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Overcoming barriers to knowledge integration for urban resilience: A knowledge systems analysis of two-flood prone communities in San Juan, Puerto Rico

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A R T I C L E I N F O

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A B S T R A C T

Despite increasing attention to the role that multiple sets of knowledge, including citizen-based knowledge, have in developing more resilient and sustainable pathways for flood management, informal knowledge systems have yet to gain legitimacy and be integrated into formal planning and decision-making process. Here we show that a knowledge systems lens can bring to the fore the prospects and barriers to align different knowledge systems for urban resilience. Focusing on two communities in San Juan, Puerto Rico, we use knowledge systems analysis to identify, analyze, and compare the elements and functions of formal and citizen knowledge systems coming to bear on urban flood management. We found key aspects of these knowledge systems that deserve attention to overcome integration barriers, including different frames about how stormwater and riverine flood systems work, a fragmented and unclear formal knowledge system for stormwater management, and a focus on short-term approaches that limit anticipatory capacities in both community and governance. We discuss how citizen knowledge systems have a more nuanced and granular understanding of riverine and stormwater flood dynamics and the opportunities that exist to integrate knowledge systems through co-production, citizen science, and other governance interventions. As officials and citizens continue to learn from experiences with extreme events like Hurricane María, a goal of knowledge integration interventions should be the transformation of our knowledge infrastructures to build climate resilience in more just and sustainable ways.

1. Introduction

Urban flooding is becoming a more urgent and challenging problem given urban expansion (Seto et al., 2011) and the likely increase of more frequent and intense extreme precipitation and storm events that cities will experience in the future (Milly et al., 2002; Field et al., 2012). Despite major advances in engineered structures to control pluvial, riverine, and coastal waters, problematic or nuisance flooding that causes major damage has increased around the world in the last two decades (Liao, 2012; McCully, 2007). The human loss and infrastructure failures experienced recently with unprecedented storm events like Hurricane Harvey in Houston and Hurricane María in San Juan make evident that a shift from rigid and centralized management towards more resilience-based modes of flood governance is urgently needed (Baud and Hordijk, 2009; Codutra Dobre et al., 2018; Porse, 2013). Engineered assessments traditionally used in the design of urban flood control infrastructure assume a static land use and climate (Rosenzweig et al. 2018). An example is the 'design storm', the estimate of 100-yr flood events used to inform the US Federal Emergency Management Administration (FEMA) flood risks maps that influence flood-prone area designations and structural solutions that are implemented, such as drains, levees, and channels (Luke et al., 2018). The 'design storm' estimate is derived from historical climate data and does not consider the deep uncertainties that decision makers face with climate change (Rosenzweig et al., 2018; Watt and Marsalek, 2013). As such, these classic, risk-based approaches are not enough to support the type of forward-looking (anticipatory) institutional learning that resilience and adaptation to climate change requires (Pahl-Wostl, 2009;

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Tschakert and Dietrich, 2010).

Resilience-based approaches to flood management rely on more flexible, decentralized and adaptive forms of governance that account for the interdependence of infrastructure and incorporate non-structural and nature-based solutions that can be adapted to unpredictable and changing flood risks over time (Lawrence et al., 2015; Miller et al., 2018; Codutra Dobre et al., 2018). Instead of formulating flood policies based on predictions, adaptive and anticipatory approaches are centered around developing strategic actions whose social, ecological, and technological effects can be monitored (Haasnoot et al., 2013). At the same time, approaches such as foresight exercises and scenario development are implemented to identify long-term visions and unprecedented risks (Boyd et al., 2015; Quay, 2010). The knowledge systems participating in these activities are multi-disciplinary and come from sectors beyond government, including private and non-profit organizations, research institutions, and citizens (Baud and Hordijk, 2009; Codutra Dobre et al., 2018; Lawrence et al., 2015; Haasnoot et al., 2013).

Integration of citizen-based knowledge is a key element in resilience and adaptive governance approaches (Bergsma, 2016, van der Molen, 2018, Paul et al., 2017). Citizen knowledge can include information about the location and magnitude of typical flood events, flood conditions in real-time, status of infrastructure (e.g., identify failures in stormwater infrastructure), as well as innovative approaches for mitigating flooding and methods for responding to flood hazards. This knowledge has been valuable for the coproduction of flood models, policies, and the education of citizens in increasingly flood-prone areas about strategies for building individual, household, and community flood resilience (Lane et al., 2011; Lawrence et al., 2014, 2015, Codutra Dobre et al., 2018). Yet, there is still a persistent notion in the hazards management community that citizens are passive consumers or recipients of information instead of active agents or producers of knowledge, thus further challenging the integration of diverse knowledge sources (Coles and Quintero-Angel, 2017; Mei-Fang, 2015).

In this paper we use a knowledge systems analysis framework to bring to the fore the workings of citizen knowledge and the prospects and barriers of incorporating this knowledge with flood management knowledge systems in the city. We identify, analyze, and compare the elements and functions of the formal and citizen knowledge systems in two flood-prone communities and the institutions responsible for managing flood infrastructure in San Juan, Puerto Rico. We hypothesize that informal, citizen knowledge based on lived experiences can play a crucial role in flood governance by revealing what is happening on the ground and providing complementary knowledge to flood managers about the complexities of the social, ecological, and technological dynamics of the urban hydrological system. Our objectives are to: 1) describe, compare and contrast how residents and managers come to know what they know about how stormwater and riverine flooding occurs, and 2) explore the prospects and barriers that exist to align these knowledge systems and support resilience transitions in light of climate uncertainty. Next, we describe the knowledge systems analysis framework we use to characterize how these knowledge systems work.

2. Analytical framework: knowledge systems analysis

Knowledge systems analysis is a framework that evolved from the science and technology studies (STS) strands of co-production research that views knowledge as the outcome of complex judgments, claims, ideas, framings, and rationalities forged by different social groups and political cultures (Jasanoff, 2004). From this perspective, knowledge systems are the social and organizational norms and practices that make, validate, communicate, and apply knowledge in decision-making and governance (Miller and Muñoz-Erickson, 2018). Moving beyond descriptions of the content of the knowledge (i.e., what people know about flooding or "ways of knowing"), this framework aids in understanding *how* these different knowledge systems work in practice by

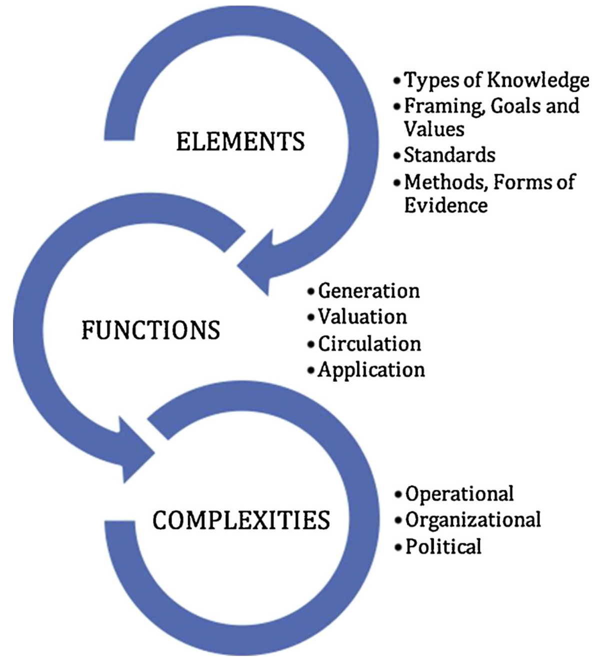

Fig. 1. Framework of Knowledge Systems Approach. (Adapted from Muñoz-Erickson et al., 2017).

examining their elements and functions, including the types of knowledge produced, the standards and ways of reasoning that shape its content, and the methods used in its production (Fig. 1). These elements shape what questions get asked (and which do not), what assumptions and methods to use, how much uncertainty is acceptable, and, most importantly, who decides (Muñoz-Erickson et al., 2017). The standards for data, illustrated by what information is produced, collected and then used to inform a policy document or infrastructure design, are part of the evidence we use to indicate perceptions of legitimacy that actors have around a knowledge system. We argue that knowledge systems analysis can serve as a useful tool for researchers and practitioners who are working towards transitioning to more resilience-based flood management in cities, by helping unpack and reveal the who, what, where, and how citizen knowledge can be integrated in the process.

Several studies have reviewed and highlighted the role and value of citizen knowledge in the flood management literature. In New Zealand, for instance, harnessing the knowledge and experiences of residents directly affected by floods through public engagement strategies has been helpful in forging citizen-government dialogues. This communication has shifted the focus from citizens' expectation that governments should always provide flood protection to citizens being more risk-aware and taking a proactive approach to assuming flood risk reduction (Lawrence 2014). Other studies have shown that participatory initiatives that engage citizens in the hydrological data collection process, such as citizen science (Paul et al., 2017) and citizen observatories (Wehn et al., 2015), or that use digital technologies, including smart phone apps, social media, and online websites (Le Coz et al., 2016; Holderness and Turpin, 2015), can be effective mechanisms to incorporate citizen experiences about flooding and enhance technical experts' knowledge systems (Desportes et al., 2016, Geaves and Penning-Rowsell, 2015, Hendricks et al., 2018). Furthermore, engaging citizens in collaborative knowledge production around flooding has been found to enhance the legitimacy and credibility of different sets of knowledge, which is vital for the adaptive governance approach (Jameson and Baud, 2016).

Despite the progress that has been made in recognizing the value of citizens' knowledge, challenges remain for the integration of citizen knowledge in urban flood management and its potential role in the transition to more resilient-based approaches. Understanding the political, social and cultural factors at play in a knowledge system and/or interacting knowledge systems can make barriers to knowledge integration more visibly apparent and easier to address. Recent research has studied some of these factors around citizens as consumers or participants in formal knowledge systems; such as the role of a person's interpersonal connections to a place, or community attachment, in sustained engagement of citizens in water management (Pradhananga and Davenport, 2017). However, there is a lack of in-depth understanding of citizens as *producers* of knowledge. In this paper, we focus specifically on the elements and functions of the knowledge systems framework to characterize how citizens' produce knowledge alongside the formal knowledge systems used by government actors. The elements of knowledge systems include framing and epistemologies and the functions include generation, validation, circulation, and application (Fig. 1, adapted from Muñoz-Erickson et al., 2017). The dynamics of knowledge systems are iterative and at each step influenced by, and reflective of the political, social, and cultural factors at play in the system of study. By treating different actors both as producers and consumers of knowledge, the analysis brings to the fore the social and power dynamics of knowledge-making and how these could be reconfigured with a true exchange and collaboration of knowledge (Miller and Wyborn, 2018). The analysis also offers practical lessons to practitioners on how to interact with citizens' knowledge systems, as well as help residents see their own knowledge production process and the ways they can interact with formal knowledge systems.

We use the term citizens' knowledge systems to describe the knowledge of residents that may be derived from their direct experience with the biophysical, social, political, and cultural dynamics of their place of residence, community, and larger city. It can be described as situational (Leino and Peltomaa, 2012), informal, or local, lay knowledge (Fischer, 2000). We compare citizens' knowledge with the formalized or codified knowledge that is developed from specialized educational training and used by management institutions that tend to rely on technical expertise and rationalities (Fischer, 2000). Although for the purposes of our analysis we contrast the knowledge systems of citizens and formal stakeholders, we recognize that this categorization is simplistic; knowledge systems are more complex and have elements of multiple types of knowledge (Raymond et al., 2010), as will be described later with respect to flood responses in San Juan.

3. Case study: context and methods

The urban communities of University Gardens (UG) and Jardines Metropolitanos (JM) are located within the Río Piedras sector of the San Juan metropolitan area of Puerto Rico (Fig. 2). The two neighborhoods straddle the lower reaches of the Río Piedras River, which drains a watershed of about 67 km^2 into the San Juan Bay Estuary (de Jesús-Crespo and Ramírez, 2011). We selected these communities in response to a request made by the Municipality of San Juan's Planning and Land Use Office to better understand how San Juan residents experience and understand flooding in an area with high incidence of nuisance flooding. Much of the area of these two neighborhoods are within the Special Flood Hazard Area designated by FEMA and are characterized by a 100-yr flood event. Smaller portions of the two neighborhoods fall within the 500-yr flood event zone, and the remainder of the area is characterized as being outside either of these zones. Current flood problems in the area are partly an artefact of past governance failures, such as allowing developments along river banks in the low-lying areas of the watershed and large-scale river flood control projects that did not address known mechanisms such as the need for maintenance of stormwater infrastructure (Lugo et al., 2014). These challenges are compounded by a fiscally-constrained state that has not invested in flood mitigation infrastructure (Puerto Rico Climate Change Council (PRCCC, 2013) or enforced policies preventing development in flood vulnerable areas (Torres, 2018). The limited financial capacity to fund flood mitigation projects is due in part to federal policies regarding Puerto Rico's territorial status, such as lack of direct congressional representation and reduced federal appropriations (Center for Economic and Policy Research and Merling, 2018, Weeks, 2014). The alleged mismanagement of funds by the PR government (GAO, 2018) has resulted in limited financial capacity for the local government to finance flood mitigation projects. The vulnerability of the city's stormwater infrastructure was exposed and further impacted when it was overwhelmed by over 30 in. of storm rain brought by Hurricane María (U.S. National Weather Service, 2018). Additional background information on the case study is provided in the Supplementary Materials.

We used a case study research design (Yin, 2009) and multiple sources of evidence. To analyze formal knowledge systems, we consulted with staff from government agencies managing flooding (Table 1), official agency documents, flood maps of recurrence intervals, and hazard mitigation estimates between 2014 and 2018. The citizen knowledge system was characterized using data collected from interviews of residents in two neighborhoods during the summer of 2015. One hundred (100) parcels were chosen using a stratified random sampling design to represent the existing socio-economic and FEMA flood zone distribution within the two neighborhoods. Residents were recruited by door-to-door visits and a total of 97 residents agreed to the interviews (75 from UG, 22 from JM; see Supplementary Materials, Table 1). Further details about our research design, interview methods, and sampling design are provided in the Supplementary Materials.

We focused on the formal knowledge systems directly involved in the management of flooding in the city due to riverine, stream and urban stormwater. This made the analysis tractable, but it also meant leaving out other formal knowledge systems in San Juan and Puerto Rico with expertise relevant for flood management, such as academic and professional scientists and engineers, respectively. However, the scope of this analysis is a crucial first step for future studies where we expand the applications of the framework (Fig. 1) to examine the operational, organizational and political complexities that arise as the flood knowledge systems presented here interact with other relevant knowledge systems in the city. In addition, our analysis of the informal knowledge systems focused on two specific communities in San Juan representing their flood experience pre-Hurricane María. While this is a limitation, we argue that understanding the citizen-based flood knowledge of a city prior to a disaster is still relevant (and arguably more relevant) as it provides a baseline against which innovations to the knowledge system regarding risk decision-making, disaster preparedness, flood mitigation, and insurance policies can be evaluated

4. Case study findings

In this section we present the organizational structure and the knowledge systems' elements and functions around flood management in San Juan and summarize them in Table 1 and 2, respectively. We address stormwater and riverine flooding separately to reflect the existing governance structure and framing of flooding problems in the city, with the exception of flood hazard mitigation.

4.1. Formal flood knowledge systems

4.1.1. Stormwater

The governance structure of urban stormwater in San Juan is dispersed amongst several municipal, state, and federal agencies that are responsible for managing water quality and meeting the standards outlined in the U.S. Clean Water Act and the EPA's National Pollutant Discharge Elimination System program (see Table 1). The main actions addressing stormwater management in San Juan are related to infrastructure mitigation and maintenance (cleaning, repairing, and retrofitting) and are the sole responsibility of the municipality.

The knowledge claims and framing of the problems and potential solutions around official stormwater flood management are narrowly defined in this knowledge system (Tables 1 and 2). Notably, the

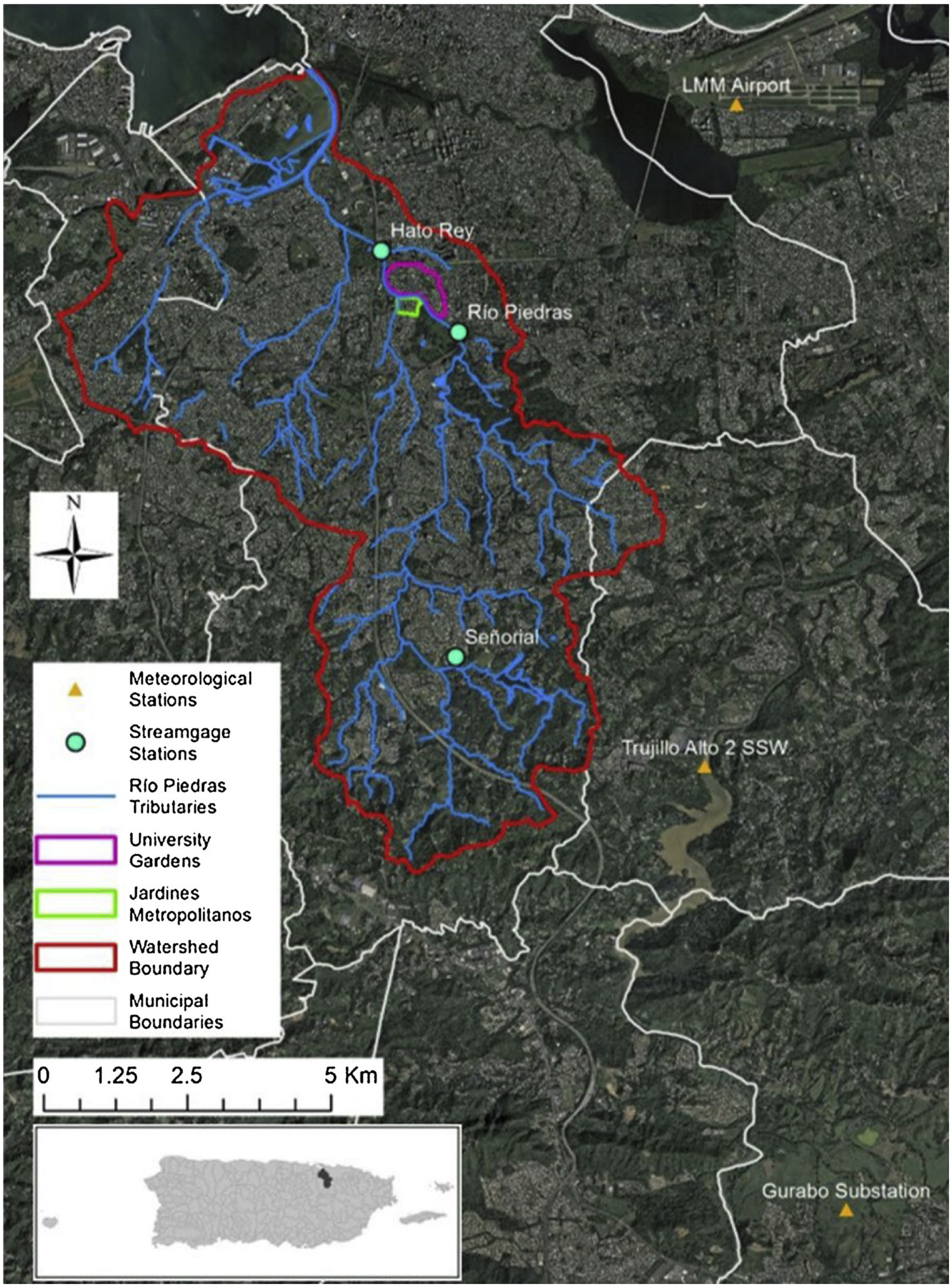

Fig. 2. Map of Rio Piedras watershed showing location of two focal communities, University Gardens and Jardines Metropolitanos, relative to the Río Piedras, in addition to hydrometeorological stations in the region.

municipality's Stormwater Management Plan does not explicitly discuss problems with stormwater flooding, but rather stormwater flooding is framed as a water quality problem. The plan discusses protocols to maintain and clean drains and inspect pipes, but not how to address the quantity of stormwater runoff, the role of stormwater in flooding, or how stormwater flooding is managed in the municipality (San Juan Environmental Compliance and Planning Office, 2018), despite available data and analysis on stormwater flooding produced by other organizations. The plan's framing of solutions adopts the conventional engineering approach of structural responses based on the predicted 100-yr design storm, using historical conditions of peak discharge and precipitation (e.g., peak discharge from a 1-in-100-year flood event) as the forms of evidence. This standard of the municipality's knowledge system, the 100-yr storm, is the maximum level of service that will be provided by the designed infrastructure (design storms vary e.g.10-year, 25-yr or 100-yr). Uncertainties around this standard, such as climate change and the age and condition of the infrastructure, are not discussed in the management plan.

Knowledge generation around stormwater flooding by municipal staff is not collected or documented using official standards or protocols. Rather, municipal staff unofficially monitor flood conditions by observing the streets around their offices which are located in multiple locations around the city. Based on our interviews, municipal staff appear to perceive citizen knowledge of flooding as having a minimal utility. Staff from the Municipal Office of Environmental Compliance do not consider the engagement of citizens in monitoring stormwater infrastructure as a viable option. Citizen reports of flood conditions recorded by the municipality's hotline about localized flooding emergencies or problems due to urban water infrastructure (e.g., problems with stormwater or drinking water infrastructure) are not viewed as

Table 1
Organizational structure of stormwater and riverine management in San Juan, Puerto Rico.

Scale and Actor	Responsibilities and Practices
Federal	
• US Federal Emergency Management Agency (FEMA) • US Army Corps of Engineers (USACE) • US Environmental Protection Agency (EPA) Region 2 Office • National Oceanic Aeronautics Administration (NOAA) • US Geographical Survey (USGS)	• Administer flood insurance rate program, Coordinate with state government agencies and land use boards to develop flood insurance rate maps (US federal laws: 1936 Flood Control Act, Flood Disaster Protection Act 1973, National Flood Insurance Act 1968, Biggert – Reform Act 2012) • Design and construct infrastructure to control and mitigate natural hazards including flooding (US federal laws: Stafford Disaster Relief and Emergency Assistance Act of 1988) • Develop laws and regulations protecting human and environmental health; enforce Clean Water Act; ensure states and territories compliance with Clean Water (US federal laws: Clean Water Act) • Develop and publicize flood hazard alerts; develop hydrologic information regarding flood hazard maps and reports on past flood conditions, e.g., monthly hydrologic reports with information on sites/dates of flood USGS gages • Record and publicize in real-time stream discharge and flood stage conditions along major streams/rivers
State/Territorial	
• PR Department of Natural and Environmental Resources • PR Permits and Endorsements Management Office • PR Aqueducts and Sewer Authority • PR Planning Board: Flood Unit • Caribbean Area Division: FEMA NFIP • PR State Hazard Mitigation Officer • PR State Agency for Emergency and Disaster Management • PR Environmental Quality Board • PR Environmental Protection Agency, Caribbean Environmental Protection Division	• Partner involved in USACE flood control projects such as coordination of river channelization project on Río Piedras/Río Puerto Nuevo • Operate and maintain flood control pumps in coastal zone • Permitting of development projects within flood vulnerable zones; approval of stormwater infrastructure designs • Delivery and maintenance of drinking water and infrastructure • Develop the PR Land Use plan, Special Flood Vulnerable Zone, floodplain ordinances, and management of the National Flood Insurance Rate Program (NFIP) via the Map Modernization Management Support Coordinator • Help coordinate emergency management programs in PR and the U.S. Virgin Islands; help support activities to prepare and mitigate hurricanes, flooding, and earthquakes • Select local government hazard mitigation grant applicants and submit applications to federal FEMA office • Coordination with federal and city government officials on FEMA NFIP flood disaster projects; public outreach on disaster risks • Create standards and ensure compliance with standards set in the 'Law for Public Policy for the Environment' for protecting water quality of coastal water bodies, surface water, and groundwater; Citizen Hotline (citizen calls regarding flooding, water quality concerns) • Plans and coordinates activities related to the MS4 program
Municipal	
• Municipality of San Juan Office of Planning and Land Use • Municipality of San Juan Office of Environmental Compliance • Municipality of San Juan Office of Operations and Decoration: Flood Control • Municipality San Juan Office of Emergency Management • Municipality of San Juan Office of Permit Management • San Juan City Manager	• Mapping stormwater (SW) infrastructure • Comprehensive Land Management Plan, Transportation Plan • Approve stormwater infrastructure designs • Hazard Mitigation Plan • Identification of Illicit Discharges, Monitoring Municipal Storm Sewer Systems (MS4) • Stormwater Management Plan • Education about stormwater and water quality • Repair Infrastructure • Cleaning debris from rivers, streets, SW infrastructure • Warning communities about flood hazards • Coordinate with Ornatos to remove debris from rivers and SW infrastructure • Approval SW infrastructure design, retrofit • Coordinate river channelization project with PR DNER and USACE
Community	Special Communities, Community groups (unofficial e.g., University Gardens group meeting to discuss crime and flood hazard issues)
Household	Individual households, a network of households (e.g., families, neighbors on a street)

official data. Citizen reports are used as indicators of suspected infrastructure problems or areas vulnerable to flooding that must be confirmed by municipal staff. While the municipal staff from the Office of Planning and Land Use recently recognized the importance of citizen knowledge and participation in flood management in a 2015 Resolution (OPOT-2015-1, see Supplementary Materials) it remains a limited strategy. Communities are consulted by municipal staff about newly released FEMA maps asking them to verify new flood zone boundaries, but this citizen information is not used in an official capacity alongside state and federal flood data. Municipal staff have expressed that they would be willing to integrate citizen knowledge about flood events if a smartphone app or similar technology was available that recorded both photographs and a time-stamp as this would provide a source of data that does not rely on personal recollection of time.

Most recent knowledge generation around stormwater infrastructure in San Juan involves assessing the functionality of the stormwater infrastructure (Table 2). A study conducted in 2009 by a private engineering firm provided a detailed analysis of the functional status of the stormwater infrastructure and issues contributing to flooding in San Juan. In 2013, a state Flood Commission (Colegio de Ingenieros y Agrimensores de PR, (CIAPR, 2013) made 11 recommendations for addressing flood problems in Puerto Rico that included alternative stormwater infrastructure solutions such as increasing permeable areas, as well as management recommendations such as the creation of interagency agreements to address flood problems on the island and the development of municipal flood control offices.

4.1.2. Riverine

Management of riverine flooding is different from urban stormwater in that it has clear mandates for flooding and an organized governance structure that involves funding and operation of activities at the federal, state, and municipal-level (see Table 1). Knowledge is generated directly for the long-term monitoring of riverine flood conditions and weather at the federal level, the design and construction of major riverine infrastructure projects at the federal and state-level, the design of hazard mitigation plans at the federal, state, and municipal level, and the design and implementation of zoning laws determine development in flood-vulnerable zones at the state and municipal level (Table 1).

The goal and framing of the problems and solutions around riverine

Table 2
Elements of knowledge generation of the formal and informal knowledge generation around flooding in San Juan.

	Formal KS – Stormwater	Formal KS – Riverine	Informal KS – Riverine and Stormwater
CLAIMS and FRAMING: Causes and Solutions of Flood Problem	**Causes of problem:** poor maintenance, limited infrastructure capacity; structural limitations; **Solutions to problem:** **r**etrofits of infrastructure, better maintenance **Scale of problem:** drainage area of development project (sub-watershed)	**Causes of problem:** watershed built-out, poor condition and size of channels and bridges **Solutions to problem:** Improve structure of tributary junctions and bridges, cement channelization of river **Scale of problem:** Rio Piedras drainage basin, 50 years	**Causes of problem:**lack of infrastructure maintenance, location in watershed **Solutions to problem:** Improve maintenance of river and stormwater infrastructure, retrofit of bridge infrastructure, Increase green space, channelization of river **Scales:** Yard, adjacent streets, community, city, watershed
ELEMENTS: Epistemologies	Technocratic, runoff discharge coefficients, design storms using rainfall intensities estimated	Technocratic, hydraulic engineering, watershed hydrology	Experiential, direct observation, Specialized (hydrology/hydraulic engineering)
ELEMENTS: Actors and Institutions	- Municipal Office of Environmental Compliance and Planning; Office of Ornatos, Flood Division, Office of Emergency Management - Puerto Rico Planning Board	- Municipal City Manager, Office of Planning and Territorial Ordinance, SJ Office of Emergency Management - Puerto Rico Department of Natural Resources, Puerto Rico Office of Emergency Management - USACE, FEMA	Household residents, community groups e.g., University Gardens community monthly meetings
ELEMENTS: Values and Standards	PR and San Juan Land Use regulations: peak discharge estimates to be less than those experienced in area for 1-in-100-year storm based on the 10-year, maximum 24-hr storm relevant	1-in-100-yr flood, 1-in-500-yr flood; Total rain volume associated with peak river discharge conditions	NA
ELEMENTS: Types of data and evidence used	NOAA Atlas 14, TR-55 for Puerto Rico, USGS stream gage/flood stage data, citizen hotline; municipal staff brigades, media	USACE/FEMA Flood Insurance Rate Maps, Historical peak discharge/ associated precipitation, USGS stream gage	Social network (family, neighbors), media (radio/TV, newspapers), Municipal Emergency workers
Knowledge Gaps	- Vision of sustainable urban drainage instead of maximum conveyance maximize storage and transpiration, use of civic knowledge - Use of informal knowledge for stormwater infrastructure assessments, documentation of flood events - Extreme precipitation quantities and frequency associated with climate change		- Flood risk associated with changing climate - Leverage points in formal knowledge, city management processes, and structure of formal flood management - Strategies for building adaptive capacity (e.g., green infrastructure)

flood management in San Juan (Table 2) involve moving flood water in the river out of the city as quickly as possible with the singular goal to protect life and property (Lugo et al., 2014). Like the framing of solutions for stormwater flooding, management of riverine flooding relies on conventional engineered approaches based on prediction and assumptions of stationarity (see Table 1 and 2) using the standard 100-yr design storm. These goals and framings are evident in the proposed structural solution, the dredging and cement channelization of the Río Piedras from its outlet in the San Juan Bay to upstream areas (USACE, 1987,1991). The complete project design was developed by USACE engineers in 1990 and includes channelization of the portion of the river adjacent to the communities of University Gardens and Jardines Metropolitanos. Uncertainty around the channel's efficacy concerning unvalidated assumptions about the extent of urban development, the functional capacity of the stormwater infrastructure, and potential effects of a changing climate are not discussed.

The FEMA flood risk maps for the Río Piedras drainage basin are the primary knowledge system to generate knowledge on riverine flooding that informs state and city zoning laws and the municipality disaster and hazard mitigation plans (Table 1). The standard defined for stormwater infrastructure is fail-safe (i.e., designed not to fail and cause damage, localized stormwater flooding), does not consider alterations to reduce the capacity of riverine stormwater to convey downstream (e.g., sediment, tree branches, etc.), and is based on assumptions of stationarity (peak precipitation volume) (Federal Emergency Management Agency, 2009). The FEMA mapped flood zones of the Río Piedras drainage basin are based on the results of the USACE simulation model for the Río Piedras/Puerto Nuevo flood control project (United States Federal Emergency Management Agency, 2009).

4.1.3. Flood hazard mitigation

The formal knowledge systems around FEMA flood hazard mitigation planning in San Juan (Table 1 and 2) involves actors at the federal, state, and municipal level. The San Juan 2015 multi-hazard mitigation plan uses information about riverine flooding risks from the USACE/FEMA flood risk maps and informal knowledge from citizens (e.g., community meetings, data from the citizen hotline) to confirm riverine flooding and to identify areas experiencing stormwater flooding. This intention to integrate informal knowledge about on-the-ground flood conditions addresses uncertainty around the epistemologies used to design the cities riverine and stormwater infrastructure as well as the non-static functioning over time. However, it stops short of addressing potential effects of future extreme events. Mitigation actions proposed in the plan focus on USACE riverine channelization project. The plan describes intentions to update areas of the stormwater infrastructure system with known capacity issues; however, it does not describe how these improvements will be made (Municipio de San Juan, 2015).

4.2. Citizens' flood knowledge systems

Residents from UG and JM frame flooding problems in terms of their type, spatial and temporal pattern, ideas about how they occur, and potential solutions to prevent, and in some cases to adapt, to them (Table 2). UG residents describe flooding as a problem that is riverine and pluvial that occurs throughout the community while residents from JM perceive flooding as a problem that is riverine and limited to a few streets and more severe in magnitude for the residents in the UG community across the river. The informal, citizen knowledge system includes both temporal and spatial patterns of flooding. Residents from UG describe the recurrence of flooding in a variety of ways. Several residents described a temporal pattern for flooding, an event that happens approximately every 30 years (the same perceived periodicity of a major hurricane) or an event that could happen any year during the months of hurricane season (May to November). When asked about their experience of flooding, many of the residents from JM described their observations of severe flooding as a limited area in their

Fig. 3. One of the interviewed resident's map of the 2009 flood event in the University Gardens and Jardines Metropolitanos community.

community: the street and parking area of a large apartment building located along the river and the road adjacent to the channelized stream that enters the river (Figs. 3 and 4). Riverine flooding in UG was most frequently observed along the two streets located adjacent and parallel to the river and the furthest downstream. In the case of UG, the community has experienced several areas of pluvial flooding where several streets have flooded by a buried stream that was designed and installed when the community was first developed in 1950s (Personal communication, Avila Sanchez 2018, Ramos-Santiago et al., 2014). Citizen maps of flooding produced by residents along affected streets had a higher level of spatial detail than other residents' maps, which tended to be simple markings along the two main roads (Fig. 4a and b).

Unlike the formal knowledge systems that produce information and policies about riverine and stormwater flooding discreetly, citizen-based knowledge produces information about riverine and stormwater flooding. This can be seen in the composite map of all citizen maps drawn for that 2009 event which show urban stormwater flooding in the upper right area of the development and in the streets and yards along the river bank (Fig. 4a), and for five focal flood events (Fig. 4b). The citizen knowledge also reveals a finer scale spatial understanding of flood risk than the USACE/FEMA flood risk map.

Citizen knowledge frames the cause of stormwater and riverine flooding as a failure of urban water infrastructure to function, and because of a lack of municipal and state government actions to remove sediment, vegetation, debris, and trash. This perception of the river as an entity to be maintained, to be 'cleaned', suggests that residents equate the river with urban water infrastructure, not a natural aquatic system with dynamic flow conditions. Residents frequently expressed a lack of communication and engagement of agencies to ask about their concerns about flooding. In one example, residents expressed their frustration with the municipality's Environmental Quality Board lack of response after repeatedly calling about concerns over water quality problems when stormwater entered the Río Piedras via a runoff pipe. In another example, community members discussed the need to place political pressure on the state legislature to push for funding for additional upstream flow gauges. Here there is a sense that the community must organize and push for action to have access to knowledge they need to prepare for flood hazards.

The primary way that knowledge is generated is through direct, lived experiences that residents have with flooding. Participants frequently framed their expertise about flooding as narratives about flood conditions they had seen and actions they had to take during a flood event, such as where standing water affected their property and entered their homes, and how they developed practices for anticipating a flood event based on their experience. Some of the residents we spoke with had lived there only a few years, but they were familiar with the locations that were most frequently flooded because previous owners or neighbors shared this information with them. There were also several instances of specialized knowledge of residents with professional expertise in engineering. In one case, an engineer was one of the original designers of the urbanization and therefore served as a source of advanced understanding about the neighborhood's infrastructure and flood conditions.

Residents have been mobilizing to reduce flood risks with knowledge circulation, infrastructure maintenance and adaptations, and political interventions. Led by several residents with technical engineering expertise, regular community meetings include discussions about flooding, and social networking sites (Facebook, Crowdville.com) are used to share information about flood incidences. Intergenerational knowledge flow also occurs when residents pass down information about flooding that has affected a property to successive family members. There are several areas in UG where neighbors have created a network (phone, in-person) for informing one another about flood conditions and methods for preparing for an event. We found only a few examples of residents consulting formal knowledge systems as a method and form of evidence around flooding. Residents did not mention FEMA or the flood insurance rate maps as a source of information. It is unclear, however, if the residents interviewed were unaware of FEMA flood maps or they did not see it as a valuable resource. Several individuals described how, once they are aware of an intense rainstorm approaching or hear a hard rain, they go outside to look at the river level, check out the online stream discharge data from a USGS stream gage located upstream.

5. Discussion

We found several key barriers and opportunities that deserve attention to connect these different knowledge systems for sustainable flood governance in San Juan. First, we were surprised to see that neither of the formal knowledge systems considers or communicates the uncertainties surrounding the official claims about what is causing flooding and how to manage it. Because the way a problem is framed – its scope, scale, and causes – can determine the solutions to address the problem, too narrow of a framing can result in limited, and sometimes failing, results (Leach et al., 2010). The USACE plan, for instance, does not include a plan or budget for assessing infrastructure function and performance over time nor potential maintenance needs. This is important because after the project has been implemented, the municipality will gain responsibility for maintaining the infrastructure but has limited financial and knowledge capacities for providing this crucial service. The risk is even greater knowing that the channelization design has been determined using models with outdated, historical climate data and lacking anticipation of extreme weather events. Similarly, because the municipality's stormwater knowledge system is focused on water quality and not infrastructure per se, it fails to communicate to residents the level of uncertainty surrounding flooding, the condition of flood infrastructure, and key land use planning decisions that affect flood risk.

Second, our analysis shows that neither formal and citizen knowledge systems around flood management and risks have the anticipatory capacities required to address climate-related flood events. As we have discussed, the epistemologies of the FEMA and USACE knowledge systems portray the city and its water relationships as quantifiable and static, relying on retrospective climate data and flood maps that are out of date. The citizen knowledge system shows a more systematic understanding of the relationship between riverine and stormwater flooding and its residents use their experiences and social networks to learn and prevent damages from flood events. Yet, this knowledge system is also short-term, limited to localized responses, and lacks the ability to deal with unprecedented flood risks. Previous studies of flood preparedness strategies taken by San Juan residents also show that

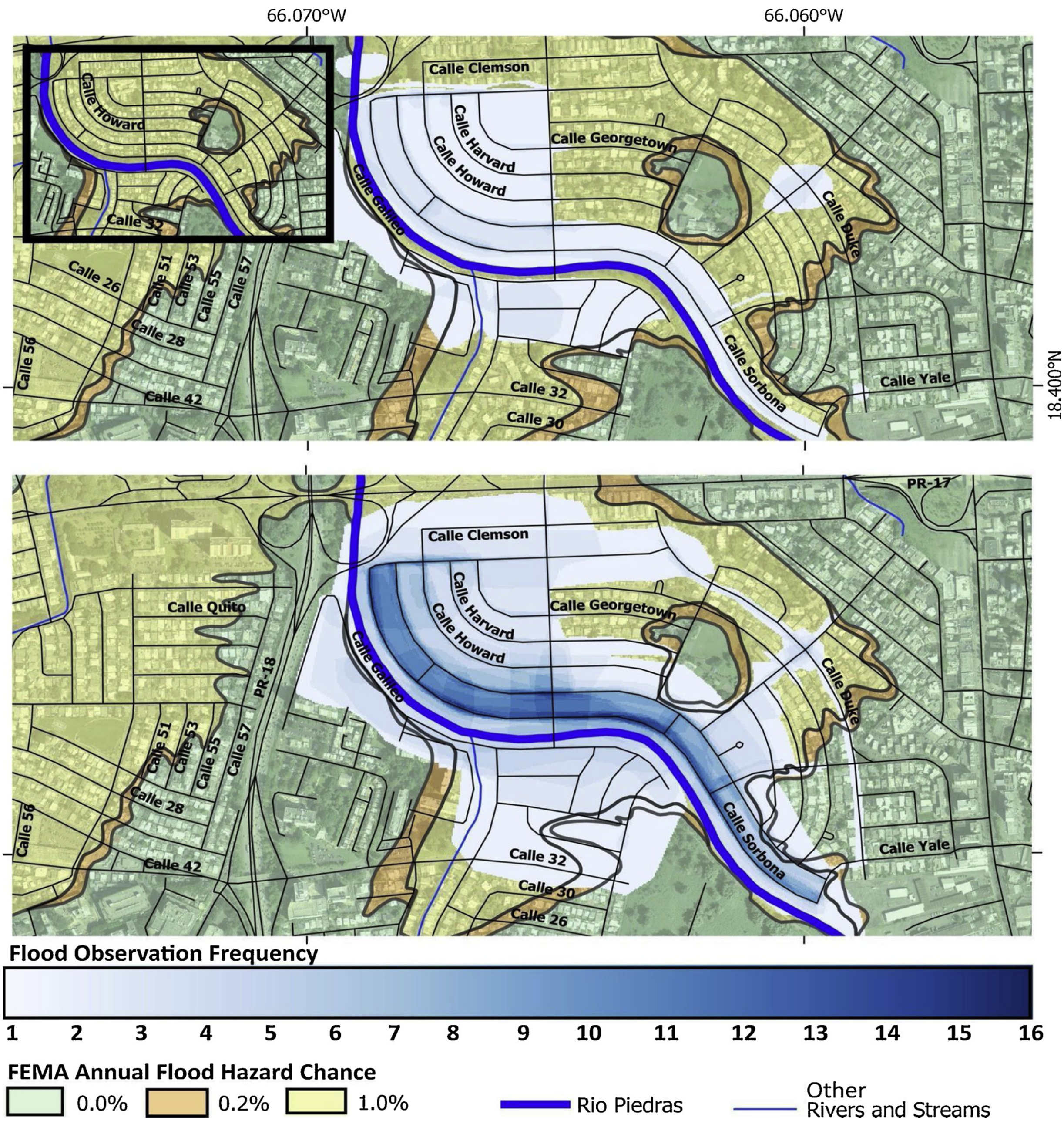

Fig. 4. a and 4b. 'Heat' map of flood areas from citizen maps overlaid on top of FEMA flood zones in University Gardens and Jardines Metropolitanos. The upper map is a composite of citizen maps for a Thanksgiving 2009 flood event and the lower map is a composite of citizen maps describing 5 focal flood events described by interviewed residents.

many only focus on short-term measures and do not consider long-term plans (Santiago-Bartolomei et al., 2015).

To build anticipatory capacities, we need knowledge systems that allow us to explore different plausible scenarios of extreme weather events and non-structural approaches for reducing flood risk (Codutra Dobre et al., 2018; Lawrence et al., 2014, 2015). The Puerto Rico Climate Change Council is a formal multi-institutional entity that provides anticipatory capacity through scientific research and scenario development, but unfortunately this capacity is not being utilized by the primary actors playing a direct role in San Juan flood management and mitigation policy; e.g. Puerto Rico Department of Natural Resources, USACE, San Juan Office of Public Works and Environmental Compliance (see Table 1). Additionally, the dynamic nature of infrastructure and its response to the physical environment means that the infrastructure can decay or become damaged or that change in the surrounding environment means that the infrastructure does not function uniformly. Therefore, anticipatory knowledge systems require protocols and funding for monitoring of infrastructure and repairs, and if necessary, retrofits. Here again, the use of citizen science approaches can be a valuable mechanism for monitoring and learning from infrastructure response to different flood situations.

Third, the institutional and knowledge framework guiding stormwater flood management in San Juan is poorly defined and communicated and this could pose a potential barrier to knowledge integration. The municipal government lacks a formal system for monitoring, documenting, and understanding flood conditions in the city. They need to rely, instead, on the expert knowledge systems of the federal knowledge systems of USACE and FEMA, yet these are not integrated into the stormwater institutional framework. Currently, stormwater flood management is not an objective of any particular agency or consortium of agencies. The lack of clarity and guidelines about which institution is responsible (and accountable) and what knowledge is coming to bear on stormwater flood management may affect the adaptive capacity of city residents. Indeed, previous studies in San Juan have suggested that the institutional framework around flooding is not adequate to protect and build the adaptive capacity of communities (Santiago-Bartolomei et al., 2015). The resilient-based flood management approach is a more holistic, integrated watershed approach that connects stormwater and riverine flooding management. An institutional structure that addresses the problem of stormwater flooding could be part of a larger watershed-scale framing of flood management.

Framing stormwater flooding as an explicit management objective can open the opportunity to establish protocols for monitoring and documenting this process as well as circulating this information to decision-makers and citizens. This study shows that citizen knowledge systems can add more granular information for understanding stormwater and riverine flooding occurring in the city. Our study also found that using an online or smartphone app for recording flood conditions in real-time could help with legitimizing the application of citizen flood knowledge alongside formal flood data in decisions around stormwater and river flood management. Use of an app or website to document citizen flood information could also be a way for citizens with flood experience to share their strategies for understanding their flood risk, and for preparing for and avoiding flood hazards.

Our knowledge systems analysis is an important first step that has helped to make visibly apparent the different forms of existing knowledge and their relevance, validity, and reliability to the scope of the problem (Miller and Wyborn, 2018; Muñoz-Erickson et al., 2017; Raymond et al., 2010). By exposing the differences in the way that flooding is understood, and solutions framed, we have set the stage for this co-production and further opened the dialogue to include a broader set of actors and knowledge systems who may represent alternative approaches with relevance to urban flooding in San Juan, including other civic actors and professionals such as landscape architects, ecologists, engineers, and planners. We expect that new framings and solutions, for instance to the Río Piedras flood infrastructure design, can emerge from this process.

6. Conclusion

In this study, we examined the formal and citizen knowledge coming to bear on urban flood management in two communities in San Juan, Puerto Rico, from the lens of knowledge systems analysis. Increased understanding about what and how citizens and government actors know about flooding helps evaluate what knowledge systems are relevant and missing from flood management. It also reveals potential barriers and opportunities to align these different forms of knowledge towards innovations in urban flood governances. We propose (and hope) that recent activity and investments in flood mitigation infrastructure post-disaster be used as a window of opportunity to re-configure formal and citizen relations around flooding and encourage more engagement and co-produced solutions to address flooding. There is a clear need to understand how different ways of knowing the city, including those traditionally excluded from the decision-making process, can come together to better prepare and anticipate complex urban challenges. Knowledge systems analysis can facilitate knowledge integration and co-production by mapping and uncovering the existing knowledge-power dynamics that shape the interactions of multiple actors in governance. As officials and citizens continue to learn from experiences with extreme events like Hurricanes María, the goal of knowledge system interventions should be the integration of diverse sources of knowledge and the evolution of cities that are resilient to the impending effects of global climate change.

Declarations of interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.envsci.2019.04.013.

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