



Water Governance in the Wake of Disasters: Implications for Resilience, Security, and Environmental Justice

Omar Pérez Figueroa and Anais Delilah Roque

ABSTRACT

When a disaster strikes, water supply systems can get impacted and amplify water security risk. This study examines community water governance after Hurricane María in Puerto Rico. We draw from the experience of 12 community-managed aqueducts and 36 interviews with community aqueduct managers, non-profit organizations, and state actors. Our findings highlight the role of the social dimensions of community water governance in alleviating the technical and economic challenges aqueducts faced after Hurricane María. Specifically, social capital, human capital, aqueduct ownership, and community participation played a significant role in restoring drinking water supply across all aqueducts. Highlighting the challenges and opportunities faced by community-managed aqueducts, we emphasize the future of water security and resilience. Our research contributes to the literature on environmental and water justice, focusing on community-managed water governance systems. Many disasters impact water supply systems, affecting distribution methods, thereby providing valuable insights for disaster risk reduction. The results emphasize challenges with intergenerational knowledge transfers and the need for investment in physical and social infrastructures to enhance community-led governance for water security.

Keywords: resilience, water governance, Hurricane María, community aqueducts, Puerto Rico

INTRODUCTION

The ability of communities to recover from disasters is shaped by existing socioeconomic and racial inequalities, as well as by state institutions and other political–

economic structures.^{1,2,3,4,5} With increased high-impact weather events, preexisting state negligence, and underinvestment to critical infrastructures, communities have

Dr. Omar Pérez Figueroa is Assistant Professor at Urbana-Champaign, Department of Urban and Regional Planning, University of Illinois, Urbana, Illinois, USA. Dr. Anais Delilah Roque is Assistant Professor at Nicholas School of the Environment, Duke University, Durham, North Carolina, USA.

Some material in this work was previously published in a dissertation authored by Omar Pérez Figueroa. This dissertation was written to fulfill the requirements for the degree of Doctor of Philosophy in Urban and Environmental Planning and Policy at the University of California, Irvine, which was conferred on September 7, 2022. The full thesis can be accessed on the University of California, Irvine eScholarship website at <https://escholarship.org/uc/item/1kk7d9n5>.

¹Arifeen, Awais, and Siri Eriksen. “The politics of disaster vulnerability: Flooding, post-disaster interventions and water governance in Baltistan, Pakistan.” *Environment and Planning E: Nature and Space* 3, no. 4 (2020): 1137–1157.

²García-López, Gustavo A. “The multiple layers of environmental injustice in contexts of (un) natural disasters: The case of Puerto Rico post-Hurricane María.” *Environmental Justice* 11, no. 3 (2018): 101–108.

³Laska, Shirley, and Betty Hearn Morrow. “Social vulnerabilities and Hurricane Katrina: an unnatural disaster in New Orleans.” *Marine technology society journal* 40, no. 4 (2006).

⁴López-Marrero, Tania, and Ben Wisner. “Not in the same boat: Disasters and differential vulnerability in the insular Caribbean.” *Caribbean Studies* (2012): 129–168.

⁵Bullard, Robert D., ed. *Growing smarter: achieving livable communities, environmental justice, and regional equity*. MIT Press, 2007.

an increased risk of being water insecure after hazards and disasters.^{6,7} This makes water governance—the political, social, organizational, and administrative processes and institutions that shape water resource management—an essential area of focus to ensure equal access, consumption, and conservation of water for human health and wellbeing. Currently, much of the discussion on water governance in the hazard and disaster context focuses on large-scale centralized systems. In this research, we center community-level water governance to explore postdisaster water supply resilience and community water security to disasters.

This research focuses on the experiences of community aqueducts after the impact of Hurricane María (2017) in Puerto Rico. Puerto Rico, a colony of the United States, faces several challenges that hinder its ability to withstand hazards and disasters. From decades of economic instability, over 40% of the population is dependent on the welfare state, high unemployment rates, and weak critical infrastructures such as energy and water systems.⁸ When it comes to water, Puerto Rico has a plethora of water justice problems, many of which were present before Hurricane María.⁹ Puerto Rico currently has 97% of its drinking water provided by the Puerto Rico Water System Authority (PRASA), and the remaining 3% is served by community managed small water systems (also known as non-PRASA). For the PRASA system, drinking water problems can be divided into two main areas: quality and distribution.^{10,11} Quality problems resulted from the landfill crisis, a heritage of toxic dumps,¹² and the deregulation of policies that protected

the environment.^{13,14} Distribution problems emerged from suburbanization land development driven by big engineering projects based on importing water from long distances. For small water systems or non-PRASAs, these have been operating for more than 50 years following a U.S. laissez-faire urban planning model,¹⁵ resulting in centralized water grid systems that excluded rural communities from the water provision.¹⁶

Environmental justice issues faced by community aqueducts in Puerto Rico can intensify the impact of disasters.¹⁷ The unequal allocation of water infrastructure to support local management is a prime example. Along this, non-PRASAs have prolonged periods (compared with PRASA system) to receive support for repairs or upgrades.^{18,19} Community aqueducts often report challenges for regulatory compliance and participation of important decisions about water management policies and practices.²⁰ Moreover, throughout the years, government officials have argued that small water systems are primitive, unsafe, and ineffective.^{21,22,23} Many aqueducts are also not registered yet they remain, in some cases, as the only source of clean drinking water in Puerto Rico's rural communities.²⁴ After Hurricane María (2017), there were also disparities in the recovery of water systems as it took more time for community aqueducts to have services restored than the centralized system.²⁵ Within this context, we aim to explore how community water governance was present and unfolds in

⁶Sultana, Farhana. "Living in hazardous waterscapes: Gendered vulnerabilities and experiences of floods and disasters." *Environmental Hazards* 9, no. 1 (2010): 43–53.

⁷Ho, Janice Ying-en, Emily Ying Yang Chan, Holly Ching Yu Lam, May Pui Shan Yeung, Carol Ka Po Wong, and Tony Ka Chun Yung. "Is 'perceived water insecurity' associated with disaster risk perception, preparedness attitudes, and coping ability in rural China?(A health-EDRM pilot study)." *International Journal of Environmental Research and Public Health* 16, no. 7 (2019): 1254.

⁸Sánchez Colón, Yashira M., Edna Acosta Pérez, Mayra L. Roubert Rivera, Marizaida Sánchez Cesáreo, Christine Miranda Diaz, Glenda L. Ortiz, Jean C. Meléndez González, Valeria M. Schleier Albino, and Laura Mora Lemus. "Community Forums as Amplifiers of Communities' Voices: Isolated Communities in Puerto Rico." *International Journal of Environmental Research and Public Health* 20, no. 14 (2023): 6335.

⁹Lloréns, Hilda, and Maritza Stanchich. "Water is life, but the colony is a necropolis: Environmental terrains of struggle in Puerto Rico." *Cultural Dynamics* 31, no. 1–2 (2019): 81–101.

¹⁰Torres Abreu, Alejandro. "¿Satisfacer o manejar la demanda? Perspectivas dominantes en torno al debate sobre el consumo del agua en Puerto Rico." *Revista de ciencias sociales (Río Piedras)* 20 (2009): 176–205.

¹¹Concepción, Carmen M. "The origins of modern environmental activism in Puerto Rico in the 1960s." *International Journal of Urban and Regional Research* 19, no. 1 (1995): 112–128.26. Hunter, John M., and Sonia I. Arbona. "Paradise lost: an introduction to the geography of water pollution in Puerto Rico." *Social Science & Medicine* 40, no. 10 (1995): 1331–1355.

¹²*Ibid.* García-López (2018).

¹³Concepción, C. M. "El ocaso del proceso de Evaluación de Impacto Ambiental en Puerto Rico: Un examen de la práctica a partir de 1990." *Revista del Colegio de Abogados de Puerto Rico* 68, no. 4 (2007): 755–777.

¹⁴López, Gustavo García, and William McCormick Rivera. "Declaraciones de Impacto Ambiental: ¿Buen gobierno en la política ambiental?." *Revista de Administración Pública* 48 (2018): 1–30.

¹⁵García, Kino, Inc Edición a cargo de Grupo, Creativo Siembra, and Foto de la portada: Centro de la Ciudad de Mayagüez desde las Montañas con el Pasaje de la Mona al fondo. *La planificación en Puerto Rico*. Editorial Grupo Creativo Siembra, 2008.

¹⁶Pérez Figueroa, Omar. "Disaster Recovery in Puerto Rico: Understanding Resilience Through the Island's Communities." PhD diss., UC Irvine, 2022.

¹⁷*Ibid.* Pérez Figueroa, (2022).

¹⁸*Ibid.* Pérez Figueroa, (2022).

¹⁹Opitz-Stapleton, Sarah. "Political ecology of safe drinking water in the United States with a case study focus on Puerto Rico." PhD diss., University of Colorado at Boulder, 2009.

²⁰Llano-Arias, Valeria. "Community Knowledge Sharing and Co-Production of Water Services: Two Cases of Community Aqueduct Associations in Colombia." *Water Alternatives* 8, no. 2 (2015).

²¹Rivera, D. Z. (2022). Disaster colonialism: A commentary on disasters beyond singular events to structural violence. *International Journal of Urban and Regional Research*, 46(1), 126–135.

²²*Ibid.* Pérez Figueroa, (2022).

²³Arce-Nazario, Javier A. "Resilience and community pride after a hurricane: counter-narratives from rural water systems in Puerto Rico." *Alternativas* 5, no. 2 (2018).

²⁴*Ibid.* Arce-Nazario, (2022).

²⁵Fischbach, Jordan R., Linnea Warren May, Katie Whipkey, Shoshana R. Shelton, Christine Anne Vaughan, Devin Tierney, Kristin Leuschner, Lisa S. Meredith, Hilary J. Peterson, and HPRR TEAM. *After Hurricane María: Pre-disaster conditions, hurricane damage, and recovery needs in Puerto Rico*. RAND Corporation, 2020.

postdisaster environments and its relationship to postdisaster water supply resilience. To do this, we draw from the community water governance literature and Balaei and colleagues (2018)²⁶ dimensions to consider in water supply resilience to disasters. We conclude by highlighting challenges and opportunities community managed aqueducts face for the future of water security and resilience.

COMMUNITY WATER GOVERNANCE AS CRITICAL JUNCTURE FOR POSTDISASTER WATER SUPPLY RESILIENCE AND WATER SECURITY

In general, water governance refers to the political, social, organizational, and administrative relations and systems that establish water resources services and distribution procedures.^{27,28,29} Contrary to government, the concept of governance opens the process of governing to other nonstate actors such as nongovernmental organizations, private companies, individual citizens, and communities.^{20,30,31} These stakeholders are recognized for having the capacity to affect governance outcomes,³² a difference that has the potential to illustrate why or how some water governance systems are more resilient than others in the face of extreme weather events.

Community water governance (CWG) brings a focus on local community members' organizational, administrative, and institutional arrangements to make decisions and hold accountable stakeholders (governmental and nongovernmental) regarding their communities' water supply for drinking, sanitation, or both.^{33,34} CWG arises as a response to inadequate or nonexistent water systems

given histories of exclusion from formal water supplies or neoliberal reforms.³⁵ As part of their structure, their management follows three principles "(both explicit and implicit) that include: 1) community participation in the development of the water system; 2) community ownership of the system, and 3) willingness and ability of the community to carry out operation and maintenance (p. 331)."³⁶ These configurations reclaim inclusion to water access and seek community empowerment. While there is strong evidence in rural communities, urban and periurban communities also experience the need to engage in these alternative systems for water security. In CWGs, principal actors include residents, state actors, and nonstate actors. Their configuration ranges and its influences by the historical context of the community.³⁷ Community members can be organized into committees, cooperatives, community based organizations, or associations.^{38,39,40} Nonstate actors include private donors, local vendors, transnational companies, international organizations, and faith-based organizations.^{41,42} State actors include local municipalities and other national or federal agencies that oversee community water management.⁴³ Through their different roles, these actors support residents with technical or infrastructure needs, capacity building, financial needs, intermediaries, or linkages with stakeholders with resources among others.^{44,45,46} At an institutional organizational level, CWGs can be classified as working without external actors, being in partnerships

³⁵Ibid. Adams et al., (2020).

³⁶Moriarty, Patrick, Stef Smits, John Butterworth, and Richard Franceys. "Trends in rural water supply: Towards a service delivery approach." *Water alternatives* 6, no. 3 (2013): 329.

³⁷Ibid. Adams et al., (2020).

³⁸Adekitan, O., A. O. Oyerinde, and A. I. Musa. "Community participation in urban water supply management in Abeokuta—Lessons for sustainable water supply in urban communities." *Journal of Environmental Sciences* 2, no. September (2010): 95–108.

³⁹Njoh, Ambe. "Determinants of success in community self-help projects: the case of the Kumbo water supply scheme in Cameroon." *International Development Planning Review* 28, no. 3 (2006): 381–407.

⁴⁰Sletto, Bjørn, Samuel Tabory, and Kelly Strickler. "Sustainable urban water management and integrated development in informal settlements: The contested politics of co-production in Santo Domingo, Dominican Republic." *Global Environmental Change* 54 (2019): 195–202.

⁴¹Ibid. Llano-Arias, (2015).

⁴²Behailu, Beshah M., Arto Suominen, and Tapio S. Katko. "Evolution of community-managed water supply projects from 1994 to the 2010s in Ethiopia." *Public Works Management & Policy* 20, no. 4 (2015): 379–400.

⁴³Ibid. Adams et al., (2020).

⁴⁴Ibid. Adams et al., (2020).

⁴⁵Nickson, Andrew. *Organizational structure and performance in urban water supply: The case of the SAGUAPAC co-operative in Santa Cruz, Bolivia*. The University of Birmingham, International Development Department University of Birmingham. The Role of Government in Adjusting Economies. Paper. 38 (2000).

⁴⁶Hanchett, Suzanne, Shireen Akhter, Mohidul Hoque Khan, Stephen Mezulianik, and Vicky Blagbrough. "Water, sanitation and hygiene in Bangladeshi slums: an evaluation of the WaterAid—Bangladesh urban programme." *Environment and Urbanization* 15, no. 2 (2003): 43–56.

²⁶Balaei, Behrooz, Suzanne Wilkinson, Regan Potangaroa, Nemat Hassani, and Maryam Alavi-Shoshtari. "Developing a framework for measuring water supply resilience." *Natural Hazards Review* 19, no. 4 (2018): 04018013.

²⁷Rogers, Peter, and Alan W. Hall. *Effective water governance*. Vol. 7. Stockholm: Global water partnership, 2003.

²⁸Pahl-Wostl, Claudia. *Water governance in the face of global change*. Switzerland: Springer, 2015.

²⁹Bakker, Karen J. "From public to private to... mutual? Restructuring water supply governance in England and Wales." *Geoforum* 34, no. 3 (2003): 359–374.

³⁰Bakker, Karen, and Cynthia Morinville. "The governance dimensions of water security: a review." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 371, no. 2002 (2013): 20130116.

³¹Wiek, Arnim, and Kelli L. Larson. "Water, people, and sustainability—a systems framework for analyzing and assessing water governance regimes." *Water resources management* 26, no. 11 (2012): 3153–3171.

³²Rui, María Laura, Sante Maurizi, Simone Sassu, Giovanna Seddaiu, Olga Zuin, Chris Blackmore, and Pier Paolo Roggero. "Re-staging La Rasgioni: Lessons learned from transforming a traditional form of conflict resolution to engage stakeholders in agricultural water governance." *Water* 9, no. 4 (2017): 297.

³³Bakker, Karen, and Munk Centre Program on Water Issues. *Good governance in restructuring water supply: A handbook*. Ottawa, Canada: Federation of Canadian Municipalities, 2003.

³⁴Adams, Ellis A., Leo Zulu, and Quinn Ouellette-Kray. 2020. "Community Water Governance for Urban Water Security in the Global South: Status, Lessons, and Prospects." *WIREs Water* 7 (5). <https://doi.org/10.1002/wat2.1466>.

with utilities, being in partnership with private institutions, or following a cooperative model.⁴⁷

In CWGs, participation plays an important role in enabling social justice, bonding social capital, and overall empowering communities to make decisions about their water services.^{48,49,50} As such participation in CWGs is both informal and formal. Formal participation is expressed through how decisions are made in associations, cooperatives, or management committees in which members are elected by residents, and these are responsible for financial, organizational, and technical operations. On the contrary, informal participation is expressed through volunteering activities or groups, unstructured committee organization, as well as assistance when needed.^{51,52}

While CWG offers many benefits, such as encouraging active participation, fostering bottom-up initiatives, and promoting community control, research has also highlighted several challenges. These include residents' limited capacity to address technical or infrastructural issues, financial difficulties in covering system repairs due to preexisting low-income conditions, power imbalances among community members, and the reliance on volunteer work to meet water needs.^{53,54,55} Much of the scholarship in urban, periurban, and rural experiences point to similar changes in poor economic conditions, environmental risks due to location, and managerial limitation.^{56,57,58} However, water systems need to also adapt to uncertain conditions, as problems like climate change

and the lack of funding to build safe drinking water systems continue to increase.⁵⁹ Considering the central role that CWG plays in community managed water systems, it becomes imperative to understand how this is manifested in the context of high-impact weather events or disasters.

Many disasters are water-related or impact the water supply systems, especially their distribution methods.^{60,61,62,63} This is of concern to decision makers across scale (i.e., state actors and local water aqueduct managers) due to water's vitality for human health and wellbeing (Balaei et al., 2018). We follow Balaei and colleagues (2019) definition of water supply in community context "as the physical status of water supply system and social, organizational, and economic capacity of the community to withstand the disaster and recover to a normal level of functionality in a timely manner" (p. 1). Central to this are the physical conditions of the water system, the economic ability of the community, and the social capabilities of the communities to address their water system and return it to a state of water security.^{64,65}

We utilize four dimensions to consider water supply resilience to disasters: technical, organizational, economic, and social. We modify Balaei et al.'s (2018) categories for these dimensions given our focus on community managed aqueducts (versus centralized systems) and the usage of qualitative data instead of national quantitative data. For the technical category, we focus on the water supply system's physical vulnerability, particularly, preexisting damages to the infrastructure and technology that could support faster recovery (e.g., solar panels). The organizational category refers to existing emergency management plans, support for operations, as well as how their organizational structure supports water availability.⁶⁶ The economic category represents financial capacity to buy broken pipes and related as well as external financial assistance postdisaster.⁶⁷ Furthermore, the social category refers to social capital as expressed through bonding, bridging, and linking social

⁴⁷Ibid. Adams et al., (2020).

⁴⁸Delilah Roque, Anais, David Pijawka, and Amber Wutich. "The role of social capital in resiliency: Disaster recovery in Puerto Rico." *Risk, Hazards & Crisis in Public Policy* 11, no. 2 (2020): 204–235.

⁴⁹Blaikie, Piers. "Is small really beautiful? Community-based natural resource management in Malawi and Botswana." *World development* 34, no. 11 (2006): 1942–1957.

⁵⁰Adams, Ellis Adjei, and Godfred Odei Boateng. 2018. "Are Urban Informal Communities Capable of Co-Production? The Influence of Community–Public Partnerships on Water Access in Lilongwe, Malawi." *Environment and Urbanization* 30 (2): 461–80. <https://doi.org/10.1177/0956247818792059>.

⁵¹Ibid. Adams et al., (2020).

⁵²Ruiz-Aviles, Victor Dionel, David Pijawka, David Manuel-Navarrete, Dave White, and Cecilio Ortiz-Garcia. "Restoration versus transformative adaptation of community drinking water systems after Hurricanes Irma and Maria in Puerto Rico." *Journal of Emergency Management* 19, no. 8 (2021): 25–40.

⁵³Poupeau, Franck, and Sébastien Hardy. "The social conditions of self-organized utilities: water cooperatives in La Paz and El Alto, Bolivia." *Water International* 42, no. 1 (2017): 73–91.

⁵⁴Bakker, Karen. "The ambiguity of community: Debating alternatives to private-sector provision of urban water supply." *Water alternatives* 1, no. 2 (2008): 236–252.

⁵⁵Bakker, Karen. "The ambiguity of community: Debating alternatives to private-sector provision of urban water supply." *Water alternatives* 1, no. 2 (2008): 236–252.

⁵⁶Ibid. Adams et al., (2020).

⁵⁷Salom, Nespect, and Prudence Khumalo. "Challenges Facing Community Management of Rural Water Supply: The Case of Ohangwena Region, Namibia." *African Studies Quarterly* 21, no. 1 (2022).

⁵⁸Truelove, Yaffa. "Gray zones: The everyday practices and governance of water beyond the network." *Annals of the American Association of Geographers* 109, no. 6 (2019): 1758–1774.

⁵⁹Finewood, Michael H., and Ryan Holifield. "Critical approaches to urban water governance: From critique to justice, democracy, and transdisciplinary collaboration." *Wiley Interdisciplinary Reviews: Water* 2, no. 2 (2015): 85–96.

⁶⁰Dalton, James, Radhika Murti, and Alvin Chandra. "Utilizing integrated water resource management approaches to support disaster risk reduction." *Dans: F. Renaud, K. Sudmeier-Rieux & M. Estrella, eds. The role of ecosystems in disaster risk reduction. Geneva: United Nations University* (2013): 248–269.

⁶¹Shimazu, Takayuki, Naoki Shimazu, and Haruki Shimazu. "Regional assessment of earthquake hazard (part 2 lifeline and transportation)." In *Advancing Mitigation Technologies and Disaster Response for Lifeline Systems*, pp. 819–828. (2003).

⁶²Eidinger, J., and A. Tang. "Christchurch, New Zealand Earthquake Sequence of Mw 7.1 September 04, 2010 Mw 6.3 February 22, 2011 Mw 6.0 June 13, 2011: Lifeline Performance." *American Society of Civil Engineers, Reston, VA* (2012).

⁶³Balaei, Behrooz, Suzanne Wilkinson, Regan Potangaroa, Carole Adamson, and Maryam Alavi-Shoshtari. "Social factors affecting water supply resilience to disasters." *International Journal of Disaster Risk Reduction* 37 (2019): 101187.

⁶⁴Ibid. Balaei et al., (2018).

⁶⁵Ibid. Balaei et al., (2019).

⁶⁶Ibid. Balaei et al., (2018).

⁶⁷Ibid. Balaei et al., (2018).

capital⁶⁸ and human capital, meaning the different skills (e.g., computer skills) and knowledge (e.g., education, languages) that an individual processes that brings value to advance an objective.⁶⁹ Given that much of the discussion on water governance in hazard and disaster context have mainly occurred with large-scale centralized systems, a focus on community water governance provides an opportunity to explore how local community members, actors, and institutional arrangements address postdisaster water supply resilience and household water security to disasters.

CASE STUDY DESCRIPTION

The Environmental Protection Agency (EPA) defines small water systems as those that supply drinking water to less than 3300 people.⁷⁰ In Puerto Rico, there are currently 235 of these systems (also known as non-PRASA because they are outside centralized system), and while official sources argue that they provide 1%–2% of the island's water supply,⁷¹ our interviews revealed they supply drinking water to approximately 4% of the population (150,000). This discrepancy comes from the fact that many community aqueducts are not registered. Many of these systems originated because of a state's lack of policy to provide water to rural communities in Puerto Rico.⁷² These aqueducts can vary by size (some provide water to 25 families while other distribute water to over thousand residents) and power source; most operate with electricity, others use solar energy, and others operate by gravity. Additionally, around 58% of aqueducts obtain their water from wells and aquifers, while the 42% obtain their water from surface sources, such as rivers and small creeks.

Community aqueduct organizational structure varies (see Table A1). Many of them are operated by a board that includes presidents, vice-presidents, treasurers, secretaries, and other supporting personnel. Typically, aqueducts run by fewer people have low levels of formal education and a high poverty index. Still, there has been an effort to support these systems and get them in compliance. Diverse sectors such as government agencies, nongovernmental agencies, technical organizations, churches, academic researchers, and private donors have participated in these efforts. Some of these efforts include providing technical workshops and funds to improve their physical and organizational infrastructure. Puerto Rico and its small water systems must comply with the EPA Safe Drinking Water Act as a U.S. commonwealth and including local health regulations (see

Table A2). Compliance with the Safe Drinking Water Act requires turbidity, bacteria, and heavy metal tests. To ensure they comply with these standards, federal and local agencies (e.g., Puerto Rico Health Department) require community aqueducts with monthly and yearly water quality tests. However, in 2015, only half of these systems complied with drinking water regulations, thus becoming an important procedural justice issue.⁷³ More recently, community aqueducts have complained that these tests are too onerous for them and have forced them to decide between paying the power bill to keep running the system or complying with water standards. Beside challenges with compliance, a report by RAND Corporation⁷⁴ highlighted how after Hurricane María non-PRASA systems did not have comprehensive information regarding their damage and operation to help speed their recovery; by the contraire, PRASA systems had these reports at hand. Furthermore, the report underscores how surveys were created to find out if non-PRASA systems had electricity and/or a power generator—even after this survey was completed, not all of this information was available for all registered non-PRASA systems.⁷⁵

METHODS: DATA COLLECTION

This research draws on findings from a total of 36 unstructured interviews, collected from 14 community aqueduct leaders, 4 federal government officials, 4 local government officials, 11 nongovernmental organization (NGO) personnel, and 3 technical personnel. Additionally, this project draws from an ethnographic approach inclusive of more than 100 hours of qualitative data derived from participant observation, visits to the communities, meetings, and phone observations in 12 rural small-scale water systems in Puerto Rico for a year (2020–2021). These 12 community aqueducts varied by region, institutional arrangement, and populations served (see Table A3 for details). While these communities' drinking water came from a community aqueduct, their sewage system was operated through a septic tank. Interviews were collected from October 2020 to October 2021, when corresponding author volunteered with the grassroots organization El Bosque Modelo supporting community aqueducts. Volunteering with El Bosque Modelo, corresponding author used community-based research (CBR). A CBR approach actively brings communities to participate by informing research questions and processes.⁷⁶ The community-based approach builds on El Bosque Modelo's previous work in providing various workshops to community aqueduct on different

⁶⁸Aldrich, Daniel P. "Building resilience." *Social capital in post-disaster recovery* (2012): 1–166.

⁶⁹Woodhall, Maureen. "Human capital concepts." In *Economics of education*, pp. 21–24. Pergamon. (1987).

⁷⁰Alicea-Martínez, Adaíl, and Rafael A. Ríos. "Vulnerability assessment of small community water systems in Puerto Rico." *Interdisciplinary Environmental Review* 17, no. 2 (2016): 132–148.

⁷¹Molina-Rivera, Wanda L., and Michelle M. Irizarry-Ortiz. *Estimated water withdrawals and use in Puerto Rico, 2015*. No. 2021–1060. US Geological Survey, 2021.

⁷²*Ibid.* Perez Figueroa, (2022).

⁷³*Ibid.* Alicea-Martínez et al., (2016).

⁷⁴*Ibid.* Fischbach et al., (2020).

⁷⁵*Ibid.* Fischbach et al., (2020).

⁷⁶Strand, Kerry J., Nicholas Cutforth, Randy Stoecker, Sam Marullo, and Patrick Donohue. *Community-based research and higher education: Principles and practices*. John Wiley & Sons, 2003.

topics (e.g., applying for funds, drafting organization mission statements, and among others).

METHODS: DATA ANALYSIS

The overarching question guiding this work is: How does the water governance of community aqueducts unfold following Hurricane María, and what are its implications for water supply resilience? To address this, we follow a deductive and inductive approach and conduct theme identification.⁷⁷ Deductive codes were drawn from current literature on community water governance and Balaei et al.'s (2018) dimensions for water supply resilience. Inductive codes emerged organically from data through an open coding approach and discussions among authors in relation to the research question. This iterative process allowed us to identify seven overarching themes across water governance arrangements and water supply resilience (see Table A4).

RESULTS

Water governance: Actors

One of the factors that makes the community aqueduct a compelling case of water governance is the diverse involvement of stakeholders and how their collaboration supports its operation. Community aqueduct actors in this research included community aqueduct leaders, federal government officials, local government officials, NGO personnel, faith-based, and technical personnel. Prior to Hurricane María, interviewees reported main interaction of water aqueducts was within the residents, unless the community was receiving visits from EPA or Department of Health for compliance reasons. Communities also interact with the NGO sector especially if they are providing capacity-building training or other type of support such as grants for improving aqueduct needs. However, in the wake of Hurricane María, community aqueducts increased interactions with other actors due to the need of technical supplies (i.e., tools, pipes) for the management of the aqueduct. This was important because communities interviewed did not have emergency management plans for their aqueducts, nor did they have storage of gasoline for operations.

While stakeholders varied, NGOs and the faith sector were the most present actors in postdisaster water security efforts. They supported aqueducts with financial resources as well as connections to funding agencies and providing bottled water for residents. At the same time, some participants also mentioned the role of the federal government in accessing resources to support continued water supply. See the following quote from a community water aqueduct manager: "As president-elect, I made contacts through the EPA, and we were able to secure a power generator. That's how we began providing water to the community. I also reached out to the Puerto Rico Community Foundation, and

I am grateful to the organization Bosque Modelo de Puerto Rico. El Bosque Modelo helped us tremendously in making all the necessary contacts. Even though José no longer works there, I will be forever grateful to him for the rest of my life." (Community Aqueduct 2). However, access to these stakeholders and funding opportunities was not homogenous across communities, and it was shaped by each aqueduct prior experience with different funding institutions and existing relationships. In addition, for several of the aqueducts in this study, when asked about the status of the funds they apply for funds from federal agencies, some revealed that even 4 years after Hurricane María, the funds had been approved but had not been distributed yet.

Water governance: Community participation

From the 12 communities visited, eight aqueducts have formal participation through community boards, although they also have volunteers who assist when needed. Before Hurricane María, these aqueducts (and others) reported struggles with resident participation and board members on the aqueduct's meetings. Participants reported that unless an important decision was warranted, participation was limited to the main aqueduct board or to those who play an active role in the maintenance of the system. As a volunteer-based job within the community, factors such as time commitment, employment status, and leadership skills shape participation efforts in water monitoring, coordination of water bill payment, and related aqueduct management tasks. Nonetheless, other interviewees argued broadly how system ownership enhances active participation in maintaining water aqueduct compliance and an important role for postdisaster water supply recovery efforts. As residents were active post Hurricane María to restore system supply by getting diesel, volunteering for fixing pipes, the systems ownership was critical for community aqueducts to obtain access to drinking water in the shortest amount of time possible, especially in the aftermath of Hurricane María:

The fact that we could control when and how we receive the water, I believe gave us the control and knowledge—breaking away from the dependency on someone else. We did not have to wait for PRASA to connect the water system back. The community was super prepared and mobilized quickly. (Community Aqueduct 1)

At the same time, for these communities, the aqueduct also brings an opportunity to foster community building as it was highlighted by more than one participant (see Table A4). Importantly, participation in decision making in the wake of Hurricane María was challenging; participants described how some decisions had to be taken quickly without democratic process (e.g., voting, group discussions) because of the need to respond to the funding opportunity or to participate in technical training.

Water supply resilience: Technical, organizational, and economic vulnerability

As it has been discussed, in general, community aqueducts have historically faced challenges with technical

⁷⁷Bernard, H. Russell, Amber Wutich, and Gery W. Ryan. *Analyzing qualitative data: Systematic approaches*. SAGE publications, 2016.

constraints for water supply and Hurricane María exacerbated such experiences. In the wake of María, community aqueducts visited detailed technical vulnerability with a focus on being without water supply from days up to 6 months. The impact on the water supply came mainly from broken pipes, although some participants argued that some aqueducts' water flow was reduced too. The ability to restore services was strongly linked to their predisaster availability of sustainable technologies (e.g., solar panels, power generator) as well as their ability to connect with local municipalities and federal agencies (e.g., Federal Emergency Management Agency [FEMA]) for gasoline and financial aid. For the aqueducts with community boards, they utilized existing funds from the aqueduct (some which have extra money for emergencies). However, this was not often the case; several community aqueduct participants reported personnel have taken more financial debt to be able to buy materials to repair their system. This challenges water access from aqueducts in the aftermath as they had to depend on availability of resources and go into debt to restore water supply.

Community resilience: Social and human capital

Research has shown the value of social relationships to overcome hazards and disaster and a key variable in community resilience. Here, social capital also plays a critical role in aqueduct resilience. Bonding social capital—the relationships and trust within the communities—was important in the street cleaning and doing repairs of the community aqueducts. Another participant addresses their linking social capital—meaning relationships or ties with institutions of power to support common objectives⁶⁵—narrated how during Hurricane María, they were able to gain access to a power generator because he had previous ties with the local municipality (see Table A4, Community Aqueduct 3, quote). We also note that not only social capital was vital within communities but also human capital (i.e., the skills, knowledge, and experiences) of residents to bring back water supply for their community. For example, one community aqueduct member argued: “Our community has many resources, we have people here who know how to install cooling systems, that know how to do mild repair when a pipe breaks” (see Table A4, Community Aqueduct 7). As part of community aqueduct leadership human capital, their ability to speak English and write proposals is essential for recovery as these allow access to resources from the U.S. federal government, nonprofit, foundations, and private sector.

Water resilience and community water governance: Intergenerational knowledge transfers

While considering different configurations for effective water governance in both normal times and disaster context, across the interviews, community aqueduct members expressed concern for not being able to pass operational and organizational knowledge to future generations. When leaders and members from other sectors (i.e., NGOs, federal

government) are not able to pass this information; it can increase their vulnerability in the wake of future extreme weather events. Many aqueduct leaders are older adults (a representation of the current Puerto Rican community), and as such, the knowledge that has been accumulated through time to operate the system is vital; in some instances, it can make the difference between an aqueduct disappearing and being able to continue operating. Participants across sectors underscored the role of funding community members who built the system, as they provided a pathway for future generations, including knowledge transfer to continue operating the aqueduct (see Table A4, Community Aqueduct 12, quote).

DISCUSSION AND CONCLUSION

Approximately 150,000 residents in Puerto Rico rely on community managed water systems. The experiences of community-managed aqueducts post Hurricane María provide a case study to examine the risks for water supply resilience after disasters. Our results show that water governance plays an important role in water supply resilience. This research emphasizes that community governance, mainly the engagement of different actors (within the community and with communities of power), can mitigate the technical, organizational, and economic dimensions of water supply resilience. That is because although there were technical and economic challenges in the aqueducts prior to Hurricane María, community organization, institutional arrangement, as well as the social and human capital of community aqueduct managers and residents brought the necessary support to restore aqueduct operations. Moreover, for some community aqueducts, post Hurricane María collaborations served as a pathway or a window of opportunity⁷¹ for sustainability and resiliency efforts in some of these aqueducts (e.g., battery systems for solar panels in water systems).

Building on Adams et al. (2020) and García-López (2018) work, there is limited capacity from residents to address infrastructural challenges without the support of state institutions or external stakeholders. Moreover, communities' human capital also illuminated disparities across communities' aqueducts experiences due to its value for applying for funding or capacity building training. These dynamics that shape resilience outcomes highlight the balance needed between investing in physical infrastructure and supporting the organizational structures through funding, engagement, and capacity building, particularly to foster a process that allows for the transfer of vital knowledge to manage those systems in the present and for future generations.

These communities are geographically mainly in rural municipalities where road access after a disaster becomes a key challenge for water access and supply for aqueduct management (e.g., diesel), so community aqueducts are critical for disaster household water security in Puerto Rico. It is important to highlight that even when the local state capacities to provide aid

were limited at best, there is a clear challenge in delegating the recovery process to local residents, which are limited by predisaster social and environmental vulnerabilities and risks. It has become taxing for residents and community leaders to perform the state role of designing relief policies and supporting water recovery efforts. Even when federal and national and environmental agencies continue to support community aqueducts, their impact has been limited, and more proactive efforts (including technical assistance, financial assistance, and capacity building) can support resiliency to future events.

Participants of this research reported that decision making after Hurricane María was often quick without traditional community-level discussions or simple democratic processes such as voting. The previous argument highlights a crucial challenge to consider for future events, as it impacts resources brought into communities—such as funding or training opportunities—that can enhance long-term resilience to hazards. As such, to address prolonged periods without access to clean and safe drinking water, recognition of all areas of water governance and its interaction with resilience will be key to address inequitable distribution of water services. More frequent and intense hazards such as Hurricane María are expected to occur, and thus, water governance is expected to play a pivotal role in security and resiliency outcomes for many communities but especially for those who are socially and economically disadvantaged.

AUTHORS' CONTRIBUTIONS

O.P.F. and A.D.R. conceived and designed the article structure. A.D.R. developed the theory section. O.P.F. provided the data for the analysis. Both O.P.F. and A.D.R. drafted and completed the results and discussion sections. Finally, A.D.R. and O.P.F. made sure the final article was formatted and error free.

AUTHOR DISCLOSURE STATEMENT

No competing financial interests exist.

FUNDING INFORMATION

No funding was received for this article.

Address correspondence to:

Omar Pérez Figueroa
Urbana- Champaign
Department of Urban and Regional Planning
University of Illinois
111 Temple Buell Hall
611 E Lorado Taft Dr Champaign
Urbana
IL 61820
USA

E-mail: operez10@illinois.edu

Appendixes

TABLE A1. COMMUNITY AQUEDUCTS CHARACTERISTIC SUMMARY TABLE

<i>Aqueduct "name"</i>	<i>Type of institutional arrangement</i>	<i>Region</i>	<i>Number of household</i>	<i>Water source</i>
Aqueduct 1	Organized board, "undefined" roles	South	522	Superficial
Aqueduct 2	Organized board, "undefined" roles	South	53	Superficial
Aqueduct 3	Organized board, with defined roles	East	286	Underground
Aqueduct 4	Organized board, with defined roles	South	316	Underground
Aqueduct 5	Unorganized—one or two members	Central	350	Underground
Aqueduct 6	Organized board, with defined roles	East	154	Underground
Aqueduct 7	Organized board, with defined roles	West	360	Underground
Aqueduct 8	Organized board, with defined roles	Central	160	Superficial
Aqueduct 9	Organized board, with defined roles	Central	250	Underground
Aqueduct 10	Organized board, with defined roles	Central	28	Underground
Aqueduct 11	Organized board, with defined roles	South	58	Superficial
Aqueduct 12	Unorganized—one or two members	South	320	Underground

TABLE A2. REGULATIONS FOR COMMUNITY AQUEDUCTS

<i>Federal regulation</i>	<i>Local regulations</i>
<ul style="list-style-type: none"> • Clean Water Act) 33 U.S.C.A. §§ 1251–1387 The objective of the 1987 amendment is to restore and maintain the chemical, physical, and biological properties of waters of the North American nation and Puerto Rico. This law establishes that all point sources that discharge some pollutant into U.S. waters must have an NPDES permit. (<i>NPDES, National Pollutant Discharge Elimination System.</i>) • Safe Drinking Water Act 42 U.S.C.A. §§ 300–300J-26. Establishes health standards that require legal compliance for contaminants (18 different water tests) present in drinking water. The public is required to be notified when there is a violation of this regulation in public water systems and to be provided with the annual reports (Consumer Reliability Reports) with the information related to contaminants found in your potable water. • “Total Coliform Rule” (TCR) The purpose of the rule is to improve the protection of public health reducing fecal pathogens to minimal levels by controlling total coliform bacteria, including fecal coliforms and <i>Escherichia coli</i>. • Surface Water Treatment Rule (SWTR) The rule requires water systems to filter and disinfect water from surface water sources to reduce the occurrence of limits not sure of the mentioned microbes. • Rule Phase I, Phase II, Phase IIb, and Phase V The Environmental Protection Agency (EPA) regulated more pollutants (69 contaminants) through the Phase I, Phase II, Phase IIb, and Phase V rules. In each rule, EPA created the allowable limits for each contaminant, designed an itinerary for the water systems that had to do tests for the presence of contaminants, and described the treatments that could be used to remove contaminants. 	<ul style="list-style-type: none"> • Ley para Proteger la Pureza de Agua Potable de Puerto Rico (Ley Núm. 5 de 21 de julio de 1977). In 1977, Puerto Rico approved Law #5, known as the Law for Protecting the Purity of Puerto Rico’s Drinking Waters. This law authorizes the Secretary of Health to establish through regulations, the acceptable levels of contaminants in Puerto Rico’s drinking water. • Reglamento Núm. Fifty del Secretario de Salud de 29 de noviembre de 1977 In Puerto Rico, the agency in charge of taking care of the waters under the Act of Clean Water is the Environmental Quality Board. This is in charge of the implementation of: <ol style="list-style-type: none"> 1. Regulation of Water Quality Standards 2. Guidelines for the Assignment of Pollutant Loads 3. General Water Quality Certificate for Water Discharges Rainfall Associated with Industrial Activities 4. Regulations for the Control of Erosion and Prevention of Sedimentation • Ley Núm. 239 de 13 de agosto de 1998—Para enmendar la “Ley para la Conservación, el Desarrollo y Uso de los Recursos de Agua de Puerto Rico” Establishes a rate equal to one-fifth (1/5) of a cent for each gallon of fresh groundwater withdrawn for industrial or commercial use; establishes a special rate for brackish or sea water.

(continued)

TABLE A2. CONTINUED

<i>Federal regulation</i>	<i>Local regulations</i>
<ul style="list-style-type: none"> • Consumer Confidence Reporting Rule <p>This rule states that all community systems should prepare and distribute to all their subscribers a brief annual report on the quality of the water served by the system.</p>	
NPDES, National Pollutant Discharge Elimination System.	

TABLE A3. COMMUNITY AQUEDUCT INSTITUTIONAL ARRANGEMENTS, TYPES OF PARTICIPATION, AND ACTOR TYPE TABLE

<i>Types of "institutional" arrangements</i>	<i>Types of participation (decision making)^a</i>	<i>Type of actors^b</i>
(a) Organized "board" with defined roles	(a) Horizontal, anyone can participate and vote	(a) Government officials (from local or federal agency)
(b) Organized groups, with undefined roles	(b) Horizontal, anyone can participate, only "board" members vote	(b) Community aqueduct personnel (operator, paid or voluntary worker)
(c) Unorganized, one or two members	(c) Vertical, only the president or the person in charge takes decision	(c) Technical (external private organization providing)
	(d) Vertical, most decisions are taken by one person even when a board member is present	(d) NGO (grassroots, faith-based, environmental organizations)

^aThere are different configurations depending on the type of the decision taken. Configuration can vary depending on if the decision has to do with financial decisions, applying for aid, or day-to-day repairs. There was almost an even distribution between those aqueducts in which most decisions (regardless of the type of decision) were taken collectively versus those in which one person took most of the decisions.

^bEach community aqueduct can be operated by a combination of different actors. While most systems are operated by members of the community that provide water too, other configurations include paid external personnel and ongoing collaboration with government officials and technical personnel.

NGO, nongovernmental organization.

TABLE A4. CODES FOR ANALYSIS TABLE

<i>Theme</i>	<i>Definition</i>	<i>Example: How is this expressed across the cases</i>
Actors	Those involved inclusive of communities, state actors, and nonstate actors in prehurricane and posthurricane experience.	"The agency decided it was a waste of time and resources if we would take them to court. You know, they know I can take them to court, but it just doesn't make any sense, I try to work around that. And most time we can address the issue, without having to involve legal." (Community Aqueduct_9)
Community participation	Participation of community in aqueduct management and decisions. This includes intracommunity participation motivation (e.g., board meetings, how decisions are done and mainly by whom). It also includes participation with local government (e.g., municipality, Dept. of Health) and federal agencies (e.g., EPA). Moreover, nonprofit, foundations, or faith-based organizations.	"Perhaps our motivation when we started participating in the aqueduct day-to-day activities was to be part of their board, but also because we heard the current board had negotiations with the mayor to hand over our aqueduct system without consulting our community." (Community Aqueduct_14) "Well, this aqueduct is like glue; thanks to it, other collaborations occur; let us put it like this. Since we are all so dispersed, so far from each other, maybe those collaborations would never happen without the aqueduct. We would never have collaborated to clean up the road. The aqueduct supported us in different ways, well, I don't know, I don't know, maybe it would have happened, but we wouldn't be so close as a community." (CommunityAqueduct_2)

(continued)

TABLE A4. CONTINUED

<i>Theme</i>	<i>Definition</i>	<i>Example: How is this expressed across the cases</i>
Technical and economic vulnerability	Water supplies physical vulnerability inclusive of quality of the pipes, access to solar panels, extra generator, or gasoline to operate. Aqueduct finances available to buy equipment to restore or gasoline for the aqueduct.	“I had to learn everything, even to become an engineer. We can’t depend on anyone here. [That makes us vulnerable.] I have the phone number of the Tesla technician. They are in Puerto Rico. At first, I would call to ask what had to be done before they had to come. Now I do everything. When they have to come, is because I already tried everything.” (Community Aqueduct_6)
Organizational support (internal + external)	Disaster response plan or other type of organizational support for a fast recovery of the system.	“...as president-elect I got contacts through the EPA and then we got them to give us a power generator and that’s how we started giving water to the community.” (Community Aqueduct_9)
Social capital	Social capital (bonding, bridging, or linking social capital of community operators to bring water-related resources to the community in the aftermath of the event). Human capital: “the skills, knowledge, and experience possessed by an individual or population, viewed in terms of their value or cost to an organization or country” (e.g., education, skill sets, language, computing skills).	“After María, they came to find me because they knew I knew how to fix power generators—not even the power generator who was supposed to light up the city hall was working. When I was there, I saw a power generator in the corner of a room. They loan it to me.” (Community Aqueduct_3)
Economic (financial) vulnerability	Aqueduct finances available to buy equipment to restore or gasoline for the aqueduct.	“Even when sometimes there are funds available, they are in the form of loans, and we can’t apply for them because you have to prove you have repayment capacity, and residents barely pay their water bill. It doesn’t make sense for us to apply for loans.” (Community Aqueduct_10)
Intergenerational knowledge transfer	Challenges in the ability to pass on important knowledge to continue the operation of community aqueducts.	“There was a strong base of old men and women who initially built and took care of the community aqueduct, right? They took their time to organize the community, to give it shape. That is a beautiful story; I would write it if I were a writer. I imagine their work in organizing the community; they gave everything they had in doing so. It would not be possible to have what we have today without them. What we have today is good, so this must be true. How were they able to achieve, what they achieved, one wonders.” (Community Aqueduct_12)