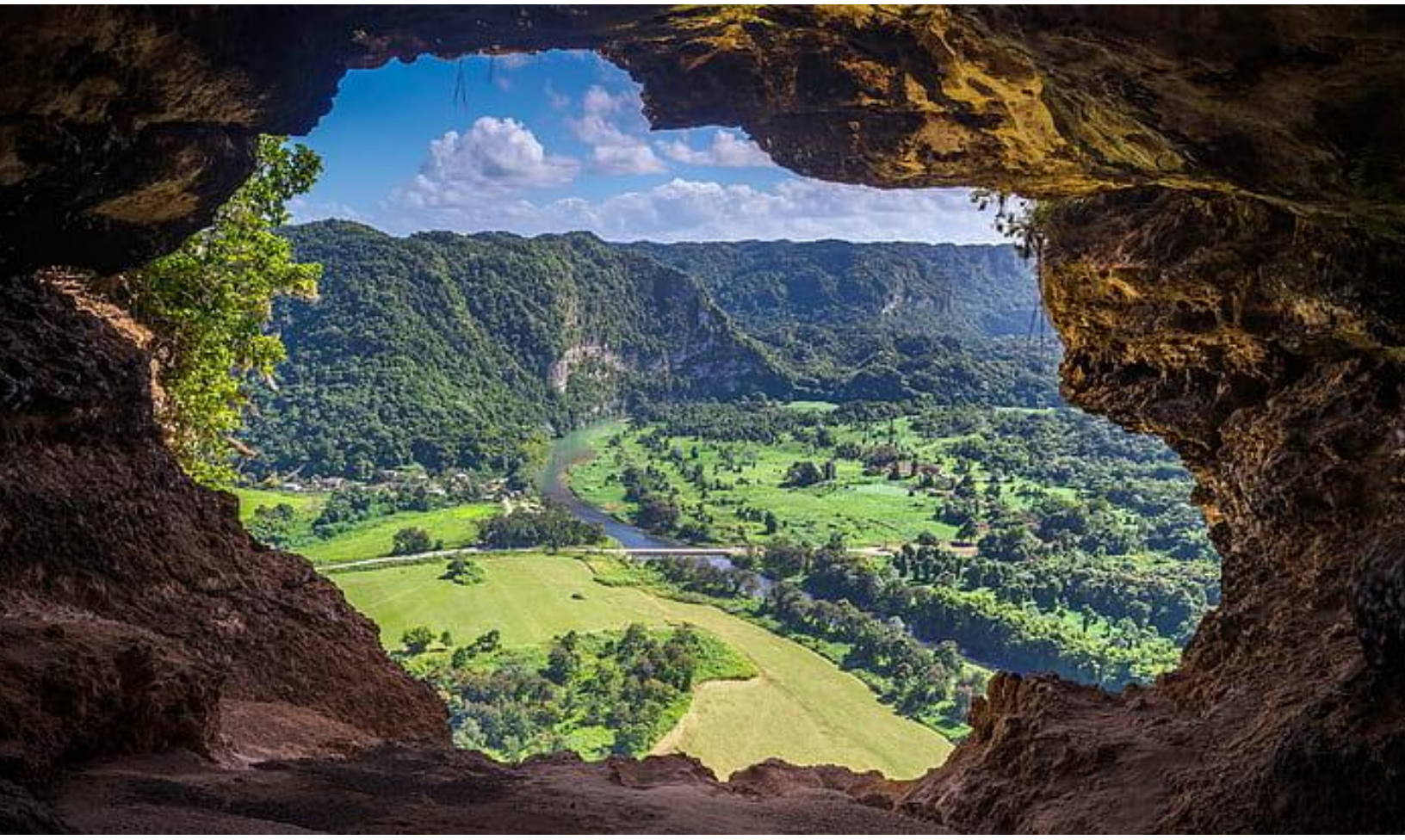
Bridging the Gap: Better Understanding Puerto Rico's Private Water Systems

Literature Review



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Introduction

The United States territories, which include Puerto Rico, U.S. Virgin Islands, Guam, American Samoa, and the Northern Mariana Islands, face unique challenges in providing safe, reliable water to their populations. Despite being home to approximately 3.6 million American citizens and under U.S. governance, these territories often struggle with water infrastructure that lags behind mainland standards, creating significant public health and economic concerns (U.S. Census Bureau, 2020). Water systems in U.S. territories operate at the intersection of geographical isolation, colonial histories, and vulnerability to climate events. Unlike the contiguous United States, these island territories contend with limited freshwater resources, aging infrastructure, and the logistical complications of shipping materials and expertise across vast oceanic distances. According to the American Society of Civil Engineers (ASCE), infrastructure in U.S. territories consistently receives lower ratings than mainland counterparts, with frequent deficiencies in drinking water and wastewater systems (ASCE, 2021). Their water utilities must balance competing needs: providing affordable service to often economically disadvantaged populations while attempting to modernize systems that in many cases date back to military installations of the mid-20th century.

The archipelago of Puerto Rico contains complex water systems, which reflect the island's diverse geographic landscape, intricate hydrology, and ongoing environmental challenges. Spanning tropical mountain ranges, coastal plains, and urban centers, these water infrastructure networks are critical to supporting the island's approximately 3.2 million residents and varied economic activities (US Census Bureau, 2020).

The primary water management infrastructure is overseen by the Puerto Rico Aqueduct and Sewer Authority (PRASA), a government-owned utility responsible for providing potable water and wastewater services across the island. PRASA manages a network of water sources that include surface water reservoirs, groundwater wells, and treatment facilities strategically positioned to serve urban and rural communities (Guerrero-Preston et al., 2008).

Geologically, Puerto Rico's water systems are uniquely influenced by its karst landscape, particularly in the northern and central regions. Limestone formations create extensive underground aquifer systems that are crucial for water supply, with some groundwater networks extending through complex cave systems and underground rivers (Monroe, 1980). These geological characteristics make water resource management both challenging and distinctive compared to other Caribbean island nations.

Climate change and natural disasters, such as Hurricane Maria in 2017, have significantly impacted Puerto Rico's water infrastructure. The hurricane exposed critical vulnerabilities in the water distribution system, leading to widespread water access issues and prompting substantial infrastructure rehabilitation efforts (FEMA, 2018). These events have accelerated discussions about water system resilience, sustainable management, and technological adaptation.

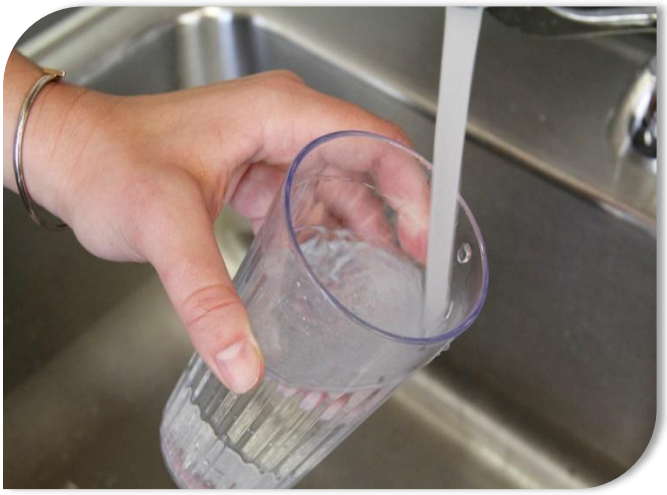
Private water systems in Puerto Rico, locally known as "non-PRASA" systems (systems not operated by the Puerto Rico Aqueduct and Sewer Authority), play a crucial role in providing water access to rural and mountainous communities. These systems are often categorized by size and use. One significant barrier that exists in studying private water systems in Puerto Rico is the lack of studies and resources available discussing

these systems. This review synthesizes the current and past research on these systems, their challenges, and their importance in Puerto Rico's water infrastructure landscape.

Literature Review

Historical Context and Development

Research indicates that private water systems emerged in Puerto Rico primarily due to geographical constraints and historical development patterns. Guerrero-Preston et al. (2008) documented how these systems developed in response to PRASA's limited reach into rural mountainous regions, particularly following the rural-to-urban migration patterns of the mid-20th century.



Infrastructure

Private water systems in Puerto Rico typically fall into several categories, including community-operated systems, individual household systems, and small-scale private operators. Studies estimate that approximately 3% of Puerto Rico's population relies on non-PRASA systems, serving roughly 100,000 residents (Tor & Rodriguez-Martinez, 2017). These systems are predominantly concentrated in the island's central mountainous region, with significant clusters in the municipalities of Orocovis, Utuado, and Adjuntas.

Well Types and Construction

Private wells in Puerto Rico generally fall into three main categories:

1. Shallow alluvial wells (pozos superficiales)
2. Deep bedrock wells (pozos profundos)
3. Spring-fed catchment systems (manantiales)

Limited information was available on deep bedrock wells and spring-fed catchment systems. A study on shallow alluvial aquifers conducted in the Colorado River Basin observed that the water in the majority of the wells were suitable for most uses. However, the wells did exhibit high levels of radon, which could be characteristic of the region, as well as high levels of nutrients, pesticides, and volatile compounds, which are more indicative of human activity affecting water quality (Apodaca, et al., 2002).

Geographical Distribution

Private wells show distinct patterns of distribution based on geographic location. High concentrations of limestone aquifer wells are observed in the Northern Karst Belt. Whereas the Coastal Plains typically exhibit shallow wells with alluvial deposits. These aquifers rely on direct rainfall and streamflow for recharge, making them particularly susceptible to drought. (Moraes, et al., 2023) Along the Southern Coast, it's common to see both shallow and deep wells. Lastly, the Interior Mountains are most commonly springs and deep bedrock wells. Research by Molina-Rivera and Gómez-Gómez (2018) indicates that shallow wells predominate in the coastal plains, while bedrock wells are more common in the island's interior karst regions. Well depths typically range from 15-30 meters in alluvial areas to over 100 meters in mountainous regions. A study on water stress,

land use, and geomorphology found that water stress is more likely in southern Puerto Rico, while chronic stress was significantly lower in more mountainous and vegetative regions. (Moraes, et al., 2023)

Challenges

The literature identifies several key challenges facing private water systems, including technical challenges, administrative challenges, regulatory barriers, and climate change/natural impacts. Technical and administrative challenges include infrastructure-related barriers, a lack of standardized protocols, limited financial resources for well repairs, and inconsistent water quality testing and monitoring practices. Extreme weather events have further exacerbated these challenges, stressing exposed systems' vulnerabilities. Approximately 65% of private water systems experienced significant damage during Hurricane Maria in September 2017, resulting in extended water access interruptions averaging 4-6 months. There were increased rates of contamination post-hurricane, as well. (Diaz et al., 2020). Research by Santos-Burgoa et al. (2018) found that 60% of sampled private water systems confirmed the presence of total coliforms after Hurricane Maria.

Regulatory and oversight challenges were also highlighted in the literature as potential barriers for private water systems in Puerto Rico. Many systems operate without formal permits. In some regions, there are unclear jurisdictional boundaries between federal and local authorities. Additionally, there are barriers to monitoring and enforcement. Jurisdictions face a limited capacity for regular inspections. All of these factors contribute to inconsistent enforcement of water quality standards.

Climate Resilience

Puerto Rico has been impacted by many climate-related events. In 2017, Puerto Rico experienced two catastrophic hurricanes, Hurricane Irma and Hurricane Maria, in the same month (Pasch, et al 2018). While Hurricane Irma did not make direct landfall, it's Category 5 storm system led to significant power outage and flooding. These effects, compounded with the direct landfall of Hurricane Maria as a Category 4 storm, destroyed the electrical infrastructure of portions of the island and resulted in an estimated $90-95 billion in damages (Pasch et al, 2018).

Considering the challenges related to climate change and severe weather events, studies indicate that necessary adaptations may help reduce the impact of climate-related events. These adaptations include both infrastructure and planning tools to better prepare for additional severe weather patterns in the future. For example, infrastructure hardening requirements could improve the resistance of the private water systems to strong winds and other characteristics of severe storms. Additionally, backup power systems were identified as a specific need in Puerto Rico after extended power outages, which significantly impacted residents' access to clean drinking water. Lastly, studies suggested improved emergency response protocols that specifically address private water system needs in response to emergency situations, specifically hurricanes and flooding.

Future Research

Future research on territorial water systems in Puerto Rico requires focused attention on several critical areas to ensure sustainable and safe water access for communities dependent on these systems, including long-

term health implications, cost-effective treatment options, climate change adaptation, and sustainable management.

The long-term health impacts of private system usage demand rigorous epidemiological studies. While Ortiz-Vélez et al. (2016) documented acute gastrointestinal illness outbreaks in non-PRASA communities, longitudinal health impact studies remain scarce. Research should examine chronic exposure to both biological and chemical contaminants common in these systems, particularly given findings by Ramos-Garcés et al. (2020) the findings by Ramos-Garcés et al. (2020), showing elevated levels of contaminants in 45% of sampled private water systems. Hunter and Arbona-Soler (2019) emphasize the need for studies tracking health outcomes in communities relying on private water systems compared to those served by PRASA, including investigation of waterborne illness rates, potential developmental impacts, and chronic health conditions.

Cost-effective treatment solutions represent another crucial research priority. Building on work by Méndez-Torres and Rivera-Santos (2017), who evaluated point-of-use treatment options in rural Puerto Rico, studies should focus on developing and evaluating affordable, locally appropriate treatment technologies. This aligns with recommendations from the World Health Organization (WHO, 2019) for sustainable water treatment in resource-limited settings. Quiñones-Aponte and Collado-Vega (2021) specifically call for research into treatment solutions that can operate reliably under local power constraints and require minimal technical expertise for maintenance.

Climate change adaptation strategies require immediate research attention, given Puerto Rico's vulnerability to extreme weather events. Studies by Díaz-Anderson et al. (2018) demonstrated significant infrastructure damage to private water systems during Hurricane Maria, highlighting the need for resilience research. Padilla-Rodriguez and Torres (2022) emphasize investigating the potential impacts of changing precipitation patterns on groundwater recharge rates and water availability, particularly in drought-prone regions. The U.S. Geological Survey (2020) further recommends research into early warning systems and emergency response protocols specific to private water systems.

Sustainable management models represent a critical area for investigation. González-Ramos and Minnigh (2019) identified successful community-based management structures in several municipalities, but comprehensive studies of governance models are needed. Research should examine various financial models that ensure system sustainability while maintaining affordability for users, building on economic analyses by Swain and Ramírez-Toro (2021). Studies should evaluate different governance structures, with particular attention to what Cortés-Vázquez et al. (2023) term "cooperative resilience frameworks" for small system operation and maintenance.

Conclusion and Recommendations

Private water systems, or non-PRASA systems, are an essential component of Puerto Rico's water infrastructure, providing access to clean water in rural and mountainous regions where centralized systems fall short. However, these systems face a host of challenges, including technical limitations, regulatory

hurdles, and vulnerabilities to extreme weather events. The aftermath of Hurricane Maria highlighted the fragility of these systems, revealing widespread damage, prolonged water access interruptions, and contamination risks.

Despite these challenges, non-PRASA systems remain indispensable for underserved communities, underscoring the need for targeted interventions to ensure their sustainability and resilience. Addressing these challenges will require a combination of infrastructure investment, regulatory reform, and research-driven innovations.

Based on the information in this review, the following recommendations are presented to enhance private water systems.

- **Strengthen Infrastructure Resilience**: Reinforce water system components to withstand high winds and flooding. Install backup power systems to ensure water access during outages. Upgrade storage and distribution systems to handle extreme weather.
- **Enhance Water Quality Monitoring and Treatment**: Standardize water quality testing and require regular inspections. Invest in affordable, easy-to-maintain water treatment technologies. Train community operators to improve water quality management.
- **Policy and Regulatory Reforms**: Clarify federal and local roles in regulating non-PRASA systems. Simplify permitting processes to boost compliance and oversight. Increase funding for inspections and enforcement of standards.

- **Promote Community-Based Management Models**: Engage local communities in managing water systems through cooperative frameworks. Provide financial and technical support for community organizations. Share best practices through knowledge-sharing networks.
- **Advance Climate Adaptation and Emergency Readiness**: Develop early warning systems and disaster response plans for private water systems. Adapt management strategies to changing weather and groundwater patterns. Educate communities to enhance emergency preparedness.
- **Expand Research and Development**: Conduct studies on the health impacts of non-PRASA water systems. Develop cost-effective treatment technologies for sustainable water access. Explore financing models to maintain affordable, resilient systems.

By implementing these recommendations, Puerto Rico can improve the resiliency, sustainability, and quality of its private water systems, ensuring they continue to provide critical services to rural and underserved communities.

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