ABSTRACT

MCGREGOR, DRESDEN GABRIELLE. Stormwater Management, Green Infrastructure, and Participatory Modeling in Historically Black Communities: A Case Study From Southeast Raleigh. (Under the direction of Dr. Louie Rivers III).

Green infrastructure has become known for its ability to alleviate the effects of increasing development on urban watersheds. However, recent findings have shown that minority communities are frequently underserved by green infrastructure developments relative to non-minority communities, as local installations of green infrastructure tend to follow patterns of gentrification. Further, urban planners who seek to implement green infrastructure may face obstacles related to both public skepticism and geospatial analysis required to optimize site-selection. Building on previous research on green infrastructure implementation in marginalized communities in urbanizing watersheds, we conducted a paper-based survey (n=95) within the communities surrounding Walnut Creek, a historically black community in southeast Raleigh that has a history of both catastrophic and nuisance flooding. Residents' perceptions of the locations of nuisance flooding were reported through a participatory mapping instrument. A hotspot model was developed to evaluate statistically significant clusters of flooding perceptions as indicated by the participatory instrument. To assess the suitability of using participatory mapping as a proxy for identifying locations of nuisance flooding, which could benefit from green infrastructure, the participatory hotspot analysis is compared to a traditional hydrologic geospatial modeling technique employed for assessing flow accumulation. For locations of high flow accumulation in the flow accumulation model, we found significant geospatial overlap with the flooding hotspots identified by residents. We conclude with a discussion of how the modeling techniques presented in this case study can be used to inform urban landscape developments in communities that may be skeptical toward urban greening proposals.

Stormwater management, green infrastructure, and participatory modeling in historically black communities: A case study from Southeast Raleigh

By
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A thesis submitted to the Graduate Faculty of
North Carolina State University
In partial fulfillment of the
requirements for the degree of
Master of Science

Natural Resources

Raleigh, North Carolina

2018

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BIOGRAPHY

Dresden McGregor's education has long been outside of tradition. As a child and young teen, she was active during her summers in recreational and ecological conservation camps in her home community of Bend, Oregon. After completing four years of study in the International Baccalaureate program—at the time, the only four-year IB program in the state—she entered Baylor University in Waco, Texas, in fall of 2010, where she studied sociology, political science, and Spanish. At Baylor, she participated in a classical education cohort known as the Baylor Interdisciplinary Core and was active in international student groups on campus. She also participated in several Baylor Law School clinics as a document translator for immigration and citizenship papers, where she developed an interest in working with underprivileged and disenfranchised communities.

Always one to make her own way, Dresden studied abroad three times, in Argentina, England, and Spain. She graduated from Baylor's Honors Program magna cum laude in 2014, completing an undergraduate thesis in criminology under the directorship of Dr. Sung Joon Jang of Baylor's Institute for Studies of Religion. That same year, she married her college sweetheart and moved with him to eastern North Carolina after losing a bet, but one she would attest is the best bet she ever lost. In 2016, after rediscovering her love of environmental science, she entered North Carolina State University's Forestry and Environmental Resources department under the direction of Dr. Louie Rivers III. In her time at NCSU, she has focused her work in flood-vulnerable minority communities at the intersection of public policy, urban forestry, and geographic information systems. She is a member of the North Carolina Water Resources Association and the Walnut Creek Wetland Community Partners. She is also a runner and a figure skater.

Acknowledgements

A project as complex as my thesis work has been has a lot of moving parts. I chiefly want to thank my advisor, Dr. Louie Rivers, for his guidance throughout this project. The current shape of this research is not originally what we envisioned—there's much more to it, now. I'm thankful for his encouragement to think creatively and move past my comfort zones, as well as for much advice and support, both inside and outside this project. In much the same capacity, I'd like to thank my committee as well, with each of whom I'm fortunate to have had the chance to collaborate.

For her assistance with data collection, her flexibility, and her patience, I'd like to thank Chantel Williams, who, this past year, spent over 150 hours walking around the neighborhood with me in the North Carolina summer while we conducted interviews. I'd also like to thank Stacy Supak, who has gone far and beyond what I expected when I initially asked for GIS advice. I'm thankful for her creative insights while developing this comparative analysis, for being a sounding board for my strange ideas, and for steering me in the right direction on more occasions than I can remember.

Additional thanks to Christy Perrin of WRRI, for helping me get connected with the Walnut Creek Wetland Community Partners; to Rev. Jemonde Taylor and St. Ambrose Episcopal Church, for hosting the focus groups and survey meetings; to Francis Carmichael-Jones, Stacie Hagwood, and the Walnut Creek Wetland Park (née Walnut Creek Wetland Center), for additional hosting help; and Amin Davis, for much help and insight into the history of environmental justice issues in Rochester Heights.

Working on environmental justice issues in this incredible community, it has never been far from my mind that, as a white girl from Central Oregon, I know very little about the experiences faced here. I'm grateful to the participants of the focus groups specifically, and to the communities of Rochester Heights and Biltmore Hills more generally, for their graciousness in engaging with and participating in these discussions. I'm also thankful personally for the chance to listen and learn. Finally, I acknowledge Peter Rabbe and American Rivers, who funded this project and helped us get the ball rolling.

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Introduction

In recent years, there has been a growing recognition that lay citizens need to have a voice in the governance of local hydrological systems (Ottinger, 2013; Cole and Foster, 2000; Schlosberg, 2007; Browns, 2011; Green et al., 2012; O'Toole et al., 2009). An evolving understanding of risk governance away from top-down regulation has similarly recognized the need for members of a given community to have adequate voice in the regulation of risks that they face (De Marchi, 2003; Checker, 2011; Laurian, 2004; Beamish and Luebbers, 2009; de Oliveira and Fra Paleo, 2016). Public participatory geographic information systems (PPGIS) have "come of age" in response, and these methods of rendering and quantifying place-based knowledge and values have become increasingly sought as ways to incorporate public knowledge and input into land-use planning (McCall and Dunn, 2012; Voinov and Gaddis, 2008; Taylor and de Loë, 2012; de Loë et al. 2015). PPGIS methodologies, which capitalize on knowledge of, experience with, and perspectives toward spatially contextual factors, allow for public participation in the risk governance process by directly involving relevant stakeholders in the assessment of both technical and perceived causes and consequences of risk. While the precise definition of PPGIS is "nebulous," there is general consensus that these methods involve the use of geographic information systems (GIS) technology to spatially render local knowledge of place in a manner that is sensitive to the complexity of human relationships with the environment (Tulloch, 2007; Brown and Weber, 2011; Brown et al., 2014; Dunn, 2007; McCall and Dunn, 2012; Cutts et al. 2011). The rise of PPGIS as a method of assessment has coincided with increasing awareness of the importance of local, experiential, or place-based knowledge as a means of inference into local realities, a subject that has been explored at some length in disciplines such as anthropology and human geography (McCall and Dunn, 2012; Starbuck, 2006; Brace and Geoghegan, 2011; Krauss and von Storch, 2012; Reyes-García et al., 2016).

As PPGIS is a method rather than a science, its applications are myriad. Recent studies have utilized PPGIS to assess resource management resources on public lands; assess differences in priorities for urban and rural water resource needs; assess the "co-production of science and policy" in the water resource sector; “map” individual values over parks and urban green spaces; assess cumulative environmental justice impacts in the context of “wicked” problems; compare conflict potential amongst multiple and variant stakeholders in a land-use context; and inform “village-level agricultural zoning” in the Democratic Republic of the Congo (Sieber, 2000; McIntyre et al., 2008; Jankowski, 2009; Cutts et al., 2011; Fagerholm et al., 2016; Pietrzyk-Kaszynska et al., 2017; Ives et al., 2017; Balram and Dragicevic, 2005; Bijket and Sijstma, 2017; Huang and London, 2016; Brown et al., 2017; Nackoney et al., 2013). Other mixed-methods study models have already begun incorporating spatial considerations into the distribution of social factors, and vice versa (Comber et al., 2008; Fagerholm et al., 2016; Crompton, 2005; Heynen et al., 2006). However, while some PPGIS research has incorporated themes of environmental quality and management, there is a present lack of research into the correspondence of local spatial knowledge with observed ecological, hydrological, and geological realities. This research aims to address that gap.

Building on previous studies pertaining to assessment of spatially-dependent experience, this study probes the intersection of the social and hydrological factors that both contribute and respond to nuisance flooding in Rochester Heights, a historically black community in southeast Raleigh, North Carolina. Specifically, this project assesses the confluence of nuisance flooding as reported by community residents through a participatory mapping instrument and actual hydrological flow accumulation in the communities surrounding the Walnut Creek wetland, located immediately north of Rochester Heights. Our participatory mapping instrument was developed in March 2017 as part of a larger survey instrument designed to examine barriers to the implementation of low-impact stormwater mitigation in this community. These barriers, which take the form of issues of institutional and social trust between communities and the environmental authorities who serve them, often stem from a skepticism toward urban improvement efforts that is rooted in a history of environmental racism (Comber et al., 2008; Heynen et al., 2006). We present a case study that may inform future incorporations of participatory data into land use planning and local governance.

1.1 Environmental iniquities and stormwater in Rochester Heights

PPGIS and stormwater management present a natural intersection point in the American South, where patterns of spatial segregation can be found in many cities where urban minorities, particularly African-Americans, have historically been relegated to undesirable tracts of land. The establishment of "locally undesirable land uses" (LULUs) including major transportation corridors, industrial facilities, and waste sites in communities of color has been well-studied since 1987, when the United Church of Christ's *Toxic Wastes and Race* first suggested a significant positive correlation between the presence of toxic waste facilities and the "nonwhite" percentage of surrounding populations that has since been corroborated at both local and national levels (Commission for Racial Justice, 1987; Cutter, 2006; Bullard et al., 2008; Mohai and Saha, 2007; Wilson et al., 2012; Bevc et al., 2007). Residential patterns in the southern United States further testify to an institutional and historical experience of communities of color bearing both environmental risk and disadvantage within urban geographies (Bullard and Wright, 2009; Schulz et al., 2016).

Since the 1990s, much research has been directed toward studying the ways in which experiences of urban nature vary along demographic lines such as race, income, and age. Studies conducted in the wake of severe weather events such as Hurricane Katrina and Superstorm Sandy have highlighted the discrepancies in disaster preparedness, adaptation, and resilience among minority, low-income, elderly, and other so-called "disadvantaged" populations compared to whiter, wealthier, and younger groups (Bullard and Wright, 2009; Faber, 2015). Along similar lines, a growing body of research has shown that the distribution of environmental amenities—and the physiological, psychological, and economic benefits that accompany their proximity—are poorly distributed along racial and socioeconomic lines (Kondo et al., 2015b; Wolch et al., 2014; Foo et al., 2015; Dale and Newman, 2009; Crompton, 2005; Abercrombie et al., 2008). In the case of Rochester Heights, the neighborhood's location in flood-vulnerable land is a direct result of discriminatory redlining and segregation patterns in the 1950s and 1960s. Rochester Heights, the first black subdivision in Raleigh, was established in 1954, and was for many years the only neighborhood in which black families could purchase homes (Focus group transcripts, fac. McGregor and Rivers, 2016).

Emblematic of trends seen nationally, flooding events have plagued the Rochester Heights community almost since its inception (Wilmington District Corps of Engineers, 1986). In addition to periodic nuisance flooding, the area suffered two instances of catastrophic flooding in 1996 and 1999 with hurricanes Fran and Floyd, and historical accounts of poor management of flooding are coupled in city records with other environmental justice issues such as industrial contamination and negligence.[1] In 1969, the construction of Interstate 40 created a physical barrier that divided the original community in half, resulting in two neighborhoods: Rochester Heights and Biltmore Hills. About half of what is now Rochester Heights is located within the Walnut Creek floodplain, and both neighborhoods have suffered from flooding after heavy rains, though investments in green infrastructure and wetland restoration have mitigated the rate of catastrophic flooding that was seen prior to 2009.[2]

1.2 PPGIS in the public sector

Many authors have noted the potential for PPGIS to provide a relatively unique interception point for science and policy, precisely because it is spatially dependent (Cutts et al., 2011; Brown and Weber, 2011; Dunn, 2007). Most urban and natural resource governance issues are also spatially dependent and are heavily rooted in local contexts, a broad category that encompasses everything from zoning and land use planning to geological, ecological, hydrological, and climatological realities (Cutts et al., 2011; Brown et al., 2017; Green et al., 2012). However, existing governance methods are also rooted in *normative* assumptions about how physical spaces should be divided and managed. Urban planning as much an exercise in learned, local knowledge as that which PPGIS typically simulate. In other words, the

[1] Local environmental justice organizations have maintained extensive records of contamination and negligence in Walnut Creek. Until the 1960s, raw sewage flowed through the wetland adjacent to the neighborhood. For more, see: https://naturalearning.org/sites/default/files/WalnutCreek.pdf and http://www.exploris.org/walnutcreek/history.php.
[2] Restoration of the Walnut Creek wetland, which began in 1996 and is ongoing, has partially mitigated the severity of flooding events in Rochester Heights.

assumptions behind spatial governance decisions are learned; as much research has shown, these assumptions are often at odds with those of the community members they serve (Ottinger, 2013; Mohai and Saha, 2007; Benson et al. 2013; de Loë et al., 2015; Pacione, 2013).

A good deal of PPGIS research in the public sector has focused on stewardship, with water resource management, parks management, and land use planning constituting a substantial part of the literature in this field (Cutts et al., 2011; McCall and Dunn, 2012; Brown and Weber, 2011; Brown et al., 2014; Pietrzyk-Kaszynska et al., 2017; Bijzet and Sijstma, 2017; Thomas, 2002; Nackoney et al., 2013; Moore and Elliott, 2016). Many recent studies have also focused on conflict management within these contexts and others (Brown et al., 2017; Brown and Raymond, 2014; Zhang et al., 2012; Moore et al., 2017; Bragagnolo et al., 2016). Because these are large and complex management issues that cross spatial boundaries and affect large varieties of stakeholders, both human and non-human, PPGIS research often involves comparison of multiple stakeholder perspectives, which further facilitates cross-comparisons against types of knowledge to create a fuller understanding of the contested space. This research framework also recognizes differences in organizational and group capacities without relegating one or the other type of knowledge as superior. As articulated by Cutts et al. (2011), it "recognize[s] a wider suite of information types, information sources, and knowledge types within geographic information systems," and can be used to collect a wider variety of spatial data than strictly computational processes allow.

2. Methods

2.1 Study area site selection & participatory exercise formulation

Because of the centrality of "community mapping and database development" to the research process, PPGIS is often resource-intensive, with data collection efforts predicated on time and the formation of relationships (Brown and Weber, 2011). Our study area was selected by a process that brought together a collection of researchers, city officials, community residents, and others over a period of several years. In 2014, the Walnut Creek Wetland Community Partnership (WCWCP) was established amidst a diverse group of stakeholders with activities and interests in the communities surrounding the Walnut Creek wetland, now home to the Walnut Creek Wetland Park.[3] Several other organizations, including Partners for Environmental Justice (PEJ), whose activities and advocacy in the late 1990s-early 2000s helped bring the Wetland Park into existence, and the Center for Human-Earth Restoration (CHER), were already active in the area, particularly in matters of environmental justice and ecological education for youth. In late 2015, this study was commissioned to assess community preferences and values around the implementation of low-impact stormwater mitigation technologies in the Walnut Creek wetland community. In August and September 2016, two focus group sessions were held with community residents to gather input and formulate questions that would address amenability to green infrastructure installation as well as environmental concerns within the neighborhood.[4] Over the course of these sessions, issues surrounding neighborhood experience with flooding and social trust emerged as issues of substantial concern in the community. These focus groups, along with additional input from the WCWCP and others, directly informed the development of a 15-minute survey-interview schedule addressing residents' experiences with stormwater, nuisance flooding, and both experiences with and perceptions of municipal environmental authorities.

2.2 Participatory data collection

Participatory data came from 95 survey-interviews conducted between April and October 2017. These survey-interviews were conducted among residents of the Rochester Heights and Biltmore Hills neighborhoods who were selected using a combination of snowball and convenience sampling over the survey period. Combined, the neighborhoods contain approximately 400 households, a figure derived

[3] For more, see https://wrri.ncsu.edu/partnerships/cewm/walnut-creek-wetland-community-project/.
[4] Six long-term residents of the neighborhood participated in these sessions, all of whom were highly-educated black women between the ages of 50-75, with an average neighborhood residency of 44 years. All participants were recruited through a snowball sampling procedure beginning with WCWCP member connections in the community, and all six attended both sessions.

from a combination of census data, property records, and individual respondent accounts of the neighborhood. High rates of vacancy in Rochester Heights resulted in a skew toward Biltmore Hills residents, though records of individual addresses were not recorded due to privacy concerns.

The survey-interview schedule included a mapping instrument in which residents were presented with a rudimentary, printed street map of the Rochester Heights and Biltmore Hills neighborhoods derived from public-access shapefiles of Wake County streets. Residents were then asked to indicate and mark sites in which they have seen or experienced nuisance flooding, defined as the prolonged collection of excessive stormwater on roads or property in the wake of heavy rain events. In general, “excessive” was interpreted to mean stormwater accumulation at levels prohibitive of everyday activity in these areas, with examples of “everyday activity” including driving, walking, and property maintenance. 76% of respondents completed the mapping portion of the survey. Once collected, participatory data were manually digitized and plotted on a replication of the participatory survey instrument that had been rasterized into a 5 x 5 key.[5] If a respondent marked a larger area, such as circling a road segment or shading a problem area, we plotted the midpoints of these indications between the extreme end of a mark and the boundary of its cell in the key. If markings crossed several cells, we plotted midpoints for each cell a respondent marked, maintaining equal distance between each point. All responses were digitized as point features, and all vector and raster data in this analysis and the hydrological assessment below were projected in the NAD 1983 North Carolina Lambert Conformal Conic StatePlane projection in U.S. Feet.

[5] The original investigation design for this experiment aggregated respondent data according to these 25 grid cells, evaluating significance at the cell level by converting fishnet polygons into weighted features, the rationale for aggregation being that the participatory mapping exercise was not an exercise in precision. After several rounds of feedback from stakeholders, we revised our PPGIS design toward interpreting respondent marks more exactly. We retained the 5 x 5 key in the input process in order to spatially contextualize respondent markings that covered large areas.

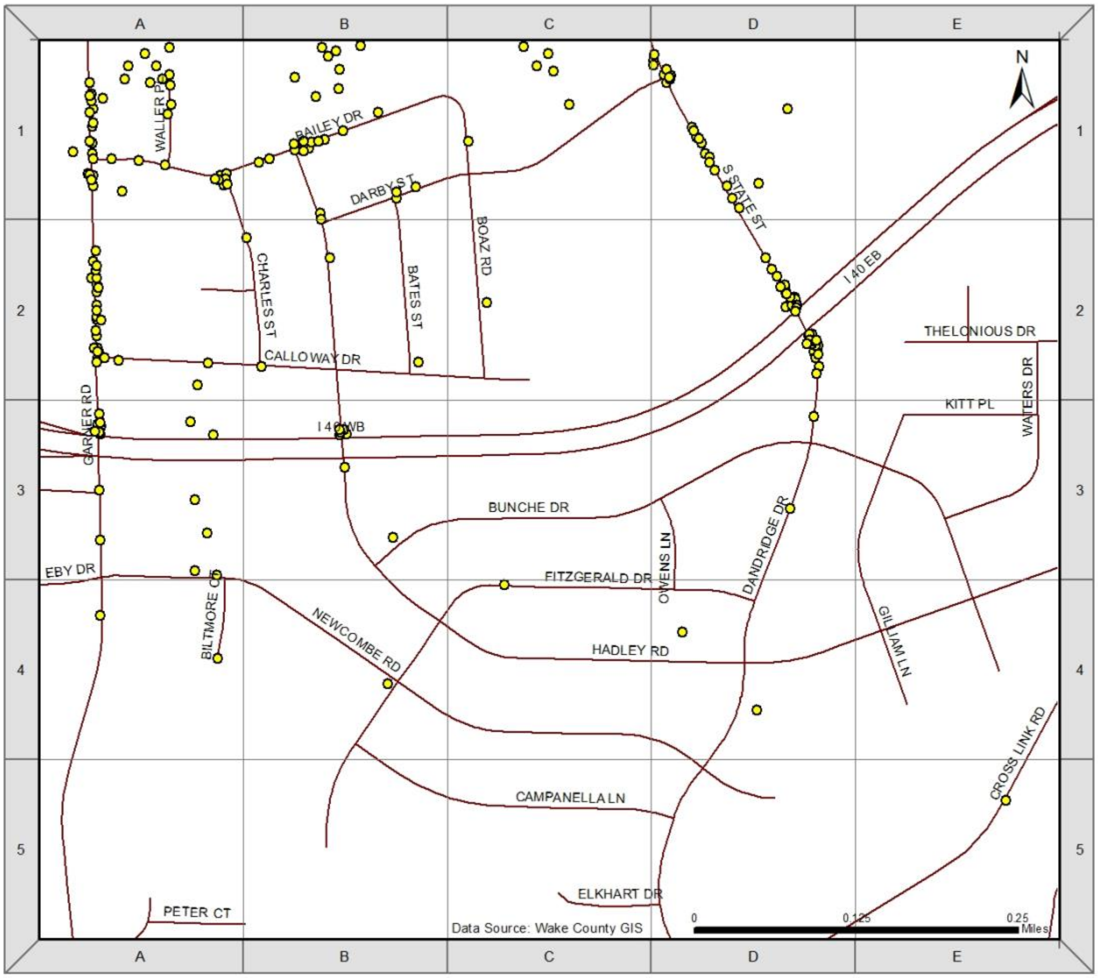

Figure 1: Study area and digitized participant-indicated areas of flooding. Survey-interview participants were presented with this instrument in printed form and asked to indicate sites of known nuisance flooding, defined as the prolonged collection of excessive stormwater on roads or property in the wake of heavy rain events. Each participant was shown a blank instrument with no marks or grid cells. In general, "excessive" was interpreted as stormwater accumulation at levels prohibitive of everyday activity in these areas, with examples of "everyday activity" including driving, walking, and property maintenance.

2.3 Hydrologic data collection

The hydrological component of the model was derived from public-access USGS geospatial and elevation data. The digital elevation model (DEM) that served as the base was mosaicked from six 1/9 arcsecond (approximately 10 ft ^{2}) tiles downloaded from the USGS National Map. These tiles were then imported into ArcMap 10.5.1, reformatted into ESRI GRID format, and re-projected. A full watershed delineation followed using ArcHydro's DEM PreProcessing toolset.[6] This analysis is based predominantly on the results of the flow accumulation analysis at the watershed level. The primary watershed in this investigation, the Walnut Creek watershed in southern Wake County, is a HUC-12 watershed that covers an area of approximately 29,422 acres and is highly urbanized, with approximately 67% impervious land cover.[7,8] We worked at this level in order to be able to accurately record flow accumulation for the Walnut Creek wetland, which is adjacent to and partially passes through the study area. The specific microcatchments of interest were captured in the larger assessment, as these minor creeks and waterways are tributaries of Walnut Creek.

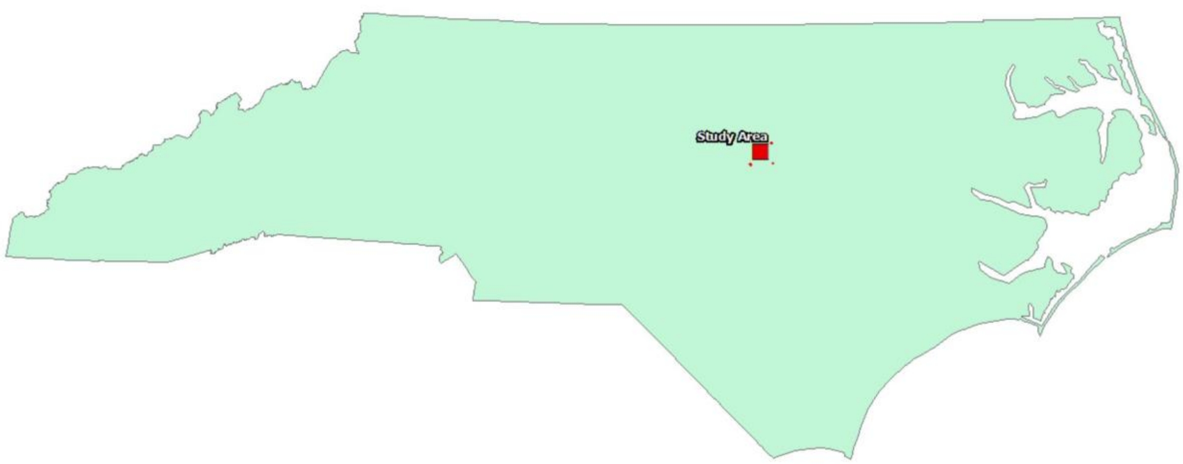

Figure 2: Study area as contextualized within North Carolina

[6] Prior to watershed delineation, we explored Planchon & Darboux's depression filling and depression breaching algorithms as alternative fill techniques to remove pits in the DEM. As both methods retained significant numbers of artifacts, we elected to use the native Fill Depressions algorithm in ArcHydro. As this model is meant to be expository in nature, rather than a specific assessment of hydrological processes, we felt justified that the resulting loss of precision in DEM conditioning would not significantly affect the results of this analysis.

[7] The HUC-12 code for the Walnut Creek watershed is 030202011101. It is part of the Neuse River basin.

[8] For more, see Laura García-Cuerva, Emily Z. Berglund, and Louie Rivers, "Exploring Strategies for LID Implementation in Marginalized Communities and Urbanizing Watersheds," Working Paper, EWRI Congress 2016, West Palm Beach, FL, May 22-26, 2016.

2.4 Characteristics of the study area

The study area was extracted out of city records of the neighborhood boundaries using a combination of individual accounts, community records, and public vector data. The participatory map extent was extracted in ArcMap 10.5 from a shapefile of Wake County streets. This geographic extent was kept uniform in all subsequent analyses, though hydrological data were computed at the watershed level to account for upstream flow.

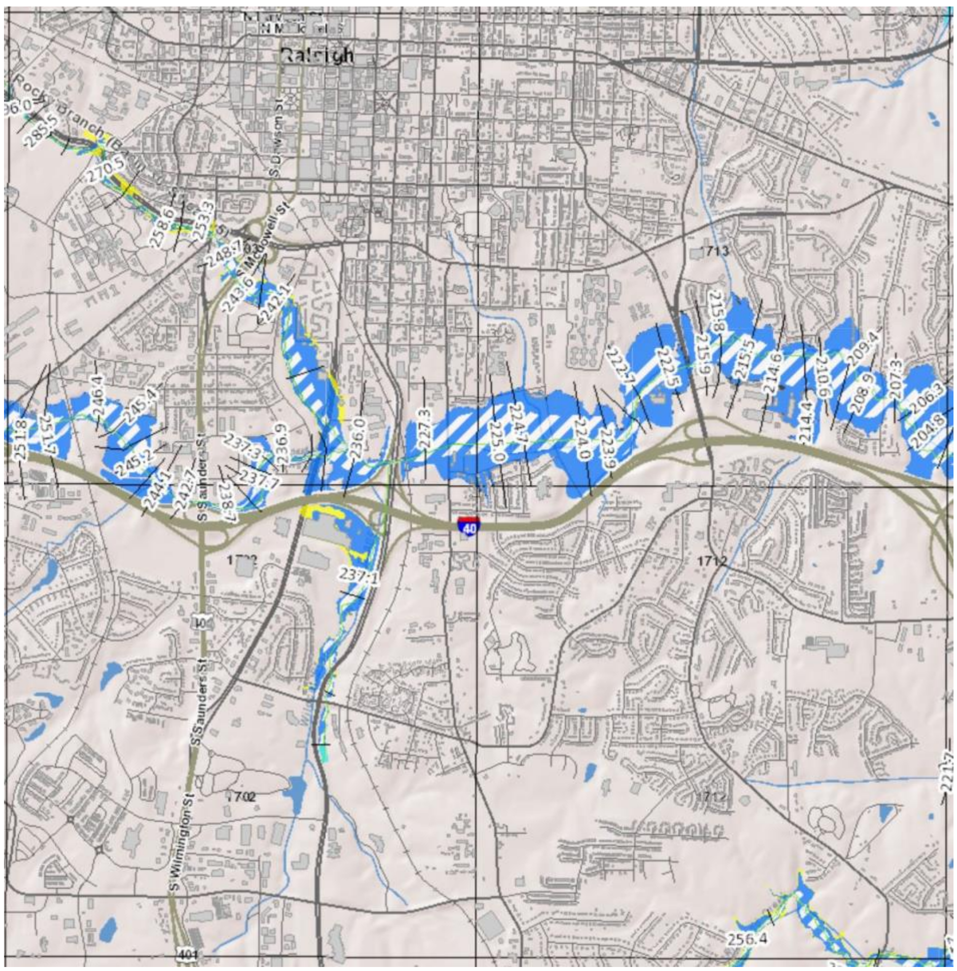

Figure 3: NC Flood Maps data tiles 1702, 1703, 1712, and 1713 with area floodplains shown. The study area (indicated in red) lies at the intersection of these. Approximately half of the Rochester Heights neighborhood is located in the Walnut Creek floodplain, with a majority of these areas falling within areas currently classified as “1% Annual Chance Flood Hazard Conditions” outside the floodway channel. (Source: http://fris.nc.gov/fris/Index.aspx)

About 60% of what is now Rochester Heights—located north of I-40, adjacent to the Walnut Creek wetland—is located within a floodplain and is largely flat, with an average topographic variation of less than 30 feet. The Biltmore Hills neighborhood exhibits more elevation variance, ranging from approximately 230 to 315 feet above sea level, with the highest locations in the study site located adjacent to Cross Link Road. The lowest sites in the combined neighborhood are parallel to Bailey Drive, which runs alongside the Walnut Creek wetland. These communities are located in the central part of the larger Walnut Creek watershed. The total area of the study site is approximately 0.56 square miles.

3. Results

3.1 Participatory data

Digitized participatory data were rendered in a single point shapefile for processing in ArcMap. The Optimized Hot Spot Analysis tool, introduced in ArcMap 10.3, utilizes the Getis-Ord Gi* statistic to create a map of statistically significant hot and cold spots based on point or polygon features. Unlike the Hotspot Analysis tool, which is also based on the Gi* statistic, the Optimized Hot Spot Analysis algorithm does not require weighted features and can be used to identify statistically significant spatial clusters based on incident data alone. As participatory data were unweighted, no additional parameters were necessary. Once the tool had run, this output was then rasterized at a resolution equal to that of the polygon hotspot output in order to facilitate direct comparison with the flow accumulation data, which were aggregated similarly. Hotspots that were statistically significant at 95% ($p < 0.5$) were extracted from both optimized hotspot outputs using binary reclassification, then rendered at the same spatial resolution as the resampled spatial resolution. No statistically significant coldspots ($p > 0.95$) were found.

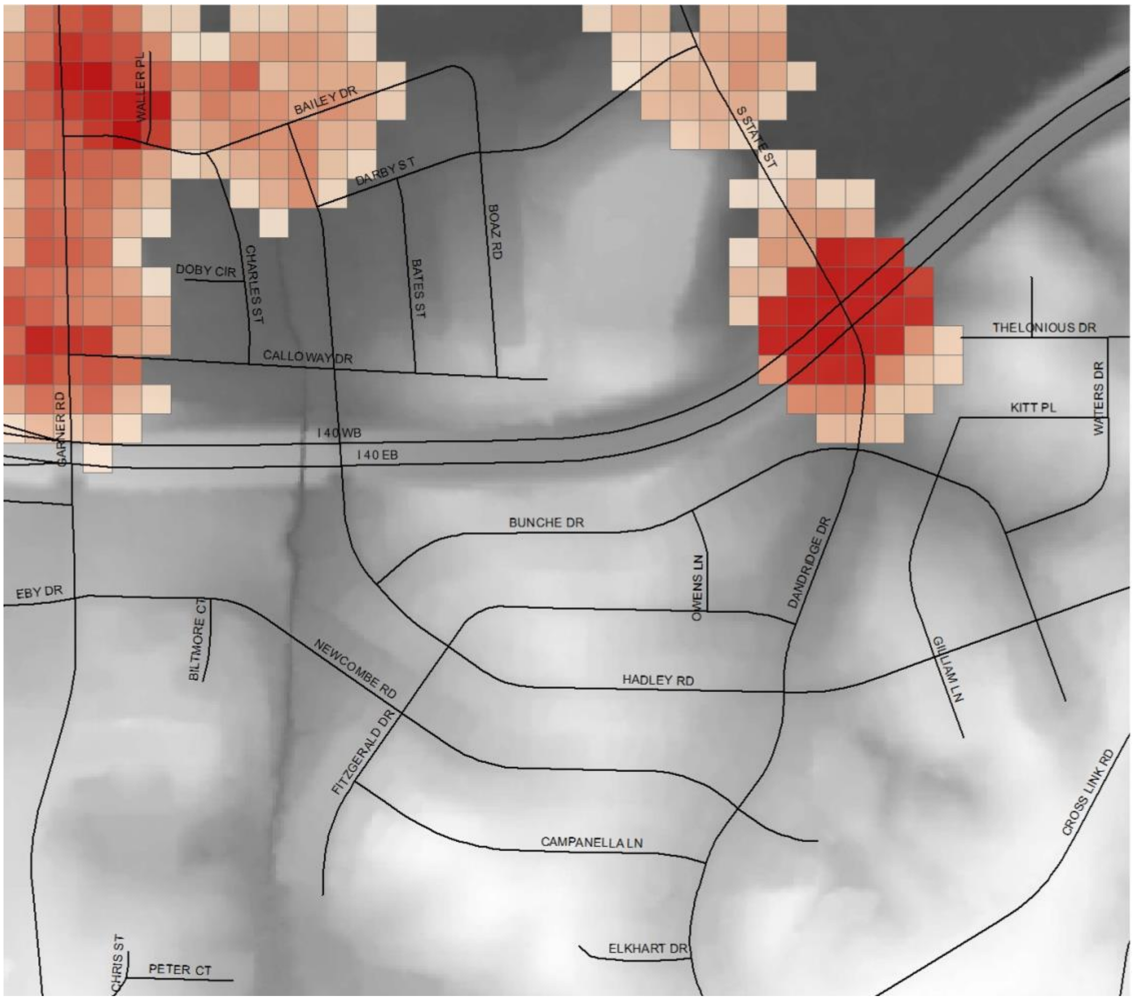

Figure 4: Participatory data hotspots over elevation DEM. Hotspots were calculated using the Getis-Ord Gi* statistic using the Optimized Hot Spot Analysis tool in ArcMap 10.5.1. All hotspots indicated above were significant at 95%. Areas shown in darker red, including Interstate 40-State Street, Bailey Drive-Waller Place-Garner Road, and Garner Road-Calloway Drive, were significant at 99%.

Statistically significant hotspots for the participatory data are concentrated in the northwest and northeast quadrants of the study region. Acute clustering is most evident at State Street and Interstate 40 (where the Interstate passes over a bridge) as well as the stretch of Garner Road north of the Interstate, which was also consistent of anecdotal accounts from respondents that were recounted during the survey process. Additional significant clusters are concentrated in low-elevation areas close to the wetland. With the exception of Bailey Drive, which is within the bounds of Rochester Heights, all statistically significant clusters are found at neighborhood access points.

3.2 Hydrologic data

Flow accumulation is an algorithm that simulates the number of raster cells in a DEM that drain into a given cell. Flow accumulation is a function of slope, calculated as the difference in elevation between two neighboring cells in a DEM, and flow direction, a determination of the downhill flow path out of any given cell. In general, flow direction is recorded in the direction of the steepest downhill slope. As all GRID cells have eight neighboring cells, the D8 algorithm, the simplest algorithm for flow routing on rasters with square pixels, identifies which of the eight directions in which water would flow, based on the greatest difference in elevation between the cell and its neighbors. More sophisticated algorithms, such as D-Infinity, have been developed that partition flow between neighboring cells, which allows for more precise flow routing over complex hillslopes (Tarboton, 1997). However, as this investigation is concerned primarily with flow channels and generalized areas of high surface water accumulation, as opposed to topographical wetness, the additional precision (and computational resources) of more sophisticated algorithms were unnecessary for our purposes.

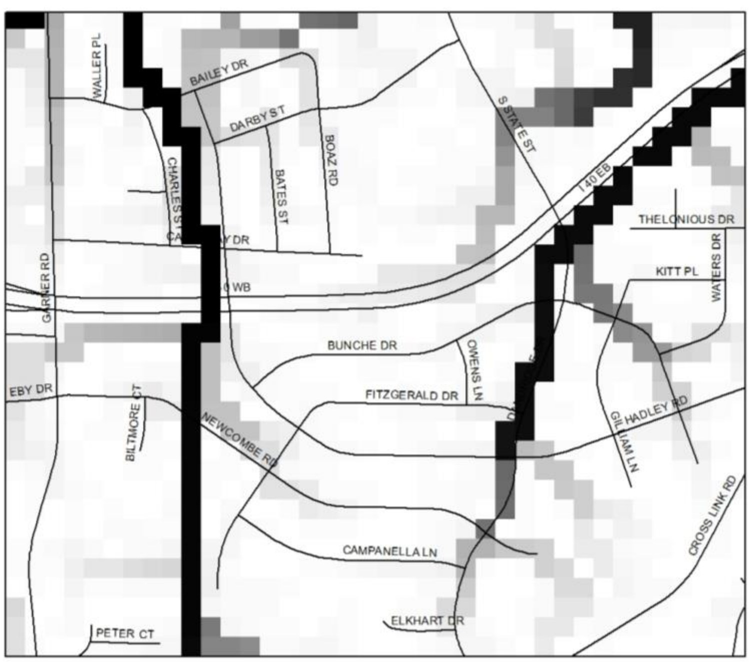

Figure 5: Walnut Creek watershed flow accumulation within the study area. Areas of high accumulation are indicated in shades of dark grey and black. Highest accumulation values follow the path of an unnamed tributary that crosses the study area from south to north between Charles Street and Hadley Road, which local records indicate has been subject to erosion due to high runoff volumes upstream. In contrast, the strong correspondence of areas of comparatively high accumulation with local streets, particularly at Dandridge Drive, cannot be explained wholly by upstream flows.

Flow accumulation patterns vary dramatically based on terrain characteristics and the size of a given watershed, with watershed being defined as the total area that drains to a given outlet point. As it is based entirely on slope and flow direction, flow accumulation is not an assessment of the actual quantity of water that would accumulate in any given area. Rather, flow accumulation indicates which cells within a hydrologically-conditioned DEM would accumulate water if the surface were inundated (Jenson, 1991; Lindsay, 2005; Planchon and Darboux, 2001; Wang and Liu, 2006).[9] While simulation of climatologically-based stormwater accumulation patterns was beyond the scope of this assessment, flow accumulation patterns allow for inference into patterns of stormwater accumulation that would likely transpire during rain events. More simply, this allows us to simulate where in the study region water would most likely accumulate if rain were to fall. Flow accumulation data were derived from the original DEM based on D8 flow paths as part of the watershed delineation conducted in ArcHydro.

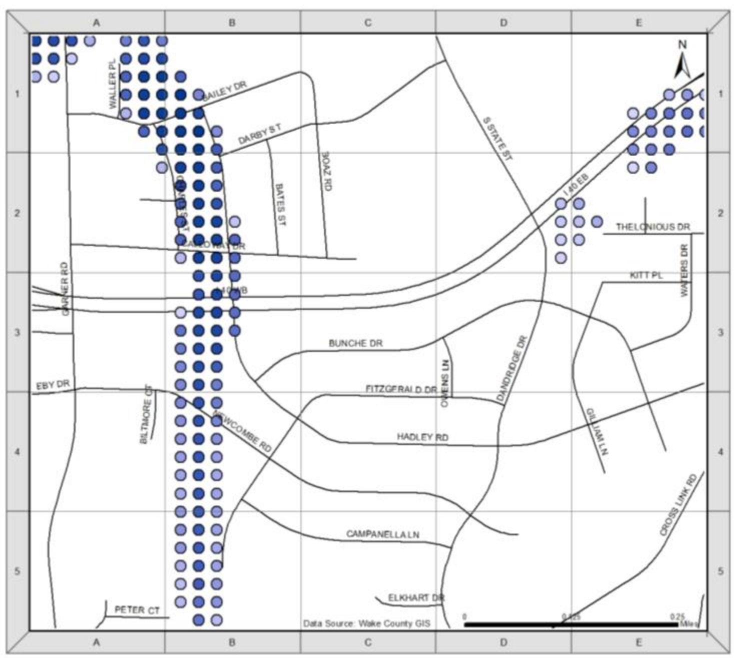

Figure 6: Flow accumulation hotspots that were significant at 95% or greater. As with the participatory data, these hotspots were calculated using the Getis-Ord Gi* statistic within the Optimized Hot Spot Analysis tool. Point weights were determined by the resulting raster cell values from resampling of the original high-resolution flow accumulation output. Values were aggregated based on the maximum value present in each resampled pixel, with pixel size determined based on the resolution of the rasterized participatory data hotspot output.

[9] As most flow routing algorithms encounter errors in the presence of cells that are lower than all cells bounding them, the first step in DEM preprocessing is to fill these “sinks,” some of which may be natural, but most of which tend to be artifacts of the digitization process. The simplest algorithm raises sinks to the height of their lowest neighbor cell, while others exist that involve more sophisticated computations. For more, see the following sources: Jenson, 1991; Lindsay, 2005; Planchon and Darboux, 2001; Wang and Liu, 2006.

Similar to the participatory data, statistical analysis of the flow accumulation data was also conducted using the Optimized Hot Spot Analysis tool. In this case, the original flow accumulation raster derived from the DEM was resampled using nearest neighbor resampling at equal resolution to the participatory hotspot output. Resampled pixels were aggregated using maximum cell values in order to maintain continuity with the original DEM.[10] We converted this output to point features for statistical assessment, weighted according to the flow accumulation values in each resampled cell. The flow accumulation hotspot output was then re-rasterized at the same spatial resolution as the participatory hotspot output.

Statistically significant hotspots of flow accumulation correspond generally to pre-existing stream channels. The majority of significant flow accumulation follows the course of an unclassified, unnamed stream bed that crosses multiple residential parcels in both neighborhoods[11], though additional significant accumulation is seen in the northeast quadrant adjacent to Interstate 40 as well as the northwest quadrant adjacent to Garner Road.[12] Comparison of the two statistical hotspot analyses concurrently reveals correspondence of significant accumulation and participatory accounts at the State Street bridge, Garner Road, and Bailey Drive, with the strongest correspondence at the neighborhood access points of State Street/Dandridge Drive and Garner Road/Bailey Drive. The implications of this correspondence are discussed in the next section.

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[10] As Walnut Creek intrudes slightly into the study area, initial statistical computations returned a number of peculiarities in distribution patterns, with significant distribution limited to the extreme northwest of the study area. The cause of this became apparent when looking through the attribute data of the hotspot output. Walnut Creek is the primary channel of the larger watershed, and flow accumulation base values for two points along the creek corresponding to the slight intrusion in the lower-resolution output were higher than those of other tributaries in the study area by a magnitude of approximately 46:1. As a result, noteworthy flow accumulation patterns in the rest of the neighborhood were obscured. Because the study area is based principally on public records of neighborhood boundaries, as opposed to hydrological boundaries, we elected to re-sample outlier values down to values consistent with cells at similar spatial placement adjacent to, but not in the bounds of, Walnut Creek in order to diminish their influence. This allowed us to more impartially assess flow accumulation patterns outside of pre-existing stream channels.

[11] The stream is unclassified as it is smaller than the smallest streams that receive formal naming and classification. For more, see Walnut Creek Wetland Park Master Plan, available at https://www.raleighnc.gov/content/ParksRec/Resources/WalnutCreekWetlandPark/WALNUTCREEKDRAFTMASTERPLAN.pdf.

[12] This location is near the intrusion point that was reclassified to lower values, but is not spatially dependent on proximity to Walnut Creek.

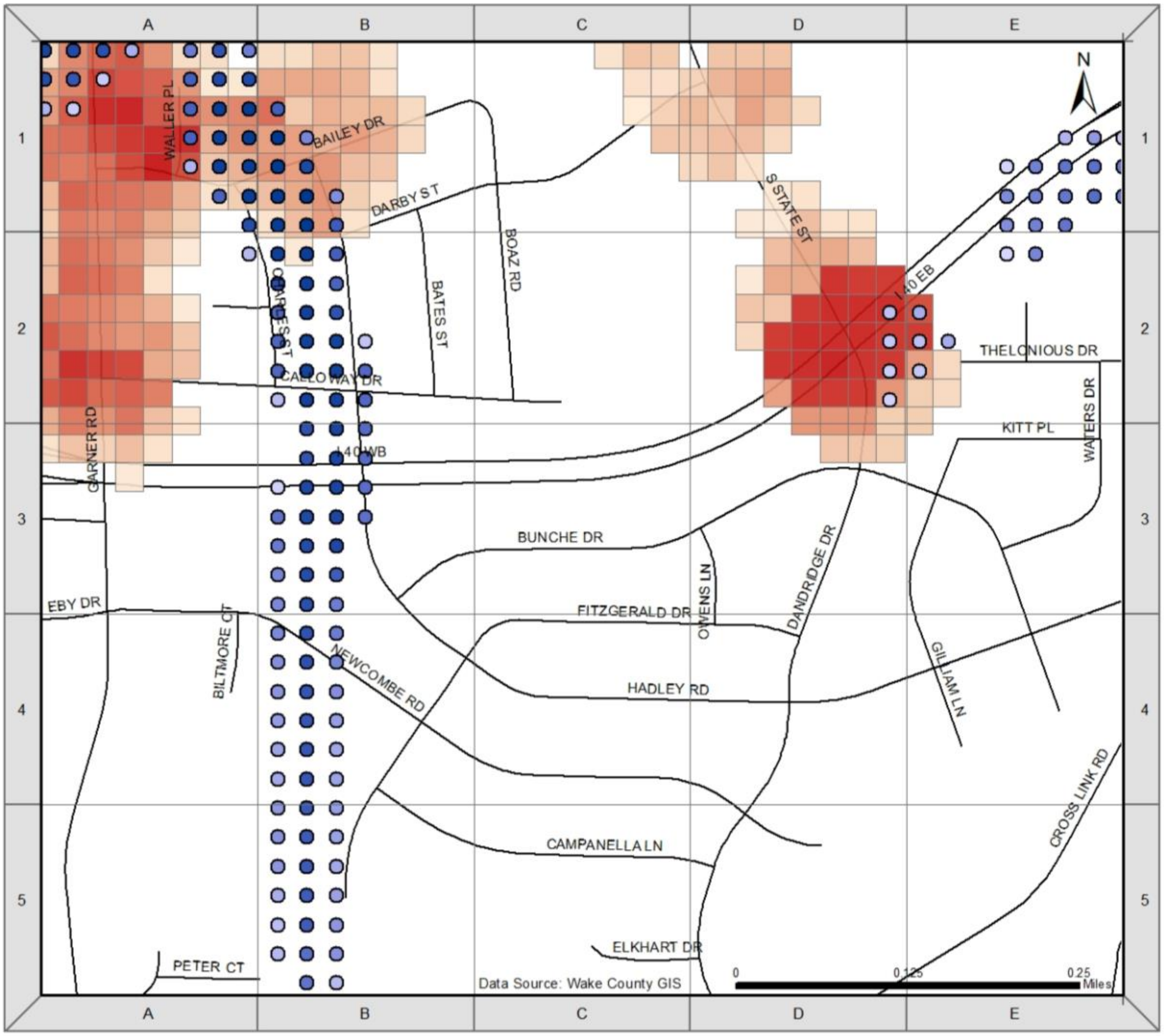

Figure 7: Participatory data hotspots with flow accumulation hotspots overlaid. We found correspondence of significance at Garner Road near the Walnut Creek wetland, Bailey Drive and Charles Street, Bailey Drive and Hadley Road, and State Street/Dandridge Drive and Interstate 40.

4. Discussion

This analysis assessed the intersection of significant clustering of nuisance flooding areas identified through a PPGIS survey mechanism with significant flow accumulation in the same area. As expected based on area topography, the areas of highest flow accumulation are located in lower-elevation areas near the Walnut Creek wetland, as well as in pre-existing waterways. Conversations with long-time residents as well as later conversations with city officials and members of the WCWCP revealed that unclassified streams are not city prerogative. As such, landowners with these streams on their property are *de facto* authorities over them—and accordingly, these residents are responsible for the erosion, flooding, and other damage that results from high peak flows, even though peak flow volumes result from far upstream.[13]

The largest areas of overlap in statistically significant hotspots between participatory and flow accumulation data were found between Garner Road and Bailey Drive. Garner Road has been raised several times throughout the lifetime of the Rochester Heights community (Focus group transcripts, fac. McGregor and Rivers, 2016). Nevertheless, severe storms still result in nuisance flooding, and anecdotes from survey respondents indicate that flooding at this level happens several times a year. Extensive wetland restoration efforts that have been under way since 1996 have increased the resiliency of Walnut Creek wetland, and in general, water levels in the wetland revert to normal ranges within two or three days. Nonetheless, because nuisance stormwater at the Garner Road entrances to the neighborhood often has nowhere to go, this may result in neighborhood access points being blocked for days at a time.

As seen in Figure 5, the significant overlap point at the State Street-Interstate 40 bridge results from upstream flows that follow streets rather than waterways. While it is possible that some of the accumulation exhibited here is the result of spillover from the wetland, the more likely relationship, given exhibited surface water accumulation patterns, is in the opposite direction, with significant accumulation "upstream" contributing to elevated accumulation levels in the wetland nearby. The reverse appears to be true at Garner Road, where significant accumulation is primarily clustered in segments near Walnut Creek. As this investigation did not consider actual stormwater accumulation based on weather events, we are limited to inference that can be made from flow accumulation patterns alone. Future research may incorporate factors such as rain event duration and severity, the influence of land cover types on expected stormwater drainage, or the role of soil loss and erosion on local accumulation patterns into a more comprehensive model.

[13] For more, see Raleigh Public Works Committee minutes, August 23rd, 1983.

4.1 Stormwater accumulation in Rochester Heights

Of the two neighborhoods, Rochester Heights is substantially more affected by nuisance flooding than Biltmore Hills. This is unsurprising for two reasons: first, as its name suggests, Biltmore Hills exhibits much more topographic variance than its counterpart, and much of the surface stormwater that drains out of the neighborhood flows in the direction of the wetland before collecting in storm drains and surrounding land cover. Additionally, Rochester Heights is located immediately adjacent to the wetland at almost the same elevation. Taken in tandem, elevation and flow accumulation patterns suggest that localized flooding in Rochester Heights, particularly on and near Bailey Drive, may be exacerbated by spillover from the wetland as well as surrounding hillsides and roadways located at higher elevations.[14]

Some final considerations concern the structure of the survey-interviews themselves. While we did not record address data due to privacy concerns, an informal review of survey-interview transcripts reveals a pattern that residents of Rochester Heights were more likely than Biltmore Hills residents to report nuisance flooding around Garner Road. This makes sense due to spatial proximity: Biltmore Hills residents have other neighborhood access points, and the most significant area of acute clustering is found at the State Street-Interstate 40 bridge, an access point shared by residents of both neighborhoods. However, another, somewhat spurious factor may be contributing to the strength of results in this cluster. While not directly addressed in this analysis, the survey-interview schedule included questions about dumping and environmental stewardship in addition to questions of flooding experience, and residents may have exhibited heightened awareness of environmental issues around State Street due to a pattern of repeated trash dumping in this area. Frequent dumping, which often occurs at the scale of tires and household appliances even after restoration of the wetland, belies a history of neglect. Moreover, it suggests that nearly two decades of wetland restoration in the context of a gentrifying neighborhood have yet to make an impact on perceptions of the wetland as an area worth protecting, though perceptions of

[14] Resident anecdotes of collapsing hillsides and backed-up storm drains further support a pattern matched here by participatory mapping accounts from survey-interview respondents.

the effects of stormwater on local waterways was found to have a significant negative correlation with trust in local environmental authorities. (McGregor, 2018).

It is difficult to overstate the importance of local memory of flooding in Rochester Heights. A historical concentration of environmental disadvantage in communities of color directly stemmed from racist housing and development practices that were in place as recently as 40 years ago, and community anecdotes collected during the survey-interview process referenced the catastrophic flooding events of the late 1990s nearly as often as the more regular nuisance flooding events on which the survey-interviews focused. With many of these communities still standing—and with many of them still inhabited by their original occupants or direct descendants, as are Rochester Heights and Biltmore Hills—the unintended consequence has been, not just in Raleigh but across the U.S., that communities of color remain "stuck" in undesirable locations. What's more, the familiar narrative to "just move somewhere else" is laden with historical and cultural assumptions that discount the experiences of communities of color, particularly black experience. Environmental injustices are compounded when black communities are relegated to undesirable tracts of land, build community there anyway, and then find themselves affected by upstream environmental refuse from the communities who forced them to establish themselves on these parcels through exclusionary settlement practices. And accordingly, the local memory of environmental injustice and its impacts on perceptions of urban nature is among the most salient predictors of trust in environmental authorities—that it corresponds to reality makes its influence difficult to ignore.

5. Conclusion

In the context of urbanizing watersheds, Rochester Heights is typical of many localities in the American south wherein environmental injustices are effectively built into the physical environment. The historical establishment of communities of color in undesirable locations predisposes these communities to inequitable experiences of urban nature. Furthermore, skepticism toward urban improvement efforts is exacerbated by the fact that the development of technologies designed to mitigate environmental issues such as nuisance flooding often follow patterns of gentrification (Heynen et al., 2006; Crompton, 2005; Wolch et al., 2014; Byrne, 2012; Hagerman, 2007). Recent efforts by local governments and other organizations to directly incorporate community voices into development planning represent a step in the right direction; in the case of Walnut Creek, risk perceptions involve institutional factors such as politics, law, structure, and communication, perceptions of which are influenced by cultural conditioning.[15] Allowing for community participation in environmental improvement processes and risk mitigation grants responsibility and agency to a wider variety of stakeholders.[16] This has the effects of "inducing collective action and strengthening social cohesion and communal health," which has important implications for the restoration of trust with minority communities over environmental issues. [17]

Beyond the stated objectives of this study, this project's further goal is to shed insight into the ways in which citizen science and more traditional scientific approaches can be combined to increase the descriptive power of both. The statistically significant coincidence of high flow accumulation and nuisance flooding as reported by local residents is a clear triumph of citizen science, showing that even a relatively simple assessment tool can provide social insight into hydrological patterns and serve as a compliment to more traditional survey methods in the social and natural sciences. Moreover, participatory feedback may be able to identify problems that hydrological simulations cannot, at least not on their own. While there is ample future work for further refinement of these methods, pairing participatory mechanisms with quantitative spatial models bridges two powerful analysis strategies in a way that allows for a more holistic view of complex, highly-interrelated socioecological systems. This seems a natural evolution of the already-interdisciplinary application of PPGIS assessment methods, which, by design, involve community and stakeholder participation in the management process, increasing the richness of developed models and incorporating forms of knowledge that purely practitioner-based models do not.[18]

[15] Ines Winz, Sam Trowsdale, and Gary Brierley, "Understanding barrier interactions to support the implementation of sustainable urban water management," *Urban Water Journal* 11 no. 6 (2014): 498; 501.
[16] Green et al., 1681.
[17] Ibid.
[18] Voinov and Gaddis, 206.

The results of this study suggest that "lay" understanding of local hydrological patterns is quite high, even though expressions of that knowledge may not always use scientific language.

With the surrounding watershed rapidly urbanizing, it remains to be seen how future expansion of impervious land cover will affect waterways surrounding the Walnut Creek wetland, particularly as stormwater mitigation technologies continue to mature and be deployed in tandem with increasing urbanization. Particularly when informed by PPGIS, the development of collaborative urban greening efforts may also present an opportunity for coalition-building that can help create trust and increase levels of subjective wellbeing in African-American communities. This is particularly the case as our findings suggest that race is not a significant predictor of ecological knowledge. Future research may consider the role of demographic factors such as age, educational attainment, income, and length of residency may influence local knowledge of hydrological or ecological patterns. But social trust also has a role in perceptions of risk and risk mitigation; insofar as participatory methods facilitate collaboration and information-sharing, there is potential for collaborative risk governance to increase the likelihood of cooperation between historically antagonistic stakeholders.[19]

[19] Sharon S. Dawes, "Interagency Information Sharing: Expected Benefits, Manageable Risks," *Journal of Policy Analysis and Management* 15 No. 3 (1996): 380.

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