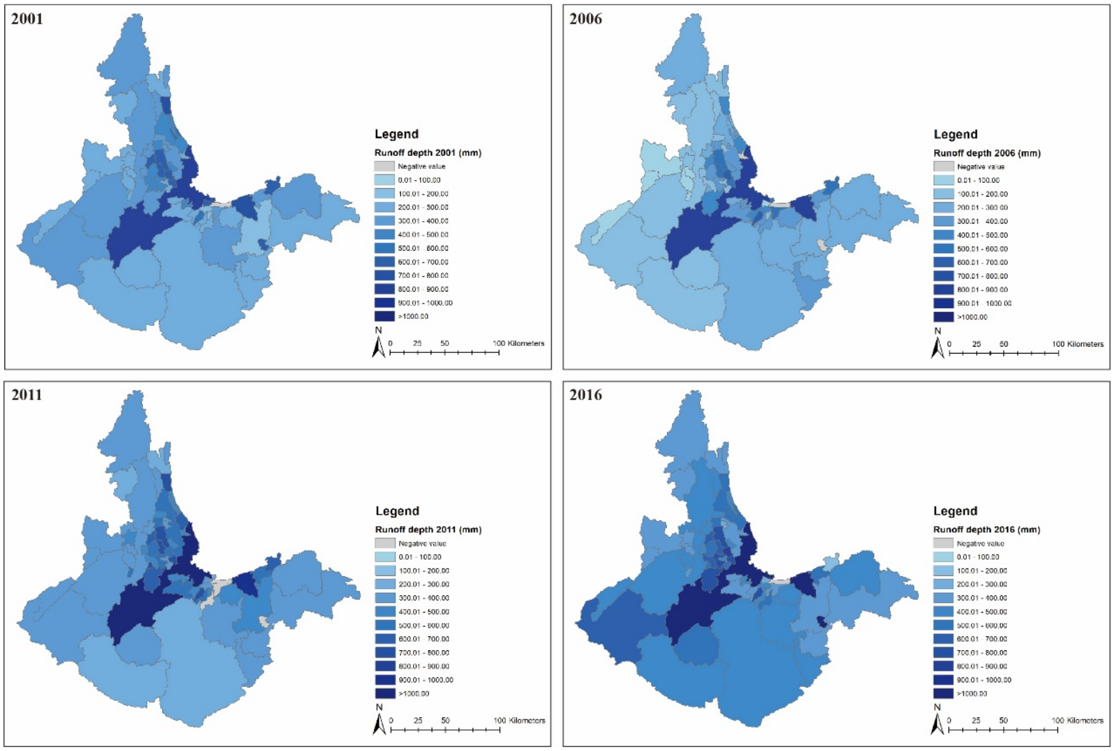

Figure 2. Annual runoff depth in the Chicago-Naperville CSA from 2001 to 2016.

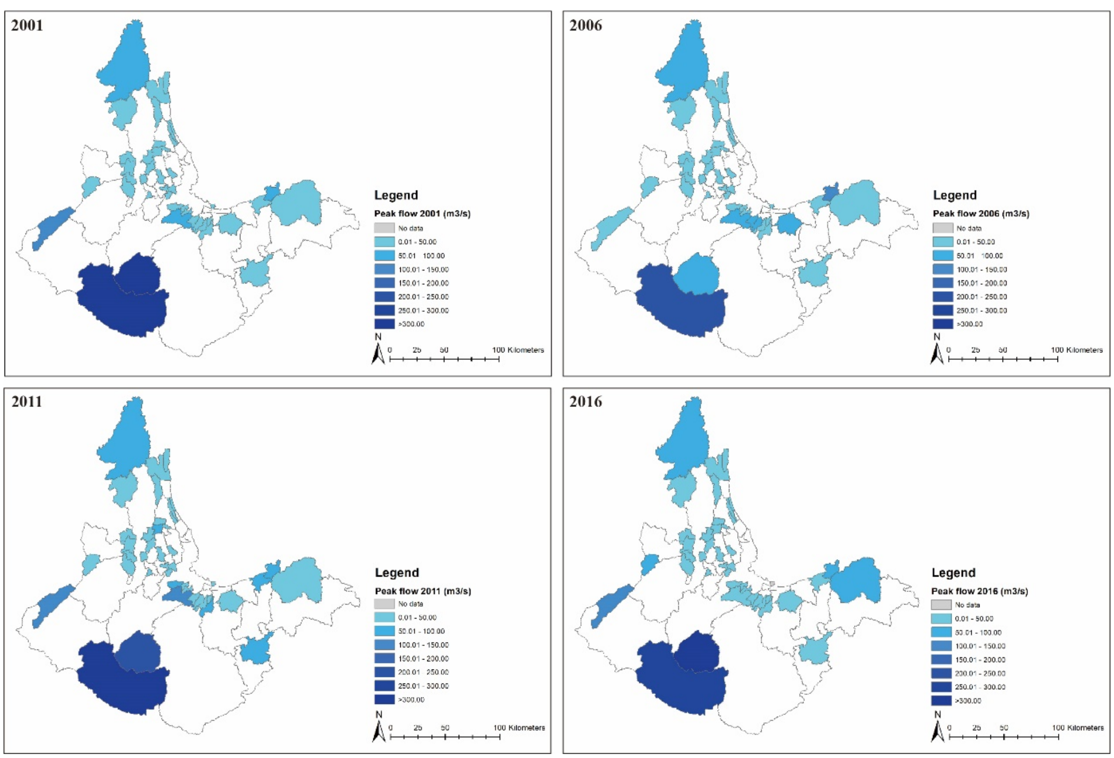

Figure 3. Annual peak flow in the Chicago-Naperville CSA from 2001 to 2016.
Note: Off-color watersheds are not head watersheds and thus were excluded from the analysis.

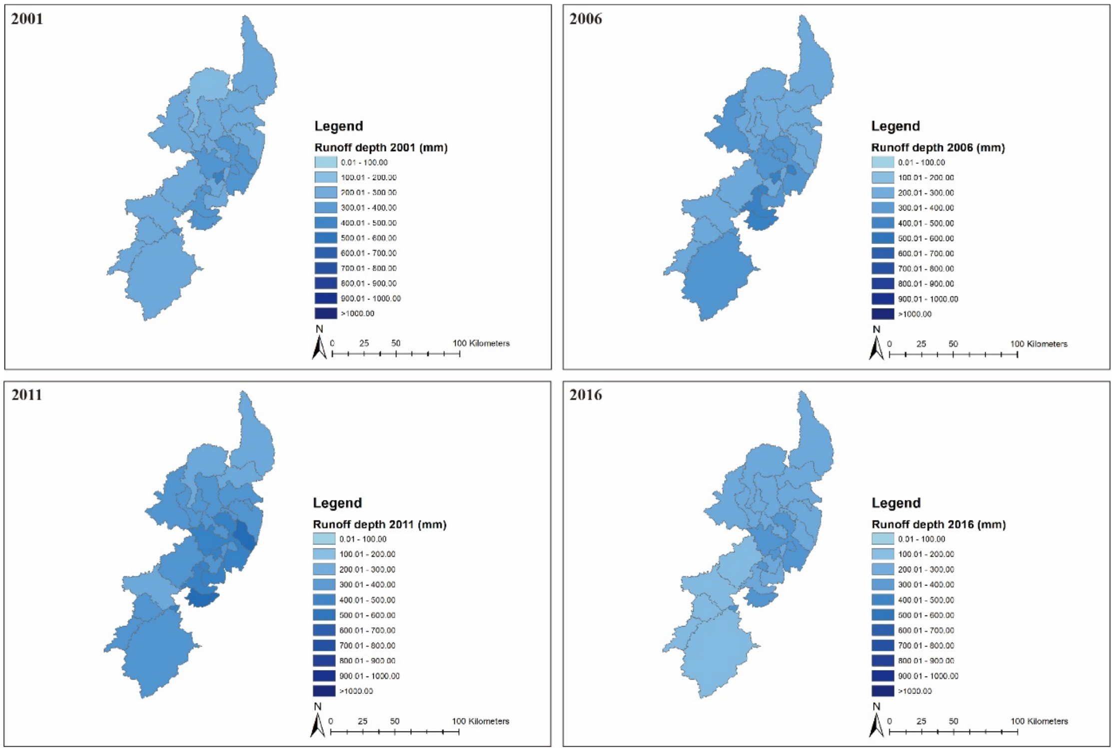

Figure 4. Annual runoff depth in the Detroit-Warren-Ann Arbor CSA from 2001 to 2016.

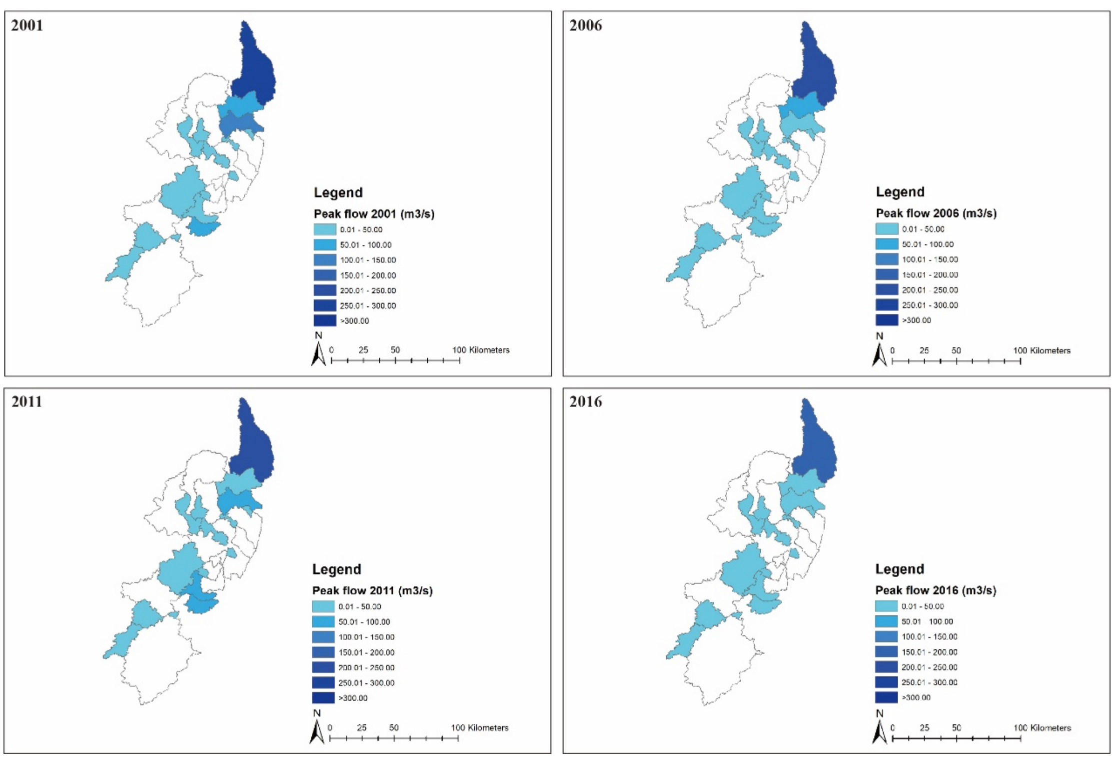

Figure 5. Annual peak flow in the Detroit-Warren-Ann Arbor CSA from 2001 to 2016.
Note: Off-color watersheds are not head watersheds and thus were excluded from the analysis.

4. Next tasks

The next tasks for the second quarterly report will focus on measuring land use variables such as time-series impervious composition and green infrastructure patterns. The selected variables will be extracted from the USGS National Land Cover Dataset using ArcGIS and FRAGSTATS software.

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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