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The development of a participatory assessment technique for infrastructure: Neighborhood-level monitoring towards sustainable infrastructure systems

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ABSTRACT

Climate change and increasing natural disasters coupled with years of deferred maintenance have added pressure to infrastructure in urban areas. Thus, monitoring for failure of these systems is crucial to prevent future impacts to life and property. Participatory assessment technique for infrastructure provides a community-based approach to assess the capacity and physical condition of infrastructure. Furthermore, a participatory assessment technique for infrastructure can encourage grassroots activism that engages residents, researchers, and planners in the identification of sustainable development concerns and solutions. As climate change impacts disproportionately affect historically disenfranchised communities, assessment data can further inform planning, aiming to balance the distribution of public resources towards sustainability and justice. This paper explains the development of the participatory assessment technique for infrastructure that can provide empirical data about the condition of infrastructure at the neighborhood-level, using stormwater systems in a vulnerable neighborhood in Houston, Texas as a case study. This paper argues for the opportunity of participatory methods to address needs in infrastructure assessment and describes the ongoing project testing the best use of these methods.

1. Introduction

A frequently referenced definition of sustainable development is from a publication entitled *Our Common Future*, also known as the Brundtland Report which defines sustainable development as: “Meeting the needs and aspirations of the present generation without compromising the ability of future generations to meet their needs” (Brundtland, 1987, p. 292). Furthermore, sustainable development is anchored by the triple bottom line of environmental conservation, economic prosperity, and social equity (Campbell, 1996). Situating these broad concepts in the context of infrastructure, we define sustainable infrastructure as systems that have the capacity to endure over a long period of time; enabling the human-built environment to thrive and providing an opportunity for human society to improve its quality of life, without compromising the integrity and availability of natural, economic, and social assets for future generations. Recent extreme events and resulting disaster impacts across the globe, including Hurricane Maria in Puerto Rico, earthquakes in Mexico, monsoon flooding in Bangladesh, flooding and landslides in Sierra Leone, and Hurricane Harvey and Irma in the USA and Caribbean have highlighted the importance of sustainable infrastructure systems, especially in historically disenfranchised communities and hazard-prone areas.

The proper management of infrastructure assets over a life cycle affects the integrity and level of service of these systems and thus the infrastructure sustainability. Proper management can include new development and installation as well as maintenance and rehabilitation of existing components. Historically, public infrastructure development has been disconnected from management of existing infrastructure assets and has contributed to years of deferred maintenance of existing systems and the contemporary infrastructure crisis (Harris, Shealy, & Klotz, 2016). Public and private agencies have begun to develop sustainability plans that focus on protecting physical systems along with community capital and public health in light of disasters and climate change (Campanella, 2006; Wilkinson, 2012). However, these emerging developments require cooperative long-term management, investments, and coordination among multiple agencies and sectors, at the same time

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that communities are facing constrained budgets and reduced capacity to address looming environmental impacts (Cutter et al., 2014; Halfawy, 2008).

Many urban areas in the U.S. and across the world are in need of affordable and effective approaches to infrastructure condition assessment. Assessment and data collection procedures will support decision-making to properly address repairs and preventative maintenance needs as well as implement endurance and sustainability measures (Chang, 2014; General Accounting Office (GAO), 2004). Without infrastructure condition assessments, municipal officials manage maintenance projects with limited knowledge of the full extent of infrastructure needs or ability to prioritize those needs, and thus, may make investment decisions that do not efficiently increase the sustainability of the city as a whole. A growing body of literature in infrastructure engineering and management are beginning to explore nontraditional approaches to infrastructure management that could address these assessment needs. For example, studies have examined public-private partnership (PPP) approaches to asset management utilizing private engineering firms to support infrastructure management through contractual agreements (Anastasopoulos, Haddock, & Peeta, 2014). These studies have shown that PPPs can successfully facilitate maintenance and rehabilitation outcomes, but these partnerships often lack insight on the social and political contexts of the local communities in which they operate and provide standard rather than context-specific approaches. Similarly, PPP's can represent a conflict of interest in terms of planning for the public good versus generating profit. This conflict could have implications for safety measures and sustainable outcomes (Regan, 2012). Public entities may consequently be stifled in attempting to moderate public works through a private market (Shrestha & Martek, 2015).

This paper describes one infrastructure assessment technique that brings together engineering and social science. Sustainable infrastructure draws upon research from both civil engineering and social planning due to the multifaceted nature of physical systems operating in a social world. This social dimension specifically illuminates the need for infrastructure management to be polycentric or decentralized and allow for contextualization, experimentation, and innovation (Goldthau, 2014). Moreover, civil engineering scholarship recognizes that physical processes have received the majority of attention and human indicators should be included and weighted equally (Dasgupta & Tam, 2005; Kaminsky & Javernick-Will, 2013). Yet because the infrastructure design and installation process is often fragmented in time and space, unintended poor outcomes result for certain communities and the surrounding environment (Harris et al., 2016). Inclusive strategies for sustainable infrastructure design, construction, and maintenance throughout a systems lifecycle support the dynamic nature of human communities. Furthermore, data collection methods that involve a wide range of actors provide opportunities to ensure the triple bottom line of sustainability is fulfilled. Cooperation between actors in infrastructure management can improve due to lifecycle linkages (Lenferink, Tillema, & Arts, 2013). There has been very little work to date in the engineering literature on stakeholder training strategies that exchange knowledge with community members, although participation can positively impact sustainable infrastructure (Opdyke & Javernick-Will, 2014). By providing a technique by which community members can receive a degree of training, exchange knowledge with public officials, and that knowledge is recorded visually and spatially, the technique we describe contributes to the design, construction, and operations and maintenance phases of sustainable infrastructure development.

Urban residents provide one avenue of knowledge that has not been fully utilized in infrastructure assessment research, even as citizen science programs are growing across a variety of other scholarly domains (Silvertown, 2009). Residents interact with public infrastructures and built environments daily and have experience with how well (or poorly) these systems function. Community members have knowledge of local socio-political contexts that impact the management of infrastructure. Therefore, a participatory approach that provides alternative means for assessment and identification of physical infrastructure vulnerabilities could help transform the way cities manage built environments. Social equity is the most overlooked element of sustainable development. In considering providing equitable critical services, sustainable infrastructure is a critical component, especially for communities already living at the social, economic, and political margins of society (Goldthau, 2014). Sustainable infrastructure should include communities in the planning, provision, decision-making, management, and installation of infrastructure systems in light of current environmental and social conditions (Agyeman & Evans, 2003; Choguill, 1996). Communities to be served need the capacity to diffuse, adapt, and implement plans and assessment innovations to have agency in their own affairs. These innovations should be bottom-up, build capacity, and facilitate community change. Incorporating innovative techniques along with community engagement might shift the neighborhood culture regarding infrastructure management with positive implications for future improvements on multiple levels and sustained physical, social, and economic capital. Furthermore, Bullard (1994), who is often described as the father of environmental justice, challenges the literature to redefine environment to include infrastructure problems that threaten the fabric of our communities and their inhabitants. The broader environmental justice literature also recognizes that currently the burden of proof for environmental issues typically falls on the communities that are being impacted. With the emergence of new technologies such as smartphones and public applications that use Geographic Information Systems (GIS), crowdsourcing, citizen science, and other participatory approaches in many scientific disciplines, the capacity to undertake such research is ripe.

In this paper, we suggest a method of combining existing assessment techniques used by infrastructure engineers to develop a participatory assessment technique for infrastructure (PATI) that is accessible to the general public while maintaining validity and reliability of the data. The primary goal in developing this technique is to provide a user-friendly approach to condition assessment that considers both hydraulic capacity and physical conditions of stormwater infrastructure systems for asset management. This paper discusses several fundamental topics as it relates to participatory infrastructure assessment and briefly highlights historically low-income and communities of color as an example where a method such as this could be especially useful nudging decision-makers to employ a whole systems design resulting in more sustainable infrastructure systems. PATI provides an opportunity that could be transformative for environmental justice communities and beyond. More specifically, we (1) provide context for environmental justice and sustainable infrastructure issues and the need for this tool at the grassroots-level, (2) discuss the basis of participatory action and the potential to expand this method in collecting infrastructure assessment data, (3) describe the development of the participatory infrastructure assessment tool, and (4) discuss opportunities, challenges, and broader impacts of such an approach.

2. Environmental justice and sustainable infrastructure

Hundreds of environmental justice studies have documented unequal exposures by race, ethnicity, and economic class regarding waste and petrochemical facility siting (Hernandez, Collins, & Grineski, 2015) as well as the distribution of urban trees (Landry & Chakraborty, 2009), liquor stores and bars (Romley, Cohen, Ringel, & Sturm, 2007), urban green space and parks (Boone, Buckley, Grove, & Sister, 2009; Wolch, Byrne, & Newell, 2014), and bicycle lanes, off-road trails, and transit services (Hirsch, Green, Peterson, Rodriguez, & Gordon-Larsen, 2017), among others. Additionally, there is a growing body of work that shows how climate change, disasters, and critical infrastructure create unequal impacts on communities of color, indigenous peoples, the poor, and in low-income countries (Mohai, Pellow, & Roberts, 2009). Climate justice work is beginning to discuss how marginalized groups experience hardships when it comes to the ability to resist and respond to climate change (Gutierrez & LePrevost, 2016), and undue burdens of climate impacts can relate to inequities in infrastructure provision. For example, the geographically isolated, low-income, and elderly are at greater risks of heat wave impacts and may not have adequate heating or cooling systems leading to early deaths as seen in the 1995 Chicago Heat Wave (Cutter et al., 2014; Klinenberg, 2015). Wright (2011) showed that changes in levee protection were closely related to the racial composition of neighborhoods in New Orleans. In fact, in the mostly white and affluent areas, in contrast to the black and working class areas, there was 5.5 feet of increased levee protection. Bullard and Wright (2009) pointed out that black victims were more than twice as likely as white storm victims to still be living in temporary housing three years after Hurricane Katrina. They also showed that neighborhoods that were in the range of 75–100% black at the time of the 2000 U.S. Census were flooded. Together, these racial disparities point to inequities in infrastructure across class and race.

Research has begun to note that on top of city-wide development issues, there is an unequal distribution of disaster impacts affecting those least likely to be able to respond, and that those impacts are not simply a function of the disaster agent (Highfield, Peacock, & Van Zandt, 2014; Van Zandt et al., 2012). Physical vulnerability to hazard events, such as flooding or storm surge, is potentially compounded by inadequate funding, investment, and maintenance of infrastructure, especially for social groups who have been segregated or marginalized into risky areas or housing. This dynamic illustrates the intersection of social and physical vulnerability to disaster. Social vulnerability, defined by Blaikie, Cannon, Davis, and Wisner (1994, p. 9), describes this process by which the social stratification of population groups results in disproportionate disaster risk and impacts within a society, specifically: "the characteristics of a person or group in terms of their capacity to anticipate, cope with, resist and recover from the impacts of a natural hazard." Importantly, these same social factors—such as, race, income, age, ability, nationality, gender, etc.—that determine social vulnerability to disaster may also explain uneven provision of public works and facilities, and thus compound disaster risk. The extent to which minority and low-income households (as well as female-headed, elderly, disabled, or transportation-dependent households) are disproportionately housed in low-quality homes in low-lying areas with infrastructure potentially in disrepair makes them susceptible to greater impacts from flooding, storm surge, and other environmental hazards (Highfield, Peacock, & Van Zandt, 2014; Masterson et al., 2014; Van Zandt, 2007; Van Zandt et al., 2012).

Recently work explicitly discussing infrastructure has emerged in the context of environmental justice and the delivery of clean water in Flint, Michigan. Butler, Scammell, and Benson (2016) show that many of the affected residents from the water crisis are living in economically depressed areas with large minority populations. Greenberg (2016) goes on to illuminate that Flint fits the pattern of poor living conditions in many physically-distressed neighborhoods. Such urban neighborhoods typically have relatively high burdens of environmental deterioration that includes water and other infrastructure systems, public problems such as crime and physical blight, poor public education systems, and a limited tax base. A continued focus on environmental justice communities and the cumulative risks faced by their residents is critical to protecting these residents and, ultimately, move towards a more equitable distribution and acceptable level of risk throughout society (Prochaska et al., 2014).

Governing structures of urban areas often react to market forces by disinvesting or refusing to invest in poor neighborhoods. The proliferation of impact fees as a way to fund infrastructure shifts capital investment to fast-growing areas and away from older, already-developed areas, for example, and has consequences for the often lower-income residents who remain in older neighborhoods (Levine, 2005). Such inequitable provisions may have far-reaching consequences for the low-income and minority individuals who live in such underserved neighborhoods, including disaster impacts (Squires & Kubrin, 2006). For example, research following Hurricane Ike in Galveston, Texas found that poor and minority neighborhoods experienced greater damage even after controlling for housing age, proximity to water, and flood zone (Highfield, Peacock, & Van Zandt, 2014). This finding suggests that one or more neighborhood-level characteristics, such as infrastructure adequacy or condition, may account for the observed differences in damage. Without adequate infrastructure and services, residents' risks increase while property values decrease, perpetuating health and wealth inequalities (Marsh, Parnell, & Joyner, 2010). Thus, these capital investment programs are thought to result in unequal provision of municipal services and infrastructure, although little empirical research is available to confirm it (Blackwell & Fox, 2006). Participatory assessment provides one technique that can immediately empower these marginalized communities in gathering data on their built environment to support advocacy for the equitable distribution of public resources and capital improvement towards sustainable infrastructure.

3. Participatory action, geographic information, and infrastructure data

Participatory action research has grown immensely over the years in the social sciences from urban planning and geography to public health (Khanlou & Peter, 2005), but has been minimally used in engineering research. Public participatory geographic information systems (PPGIS) is one type of participatory action research that utilizes GIS applications by the public in coordination with researchers to do a variety of tasks from reporting potholes to managing community forests and is an increasingly common method of resident-driven data collection. PPGIS has allowed local residents to better negotiate urban change and provided a way for urban planners and city managers to connect with residents (Foth & Brynskov, 2016). For example, in São José dos Campos Airport in Brazil, a PPGIS tool was used as a method along with public hearings to involve the surrounding community in identifying the area impacted by aircraft noise during development of land-use and occupancy codes for noise mitigation from the local airport (Santos, Arantes Gomes, & Antonio dos Santos, 2017). GIS technology was also used by HealthStreet, a community-engagement program, to identify cancer clusters (Ruktanonchai, Pindolia, Striley, Odedina, & Cottler, 2014). Similarly, the Central Corridor Friendly Streets (CCFS) was developed to improve streets in urban areas (Christiansen, 2015). Researchers have developed smartphone applications that allow users to upload transportation information to assess commuting and livability in U.S. cities (Schlossberg, Evers, Kato, & Brehm, 2012). Foth, Schroeter, and Anastasiu (2011) demonstrated a number of useful opportunities in using smartphones and GPS technology to crowdsource citizen maintenance reports for infrastructure assets including footpaths, parks and gardens, roadways, bikeways, and waterways, and stormwater drains. Smartphones and other handheld devices allow residents the ability to document, analyze, and communicate spatial narratives about local built environment needs, conditions, and assets that can then be used to negotiate for improved response from local government (Corburn, 2005).

The benefits of this method include both scientific and practice-oriented outcomes such as the ability to foster accountability, transparency, and legitimacy in government responses to resident needs (McCall, 2003). Benefits also include the facilitation of expert and local discourse, identification of low-cost and effective solutions to community problems, and increase the visibility of previously overlooked distributive justice issues (i.e., the equitable and just allocation of goods and services) (Corburn, 2005; Cutts, White, & Kinzig, 2011; McCall & Dunn, 2012). If appropriately planned, participatory data collection activities such as this can have positive influences on resident participation, empowerment, ownership of and access to spatial information, and power to challenge the distribution of public transportation and other infrastructures opportunities. Resident advocacy for the just distribution of public services can be expanded particularly with regard to natural resource and environmental management, but not limited to any particularly phase throughout the management process (Cutts et al., 2011; McCall, 2003; McCall & Dunn, 2012; McCall & Minang, 2005). In fact, an emerging concept in participatory budgeting demonstrates an innovative democratic practice that consists of giving community members the opportunity to identify spending priorities, put forth and develop concrete proposals, finalize them into feasible projects, and select which projects are worth financing and implementing (Stortone & De Cindio, 2015). Importantly, with appropriate techniques, protocols, and training, residents can collect data as valid as that collected by formally trained experts (Bonney et al., 2014). However, the continued testing of infrastructure data across collection methods can only positively shift the development of the human-built enviornment.

Environmental justice activism, in particular, is rooted in public participation, and participatory research is gaining utility among climate justice activists and researchers (Bacon, deVuono-Powell, Frampton, LoPresti, & Pannu, 2013; Balazs & Morello-Frosch, 2013; Garcia et al., 2013). Advocates and researchers have called for more community-based participatory action research as a way to generate valid and reliable science on environmental justice through researcher-community partnerships (Bacon et al., 2013). In contrast, participatory research of any kind is strikingly absent from natural hazard mitigation research and from infrastructure assessment. In terms of environmental hazard risks, residents have the local knowledge of problematic areas in their neighborhoods, such as where flooding occurs or which areas are impassable after a heavy rain, that if tapped through participatory research can provide much needed data on local conditions. That knowledge can then be further examined to connect environmental outcomes to issues of sustainable infrastructure.

PATI supports the collection of this knowledge and addresses several concerns about data needs for sustainable development. First, current data on infrastructure quality is often only accessible from municipalities and is usually in forms that are difficult for the public to use or comprehend (Bonney et al., 2014). When data is incomprehensible for the public, the likelihood of transferring knowledge to action is notably diminished. Data have to be useful across users, especially in a customer service context. However, municipalities may be reluctant to share data and include other sources of data for fear of liability, accountability, and not having the financial capacity to actually address discoveries (Aitamurto & Chen, 2017; Sahuguet, Krauss, Palacios, & Sangokoya, 2014). Second, the level-of-service of civil infrastructure can be altered significantly due to disjointed new construction or development and other anthropological factors (e.g., non-official housing or trash dumping) (Parkinson, 2003). For example, the capacity of older and downstream stormwater infrastructure may be more easily overwhelmed by land cover change, residual flooding, and runoff from upstream development (Birkland, Burby, Conrad, Cortner, & Michener, 2003; Noori, Kalin, Sen, Srivastava, & Lebleu, 2016). Thus, one-sourced data on infrastructure capacity may be incomplete, inefficient, and not capture the nonstationary level-of-service of physical assets colliding with the social world. Similarly, data may not accurately predict the lifespan of infrastructure based on its real life use and misuse. Lastly, some geographic areas lack data or lack current data on various aspects that affect sustainability. For example, following the 2010 Haiti Earthquake, volunteers produced data and maps that filled a large gap of missing geographic information about the country which affected response and recovery efforts (Zook, Graham, Shelton, & Gorman, 2010). There are parallels between where there were almost no maps, official or otherwise, in Haiti and lack of current, micro-scale data in vulnerable areas of the U.S. and other developed countries. Specifically, urban neighborhoods that are deteriorating and face issues of blight, may lack quality data and participatory data can fill a large measurement gap. To date, no such assessment techniques or protocols that support the generation and incorporation of resident-driven data collection around infrastructure and other built features are widely available to planners and managers despite calls in the literature for their development (Helbing & Pournaras, 2015; Elwood, Goodchild, & Sui, 2012).

4. Development of the participatory assessment technique for infrastructure (PATI)

In this section, we describe the detailed process of developing the participatory infrastructure technique, from the community engagement process to the structure of the technique itself. When it comes to community engagement, we provide details for our engagement process and description of a particular area where such a technique might be most useful. Several different disciplines including urban planning, civil engineering, sociology, geography, and public health provided intellectual insight for how participatory infrastructure assessment would best be implemented. The interdisciplinary effort to develop this technique contributes to the robustness of the suggested methodology.

4.1. The community engagement process

For this ongoing project, we focus on neighborhoods that are comprised of socially vulnerable populations who would be least able to respond and recover individually from a disaster and may experience the greatest need for infrastructure improvement. Harrisburg/Manchester on the east end and Sunnyside a southcentral neighborhood of Houston, Texas are the sites of our study. For example, the Harrisburg/Manchester neighborhood is located along the Houston Ship Channel at the confluence of Brays Bayou and Buffalo Bayou. The area is subjected to a variety of natural, environmental and technological hazards due to its close proximity to not only several large bodies of water but several toxic and hazardous waste facilities. Within one mile of the Manchester neighborhood, there are 21 facilities that report to the EPA's Toxic Release Inventory, 11 large quantity generators of hazardous waste, four facilities that treat, store, or dispose of hazardous wastes, nine major dischargers of air pollution, and eight major storm water discharging facilities (City of Houston Department of Health and Human Services, 2003). The population of the Harrisburg/Manchester Neighborhood is 98 percent minority, with a median income that is one-third less that the City of Houston. Half of the population have no high school diploma, only 6 percent of residents have obtained a bachelor's degree, and 44 percent of the neighborhood have an annual income less than $25,000 (City of Houston Planning and Development Department, 2014). The Sunnyside neighborhood shares very similar social characteristics in terms of the minority population and economic status. The nexus of potential exposures to hazardous substances, water contamination, and natural hazards coupled with a high level of social vulnerability shows the importance of building adaptive capacities towards a more sustainable and resilient community (Union of Concerned Scientists (UCS), 2016). The intersection of these neighborhood factors shows the need for routine and multi-level assessment of neighborhood infrastructures that are expected to mitigate hazards and protect people and property.

To begin this project, we reached out to our network of key informants in the Houston area who could connect us to community-based organizations with a reputation for working closely and successfully with partners to achieve community-centered goals, keeping in mind that many community-based organizations have limited capacity to lead multiple initiatives simultaneously. Therefore, we sought organizations 1) with a shared interest in understanding the issues we named, 2) that benefit directly from the outcomes of the project and 3) to help us identify other pertinent issues, information, or ways of gathering and interpreting data. The result of our search led us to four potential community partners, two trusted organizations in the

Fig. 1. Community members utilizing PATI during beta trial in Manchester neighborhood of Houston, TX.

community with a history of successful engagement, the Texas Environmental Justice Advocacy Service (t.e.j.a.s) and Charity Productions, and two high schools, E.L. Furr High School (FHS) and Jones Futures Academy, public schools in the Houston Independent School District (HISD) with magnet programs focused on science, technology, architecture, and health. Fig. 1 provides images from an early beta trial of community members utilizing PATI.

As our community partners, these organizations and institutions are valued as co-learners and co-designers of the most culturally appropriate strategies for information collection and dissemination, including the appropriateness of research questions, methods and interpretation of results. For example, we partnered with FHS's Green Institute to extend its curriculum into the community and expand its scientific rigor through hands-on, student-centered teaching. The students at FHS, many from the project target area in the Manchester neighborhood and other neighborhoods along the Houston Ship Channel, are part of a group of students and agriculture teachers of the U.S. Forest Service Woodsy Owl Conservation Corps that call themselves the "Green Ambassadors". Similar extension opportunities have presented themselves and are underway with Jones Futures Academy. Both these test sites and all of our community partners will act as hosts for the piloting of our ongoing and future work. Our work in these areas can set precedence for work in other similar areas around the world.

4.2. *The participatory assessment technique for infrastructure (PATI)*

The assessment technique consists of a protocol that guides user assessment of local stormwater infrastructure features. The protocol includes criteria to evaluate the capability of different infrastructure components to reducing flooding, including: roadside vegetation, ditches and front slopes, culvert and cross-drain pipes, drain inlets, litter and debris, and pavement. The survey tool was designed with statements that require a pass or fail response. An example statement for pavement is: "Pavement is free of depressions, bumps, and pot holes that can lead to ponding water."

A random sample of "face blocks" – one side of a neighborhood street between intersections – within the neighborhood is a practical sampling strategy for doing neighborhood level assessments. As the

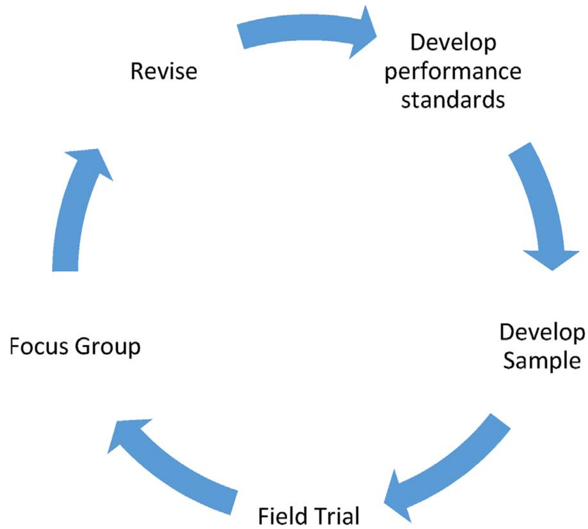

Fig. 2. The process of technique development.

technique is further developed and adopted, shorter sample units may be used and residents may be identified to assess a portion of the faceblock that is in front of or adjacent to their respective properties. To determine outcomes of the infrastructure assessment, procedures outlined by Gharaibeh and Lindholm (2014) were adopted. Finally, we are using a series of focus groups in compliment of the infrastructure assessment field trials to further refine the instrument. This will allow for further qualification of participants' experience in the field, utilization of the technique, and build capacities around sustainable infrastructure. Fig. 2 shows this cyclical process of refinement we plan to implement for the participatory technique. This process will continue until we can be confident that the data is valid and reliable. In a later section we describe the meaningfulness of the data and how we plan to test the citizen data against professional and technological methods.

This participatory infrastructure assessment technique consists of two components that were adopted from infrastructure engineering: a) a set of performance standards, and b) a level-of-service (LOS) method for assessing compliance with the performance standards. The first component was developed by adopting an initial set of performance standards related to the safety, drainage, cleanness, and vegetation of roadside assets. That initial set of performance standards were developed through an online survey of 17 maintenance personnel from the Texas Department of Transportation (TxDOT), followed by five field trials on highway corridors in the State of Texas, representing different climatic conditions, topography, traffic volume, and population density (urban vs. rural) (Gharaibeh & Lindholm, 2014). The original performance standards were then adopted to focus on stormwater drainage assets in local urban areas. The second component was developed by adopting the level-of-service (LOS) method for assessing compliance with the performance standards (Ozbek, de la Garza, & Piñero, 2010; Schmitt, Owusu-Ababio, Weed, & Nordheim, 2006). Determining a LOS for infrastructure assets and maintenance activities includes the inspection of randomly selected sample units (e.g., portion of a face block). For each sample unit, each asset type (e.g., culverts, drain inlets, etc.) is inspected against the specified performance standards to assign a pass/fail rating. A 0–100 sample unit score (SUS) is computed as a weighted average score for all elements within the sample unit. The SUS values are aggregated to determine the LOS of the neighborhood on a 0–100 scale, with 100 representing full compliance with the performance standards. This technique can then be transferred to a mobile interface using an ESRI survey/mapping application called "Survey 123." Survey 123 is a platform that provides a set of survey questions and then geocodes the location of where the survey is taken. Fig. 3 provides images of what the technique might resemble on a mobile interface.

5. Discussion: opportunities, challenges, and broader impacts

As with any other methodology, intervention, or promising practice, we recognize that certain opportunities and challenges are inherent in carrying out this type of work. One such opportunity is participatory infrastructure assessment empowers residents and provides a living platform for understanding the context of potential hazard exposures. This method allows for the pre-identification of geographic hot spots of poor and declining public infrastructure. Residents have the capacity to spatially identify hazard-prone areas throughout their neighborhood and draw connections between hazard exposures and poor infrastructure. This type of spatial data can inform and enhance both hazard mitigation planning as well as capital improvement planning.

Another opportunity occurs through the potential interactions that would take place in early field trials, community and resident training, instruction, and data exchange. This approach naturally fosters discussion amongst researchers, participants, and local residents on the street who observe the process (Meyer et al., forthcoming). There is usually a lack of diversity and inclusion in urban planning in general and the management of these more specialized areas, such as infrastructure, and has been left to professional engineers (Pitt & Bassett, 2013). Through fostered interaction that spans across the public and private realms we can potentially fulfill this need. Likewise, we know that social capital can be an important factor in adopting innovative initiatives and an important factor in every phase of the disaster cycle including mitigation, preparedness, response, and recovery, and this level of social interaction can build social capital towards sustainability and resiliency (Aldrich & Meyer, 2015).

Furthermore, if this approach were to be implemented across multiple cities at the neighborhood-level it could result in broader impacts. For example, by continuing to involve students from local school systems this activity could spark the interests of young people in various academic disciplines as it relates to this interdisciplinary work. Disciplines might include but are not limited to urban and regional planning, civil engineering, geography, sociology, and environmental science, among others.

Lastly, these types of projects provide opportunities for developing appropriate protocols that allow for alternative data collection methods. Residents including homeowners, renters, landlords, community groups, local student organizations, volunteer groups and homeowners associations could regularly provide primary data for officials involved in the management of public infrastructure to analyze, incorporate, and use to inform decisions for maintenance and rehabilitation needs. We envision that through the establishment of both physical and social capital, homeowners and tenured renters particularly, will take ownership over these infrastructure assets and recognize their contribution to issues such as hazard exposure, property values, community and economic development, health outcomes, and city accessibility and mobility, among others. Train the trainer protocols can additionally be incorporated to where communities and municipalities can continue this work without the presence of scientists and researchers.

Challenges include ensuring that the data collected is unbiased and as valid and reliable as possible for both good and bad quality infrastructure assets. In order for local governments and municipalities to embrace this data and use it for public decision-making it has to be trustworthy and as close to professional data collection as possible. While little is known about the reliability and validity of citizen-generated data, we have developed methods of testing the reliability and validity of citizen science data by comparing data collected by citizen scientists (i.e. observational datasets), data collected by professionals, data collected by technology (i.e. laser and radar datasets) and feedback data solicited from the citizen scientists about their experiences in the field trials (i.e., feedback dataset). We recognize that with citizens

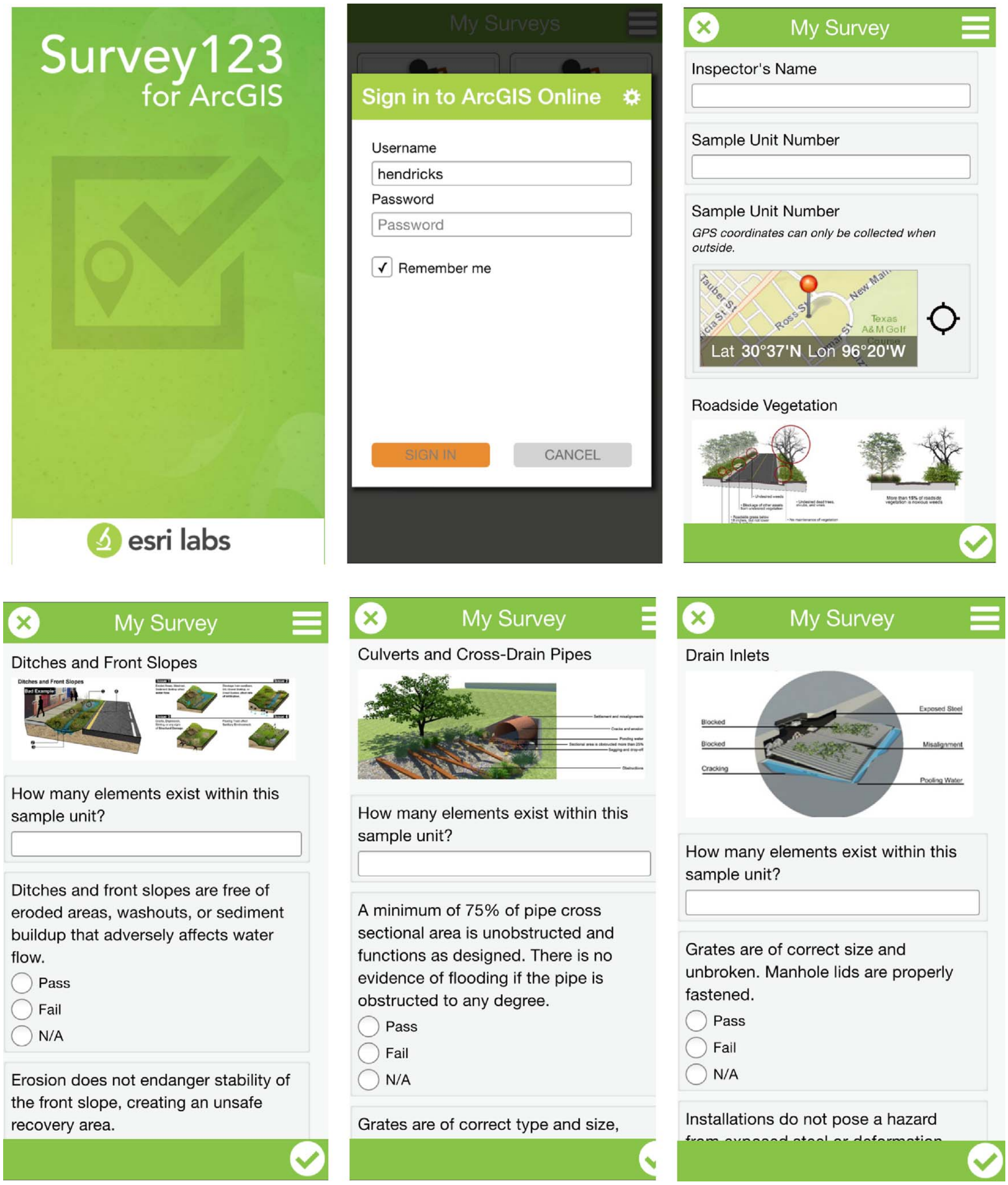

Fig. 3. PATI using ESRI's Survey 123 platform.

lacking extensive professional training there may be a greater margin of error in the data collected. Nevertheless, the data can be useful in terms of completeness and timeliness.

Another challenge may be maintaining enthusiasm and excitement for participating in the data collection. The assessment process can be time-consuming and exhausting. The lack of morale and enthusiasm can also impact the quality of data being collected. Therefore, municipalities that adopt this approach may want to emphasize the ownership of the data being collected by the residents as well as the infrastructure assets themselves. Organizations and institutions may also consider providing stipends and other types of incentives for participation. However, within this challenge a unique opportunity exists. In light of climate change impacts in terms of the increasing intensity and frequency of climate related hazards, evident from the range of events that occurred in the second and third quarters of 2017, communities across the globe may have a heightened risk perception. With more education, climate literacy, and public understanding of the local dimensions of climate change, communities will more and more become interested in both structural and nonstructural opportunities to mitigate hazards (Lee, Markowitz, Howe, Ko, & Leiserowitz, 2015). Therefore, we suspect that opportunities to participate in sustainable infrastructure management, particularly stormwater systems, will become increasingly attractive.

This methodology can be used as part of an environmental justice approach and provide voice and agency to the disenfranchised, however challenges exist when residents that occupy these communities have competing demands and lack resources. Innovation and advocacy as both individual and collective concepts often require time, financial freedom, and access to a plethora of resources. We recognize that most often these socially vulnerable communities will require an equitable amount of support in order for them to participate freely and meaningfully. This however is not to say that community members are not motivated to participate. For example, several case studies in the disaster management literature provide examples of grassroots participation in every phase of the disaster management process from mitigation to response (Palen, Hiltz, & Liu, 2007; Starbird et al., 2015). We most recently saw this phenomenon unfold in the response efforts during Hurricane Harvey in Houston. Communities have actively participated in risk communication, real-time map generation, damage assessment, and demolition and rebuilding. These activities have effectively helped to aide response efforts, both in compliment of and without expert derived data. The recognition of the indiscriminate and increasing nature of climate hazards will provide a useful amount of risk-oriented motivation. Particularly as it relates to participation in infrastructure management, studies suggest that community members, specifically marginalized communities, are willing to contribute to their community infrastructure if they have the stability and security of tenure and ongoing influence and agency (Choguill & Choguill, 1996; Chu, Anguelovski, & Carmin, 2016).

Lastly, the usefulness of this technique could be threatened by the fact that cities are becoming smarter through the Internet of Things (IOT) and the development of smart sensors that can help to prevent the failure of infrastructure components (Paciello, Pietrosanto, & Sommella, 2017; Thomas & Kinuthia, 2017). This technology presents an opportunity for the development of smart cities, where city management and citizens are given access to a wealth of real time information about the urban environment upon which to base decisions, actions and future planning. The framework encompasses the complete urban information system, from the sensory level and networking support structure through to data management and Cloud based integration of respective systems and services (Jin, Gubbi, Marusic, & Palaniswami, 2014). However, we argue that infrastructure assessment could benefit immensely from data triangulation, not only in the developmental and beta phases, but also in longitudinal management processes that include data from technology, sensors or lasers, human experts, and communities. Furthermore, there will always be a need for human monitoring and verification of technology-derived data. The human eye can capture nuanced and novel detail that stationary sensors cannot anticipate and interpret. Likewise, there's a social dimension to infrastructure sustainability in terms of the social and political processes that are necessary to provide context for maintenance, rehabilitation, management, and level of service.

6. Conclusion: participatory action, infrastructure management, and sustainability at the neighborhood-level

Creating sustainable environments is complex and relies on long-term and large-scale participation to understand more fully the opportunities and threats to the natural and human-built environment. The benefits of community engagement and participatory approaches have been well established in both the urban planning and environmental justice literature and inclusion of community members in the prioritization of needs, mediated through bidirectional communication, has been shown to accelerate the translation of environmental research (Ali, Olden, & Xu, 2008). Furthermore, research has clearly demonstrated the many benefits of community participation in conducting research and the development of interventions to improve outcomes. For example, based on case studies conducted by Berke, Cooper, Salvesen, Spurlock, and Rausch (2011) in six disadvantaged communities affected by Hurricane Isabel, recruiting a diverse set of participants for inclusive participation can increase the adaptive capacities of vulnerable groups by taking advantage of existing social networks, including local knowledge in planning, and strengthening civic partnerships with vulnerable groups. Similarly, in a case study of the work of the Southern California Environmental Justice Collaborative, Petersen, Minkler, Vásquez, and Baden (2006) identified factors for success that included university-community partnerships, philanthropic support, and strong and diverse community partners.

The project described here builds on these findings and brings expertise from a wide range of disciplines (e.g., urban planning, public health, sociology, and civil engineering), leveraging existing and ongoing research and engagement activities in Houston, Texas and the greater Gulf Coast region around sustainable communities. We combine resident knowledge of infrastructure issues with engineering knowledge of capacity and condition of systems to create and test a technique that is scientifically accurate and user-friendly. Public works officials, urban planners, and local governments that recognize residents as both the ultimate consumer and expert and make use of existing capacities will most effectively create synergy for sustainable development and fill infrastructure data needs in terms of completeness and timeliness. Our technique shows how participatory planning and provision of critical infrastructure can provide necessary data to improve existing conditions and advance policies and programs that redistribute public resources towards justice and sustainability, especially for historically disenfranchised communities with declining infrastructure. The richness of this approach is two-fold—a) it allows for community participation and the adoption of progressive techniques that engage residents, researchers, and city officials for the identification of sustainable development concerns and solutions, and b) the data can be local, current, and inclusive.

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