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Water infrastructure sustainability challenge in Nigeria: A detailed examination of infrastructure failures and potential solutions

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ABSTRACT

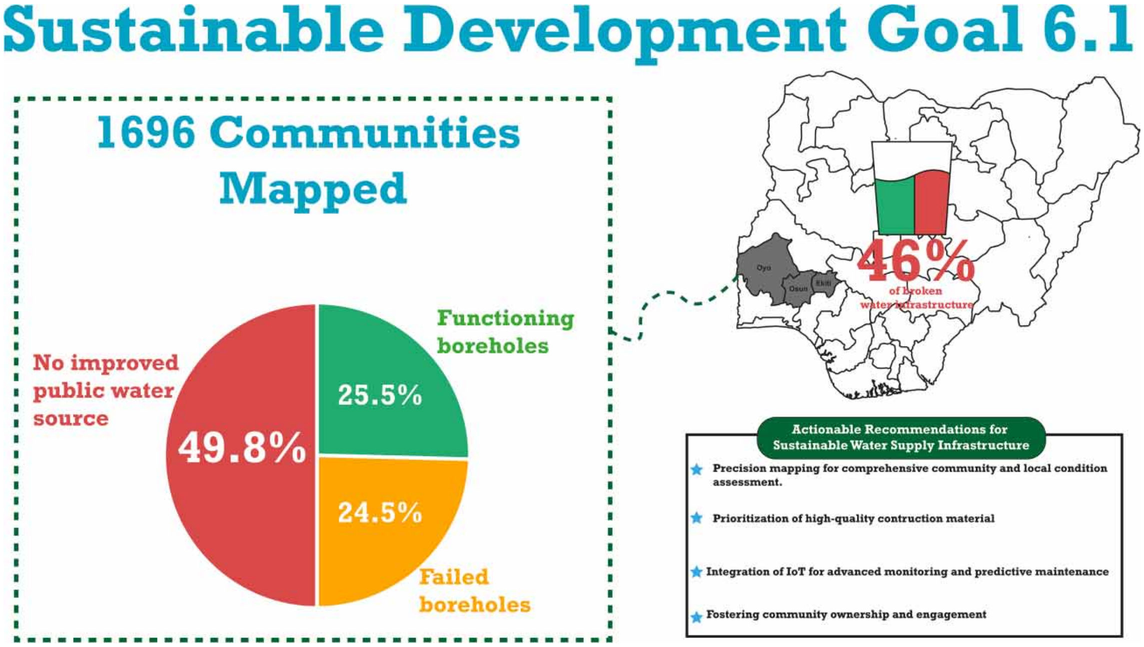
Achieving Sustainable Development Goal 6.1 – universal and equitable access to safe and affordable drinking water – is a critical global challenge. This study contributes to this aim by analyzing the functionality and sustainability of rural water boreholes in Nigeria. It employs GIS mapping, Spearman's rho correlation analysis, and interviews across 1,696 communities to investigate borehole failure dynamics, the impact of multidimensional poverty index (MPI) on water access, technical failure causes, and the influence of ownership on functionality. Findings show that while 49.8% of communities lack improved water sources, 25.5 benefit from functional boreholes, and 24.5 grapple with failures. This study reveals a complex relationship between MPI and water access, with community ownership associated with better functionality. Consequently, the study proposes holistic strategies, emphasizing community mapping and smart infrastructure, to enhance water system sustainability. Although the study is centered in Nigeria, its insights are applicable to regions with similar socio-economic conditions, contributing to the global pursuit of sustainable water access in alignment with SDG 6.1.

Key words: borehole sustainability, GIS mapping, Nigeria water infrastructure, SDG 6.1, water infrastructure failure

HIGHLIGHTS

- Borehole functionality and abandonment cause in Nigeria enhancing strategies for SDG 6.1.
- Correlation between poverty indices and borehole sustainability.
- Borehole technical failure informing design for water sustainability.
- How revealing community ownership enhances borehole infrastructure sustainability.
- Smart water infrastructure for post-construction monitoring and sustainable management.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Water infrastructure is central to achieving the Sustainable Development Goals, particularly SDG 6.1 which aims for universal access to safe and affordable drinking water for all. Studies like Murray & Koehring (2019) and Aly *et al.* (2022) reinforce its importance, while a 2018 UN report underscores the need for accelerated action (Water 2018). However, Khan *et al.* (2018) argue that both new construction and the maintenance of existing infrastructure are crucial to meet global water demand.

In developed nations, water accessibility standards are generally achieved; however, sub-Saharan Africa, as Hope *et al.* (2020) point out, struggles with significant deficits in basic water services, with over 336 million people affected (World Health & UNICEF 2019). Nigeria is emblematic of these challenges, with almost half of its water infrastructure non-functional (Andres *et al.* 2018), posing a critical issue against its rapid population growth (United Nations 2019).

In Nigeria, boreholes are essential in leveraging the abundant groundwater for household water needs (Adeniran *et al.* 2021). Yet, challenges ranging from technical failures to socio-political issues compromise their effectiveness (Andres *et al.* 2018), with broad implications for community health and economic development (World Health & UNICEF 2019).

Our study extends the systematic review of Adeoti *et al.* (2023), which synthesized research on the sustainability of water infrastructure in Nigeria. In their review, Adeniran *et al.* (2021) addressed the aging challenges of boreholes, while Oyekale & Ogunsanya (2012), as well as Popoola *et al.* (2021), highlighted construction defects and socio-economic influences. Shiru *et al.* (2020) examined water supply discrepancies and distribution issues, Oloruntade *et al.* (2014) pointed out planning deficiencies, and Olajuyigbe (2016) discussed the impacts of household income and poverty. Adeoti (2008) underscored the crucial role of community involvement in managing water infrastructure, and Ugwu *et al.* (2022) brought attention to unsustainable public sector spending and policy non-compliance. Despite these comprehensive contributions, a gap remains in fully understanding the entire lifecycle of borehole functionality – from operational effectiveness to eventual abandonment – and the intricate technical and socio-economic conditions that influence this process.

Leveraging a comprehensive analysis of 1,696 communities and building on existing knowledge within the field, this study presents a pioneering examination of borehole failure trajectories and classifies states of functionality to mirror the actual conditions encountered on the ground. By analyzing the alignment of the state-wise multidimensional poverty index (MPI) with the tangible conditions of water access and dissecting the technical and ownership factors that influence borehole longevity, our research uncovers a detailed classification system that precisely captures water access and infrastructure status. This methodical approach not only provides actionable insights for enhanced water infrastructure management but also enriches our understanding of the intricate dynamics at play in ensuring borehole sustainability. Contributing new perspectives to the ongoing discourse, this investigation aids in formulating strategies to achieve Sustainable Development Goal 6.1, offering significant implications for Nigeria and other areas with comparable socio-economic backgrounds.

2. METHODOLOGY

2.1. Study area

This study was conducted in the states of Oyo, Osun, and Ekiti, strategically chosen within Nigeria's Southwest. The selection of these states was predicated on their comparative safety, as indicated by travel advisories (Smartraveller.gov.au 2023), and the high prevalence of improved water sources, primarily public boreholes (World Bank 2017). The southwest region boasts the highest percentage of improved water sources in the country at 71.5%, with the northeast region following at 66% (World Bank 2017). The presence of such infrastructure was pivotal to this study, as the assessment of borehole functionality across the selected communities hinged on the existence and accessibility of these water sources. These states are part of the Yoruba ethnic region, a significant geopolitical zone, with populations of 5.7 million in Oyo, 3.42 million in Osun, and 2.38 million in Ekiti (Nigerian Finder 2022). Despite lower poverty rates of 48.7% in Oyo, 40.7% in Osun, and 36% in Ekiti compared to the national average of 62.9% (Nigeria Poverty Map 2023), these states face pronounced water infrastructure challenges, affecting water accessibility and quality.

The process for selecting communities within these states was guided by inclusion and exclusion criteria that prioritized rural and semi-rural areas equipped with public water systems, while urban areas and those dependent on individual household boreholes were excluded. Selection was also contingent upon obtaining community consent. A total of 1,696 communities were selected: 383 in Ekiti, 816 in Osun, and 497 in Oyo. The comprehensive distribution of these communities aimed to provide a significant sample size, thereby enhancing the study's representativeness and the generalizability of its findings, a principle supported by Vasileiou *et al.* (2018).

Figure 1 provides a detailed view of the study area within Nigeria, illustrating the geographical context and facilitating a visual understanding of the states' locations in relation to the entire country.

2.2. Data collection and analysis

The methodology of this study was designed to ensure a seamless transition from data collection to data analysis, with each step inherently addressing the research objectives through a logical sequence of actions.

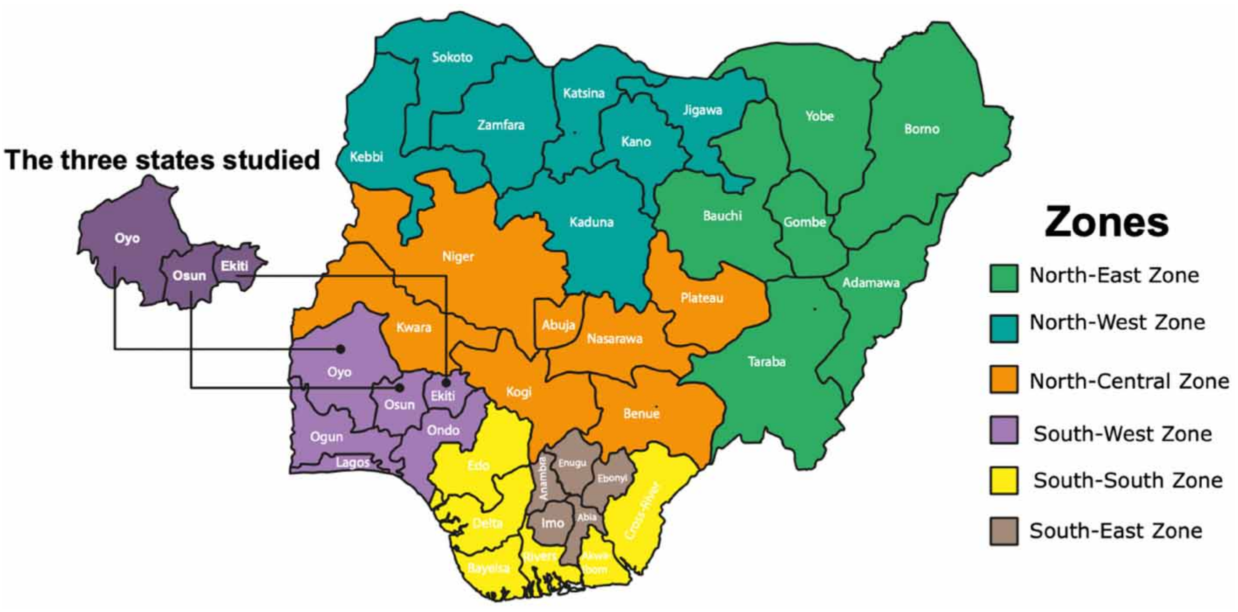


Figure 1 | Map of Nigeria highlighting the three surveyed states.

2.2.1. Data collection process

Under the guidance of the primary author of this study, a team of six university graduates in geology and field research was deployed across the three study states, with two researchers per state. This strategic composition facilitated comprehensive data collection, including borehole functionality and historical assessment, geospatial documentation, technical assessment, and ownership analysis. Such a structured approach enabled the creation of a detailed dataset, crucial for analyzing water infrastructure challenges.

2.2.2. Data analysis approach

Borehole Functionality Trajectory Analysis: The evaluation of the failure trajectory utilized a sequential model to analyze the status progression of boreholes from fully operational to completely abandoned. The analysis involved categorizing each borehole into one of several operational statuses: functioning, functioning – requires service, failed – repairable, failed – being fixed, and failed beyond repair. Descriptive statistics were applied to determine the percentage of boreholes in each category, providing a quantitative framework to understand the distribution and prevalence of each operational state within the studied areas. This model was instrumental in visualizing the transition phases of boreholes, facilitating a clear depiction of their operational lifespan and potential endpoints.

Geospatial Analysis: The Geographic Information System (GIS) was employed to meticulously visualize and analyze the distribution of boreholes within each state. This spatial analysis was designed to discern if the water infrastructure challenges observed in the sample communities were indicative of the broader multidimensional poverty rates reported for each state. By comparing states side-by-side, the study aimed to determine whether states with higher MPI exhibited more significant water infrastructure issues than those with lower rates. The analysis sought to establish a correlation between the severity of water-related challenges and the poverty level of each state, providing insights into the socio-economic factors influencing water infrastructure adequacy. Such analysis yielded initial findings that contribute to the understanding of how the state of water infrastructure correlates with levels of poverty within the regions under study.

Spearman's Rho Correlation Analysis: The analysis employed Spearman's rho to evaluate the ordinal rankings assigned to the conditions of water infrastructure, access to improved water, and MPI across the surveyed states. This non-parametric statistical measure was selected due to its appropriateness for ordinal data and its robustness in situations where a normal distribution cannot be assumed. It enabled the determination of the correlation strength and direction between the water infrastructure challenge rank or 'sum of ranks' and the state-wise multidimensional poverty rates, providing a statistical basis to identify significant associations.

The correlation analysis was conducted using IBM SPSS Version 27, adhering to Spearman's rank correlation coefficient formula:

$$\rho = 1 - \frac{6 \sum d_i^2}{n\,(n^2 - 1)}$$

where ρ is Spearman's rank correlation coefficient; d_i is the difference between two ranks of each observation; and n is the number of observations.

This calculation was integral to validating the observed spatial patterns and contributed to a statistically sound examination of the hypothesized relationships.

Technical Diagnostic Analysis: Alongside statistical analysis, a technical diagnostic was conducted on boreholes to pinpoint failure causes, which was essential for understanding the technical underpinnings of water infrastructure degradation.

Ownership Pattern Analysis: The data on ownership patterns were also subjected to analysis to evaluate their impact on the sustainability and functionality of boreholes, thereby assessing the effectiveness of various ownership structures in water infrastructure management.

This comprehensive approach – integrating GIS visualization with Spearman's rho analysis, complemented by quantitative and qualitative technical assessments – provides, for the first time, a detailed examination of the trajectory of borehole failure from functionality to abandonment. It provides an in-depth understanding of water infrastructure challenges, highlighting critical points for borehole rehabilitation interventions. By uncovering the complex interplay between community engagement, technical reliability, and socio-economic factors, this study identifies crucial stages for strategic intervention, advancing the formulation of targeted, effective policies for sustainable water infrastructure management.

3. RESULTS AND DISCUSSION

3.1. Borehole status and functionality assessment

Our survey across 1,696 communities revealed that 844 lacked any improved water sources. Of the 852 public boreholes evaluated, 434 were functioning, while 418 were non-functional, indicating an approximately equal ratio of operational to failed boreholes, as depicted in Supplementary Figure S1. Boreholes were categorized into six statuses: 271 (31.81%) as functioning, 162 (19%) as functioning – requiring service, one (0.12%) as a smart water kiosk, 239 (28.05%) as failed – repairable, 176 (20.66%) as failed beyond repair, and three (0.35%) as failed – being repaired. This classification is visually presented in a bar chart in Supplementary Figure S2, offering a comparative perspective of borehole functionality.

3.2. Trajectory of borehole functionality

Our research found a pattern in the borehole lifecycle across the surveyed regions. Post-construction, many boreholes enter a state of 'Functioning – Requires Servicing'. In the absence of adequate maintenance, these boreholes often deteriorate to the 'Failed – Repairable' phase. While timely interventions could restore functionality, prolonged neglect often leads them to an irreparable state. Our data reflect this alarming trend as shown in the sequential model in Figure 2, showing the failure trajectory and how lack of repair for borehole in the repairable state (only three or 0.35% being actively repaired) end up in failed beyond repair due to extensive delay in repair.

To avert this prevalent cycle of borehole failure illustrated in Figure 2, some strategic adaptations are recommended:

1. An institutional framework that prioritizes sustainable water management and maintenance to facilitate repair and improve infrastructure longevity (Hassenforder & Barone 2018).
2. A centralized data system with IoT integration for real-time monitoring and predictive maintenance, enhancing project efficacy and infrastructure durability (Barton *et al.* 2019; Ahmed *et al.* 2021).
3. Implementing comprehensive cost recovery strategies to ensure the financial sustainability of water services (Fonseca & Njiru 2003). The study highlights a gap in funding for repair needs, underscoring the necessity for better financial resource allocation.

3.3. Assessment of multidimensional poverty rates and water infrastructure correlation

This section examines the relationship between the multidimensional poverty rates at the state level and the condition of water infrastructure and access within communities across the three surveyed states. Utilizing GIS mapping and Spearman's rho statistical analysis, we assess whether higher poverty rates correspond with more significant challenges in water infrastructure, as commonly assumed.

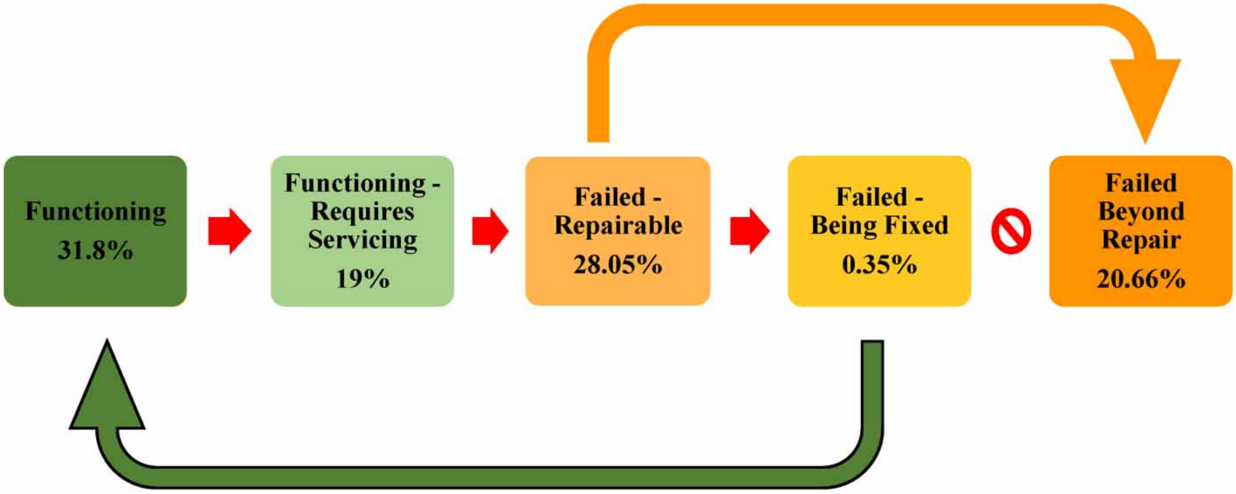


Figure 2 | Sequential model of borehole functionality, from full operation to total abandonment.

3.3.1. GIS analysis of water infrastructure disparities across the surveyed states

In our study of water infrastructure across Oyo, Osun, and Ekiti states, we find that a lower MPI does not necessarily predict better water infrastructure conditions. As highlighted in Table 1, Ekiti, with the lowest MPI, exhibits a higher rate of boreholes failed beyond repair (22%) compared to Oyo, which has the highest MPI but only a 4.8% failure rate in this category. This observation challenges the assumption that lower poverty levels automatically result in superior water infrastructure. Although further comparative analysis across additional states or with existing studies could provide broader insights into the MPI-infrastructure functionality relationship, such exploration exceeds our current study's scope, which concentrates on these three states to directly assess their correlation. The absence of comparable localized studies on infrastructure failure trajectories in other Nigerian states precludes direct comparisons, highlighting the unique contribution of our research. Our findings are corroborated by Spearman's rho test conducted in Section 3.3.2, which evaluates the correlation strength between MPI and water access. This test helps ascertain the significance of the observations made in this section.

Figure 3 provides a color-coded GIS representation of water infrastructure status in Oyo State as an illustrative example, highlighting the spatial distribution of functional to non-functional boreholes. Supplementary Figures S3–S5 show the spatial

Table 1 | State-wise comparison of community water infrastructure functionality and multidimensional poverty indices

State	Lack of improved water (%)	Functional boreholes (%)	Boreholes needing service (%)	Repairable boreholes (%)	Boreholes failed beyond repair (%)	Multidimensional poverty index (MPI) (%)
Oyo	63.4	14.1	5.4	11.9	4.8	48.7
Osun	38.7	18.3	13.5	20.7	8.6	40.7
Ekiti	55.6	13.6	6.5	2.9	22	36

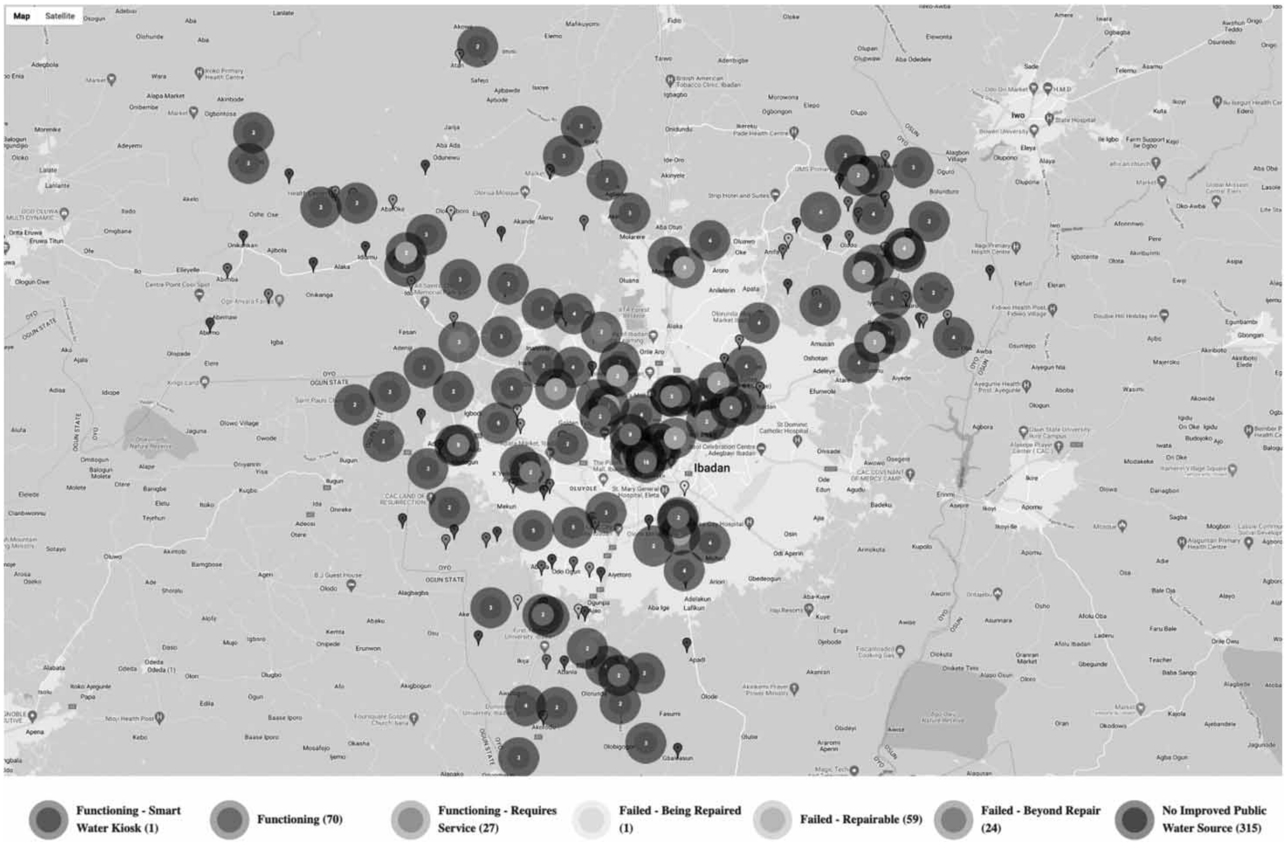


Figure 3 | GIS representation of water infrastructure status in Oyo state.

distribution of water infrastructure conditions across all three states. These visualizations offer a graphic depiction of the infrastructural disparities and are crucial for understanding the complex relationship between water access and poverty levels.

3.3.2. Spearman's rank correlation analysis

Following the data presented in Table 1, Table 2 aligns the ordinal rankings of water infrastructure functionality with the MPIs for the Nigerian states of Oyo, Osun, and Ekiti. Within each category of borehole functionality – from fully functioning to complete failure – states are ranked relative to each other, with 1 indicating the best performance in that category and 3 the worst. Osun, for instance, ranks 1 in functioning status, suggesting the best water infrastructure condition among the three states, followed by Oyo with rank 2, and Ekiti at rank 3, indicating the most challenges.

Spearman's rank correlation analysis was conducted to evaluate the potential relationship between the multidimensional poverty rates and water infrastructure challenges across the states of Oyo, Osun, and Ekiti. The null hypothesis (H0) posited no statistically significant correlation, while the alternative hypothesis (H1) suggested a significant relationship.

Spearman's rho coefficient was calculated as 0.000 with a *p*-value of 1.000, indicating an absence of correlation between MPI and the composite water infrastructure challenges. Consequently, the study fails to reject the null hypothesis, implying no statistically significant correlation between poverty level and water infrastructure conditions within the states evaluated.

The outcome of this assessment challenges the prevalent assumption that state-level poverty metrics are a reliable indicator of community water infrastructure and poverty conditions. It underscores the necessity of localized assessments over broad state-level metrics, which may mask the complexities and unique challenges of individual communities. In-depth GIS mapping, demonstrated in Figure 3, emerges as a pivotal tool for capturing the true nature of water infrastructure issues at the community level. Adopting this localized evaluation strategy ensures that interventions and resource allocations are accurately aligned with actual needs, paving the way for more effective and sustainable water infrastructure solutions.

3.4. Technical reason for borehole failures and material implications

This section explores the key technical causes behind borehole failures and their implications for infrastructure sustainability.

3.4.1. Technical causes of borehole failure

Upon analyzing 242 failed boreholes, the study identified the leading causes of malfunction through physical inspections and stakeholder interviews. The prevalent issues included pump and tap failures, accounting for 39 and 22% of total problems, respectively. Power supply and structural integrity problems were also notable, leading to further disruptions in water supply. These technical challenges, as visually presented in Figure 4, indicate specific areas that require targeted interventions to improve borehole functionality.

3.4.2. Implications of low-quality materials on borehole failures

The frequent failure of boreholes within a short span of installation is a critical concern, often attributed to the use of inferior materials, as supported by Khan *et al.* (2018). The study's findings, which resonate with insights from Water Aid (2016) and Soliman *et al.* (2022), underscore the urgent need for a paradigm shift in the material procurement strategy for water infrastructure projects. The current trend of prioritizing cost over quality has proven to be counterproductive, as evidenced by the

Table 2 | Ordinal rankings of surveyed community water infrastructure status and MPI

State	Lack of improved water rank	Functioning rank	Functional – Require service rank	Failed - Repairable rank	Failed - Beyond repair rank	Sum of ranks	MPI rank
Oyo	3	2	3	2	1	11	3 worst
Osun	1	1	1	3	2	8	2
Ekiti	2	3	2	1	3	11	1 Best
Spearman's rho	**Correlations** Multidimensional poverty rate			Multidimensional poverty rate		All functioning Status	
		Correlation coefficient		1.000		0.000	
		Sig. (2-tailed)		–		1.000	
		N		3		3	

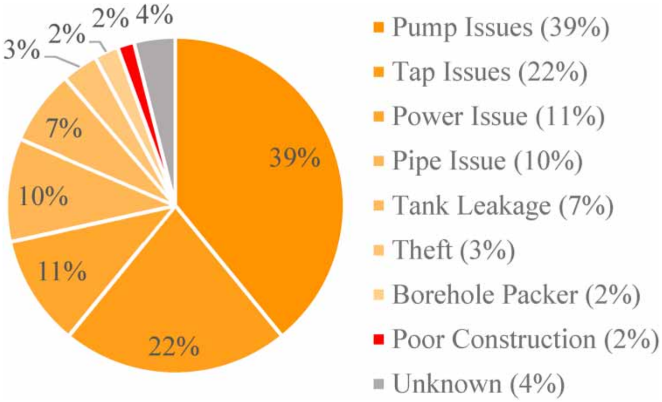


Figure 4 | Technical issues causing borehole failures.

high rate of component failures. Prioritizing the procurement of higher-quality materials could significantly enhance the longevity and reliability of boreholes, ultimately contributing to sustainable water infrastructure development.

3.5. Ownership and borehole functionality analysis

In assessing borehole failure rates in relation to ownership, the study found that state governments had a failure rate of 37%, while the federal government's boreholes failed at a slightly higher rate of 41.6%. Politicians reported a 33.8% failure rate, which was notably lower than that of local governments at 48.1%. Community groups showed a remarkable success with the lowest failure rate of 21%. NGOs and Foundations, along with Private Sponsors, experienced failure rates of 38.5 and 36%, respectively. All boreholes under schools, health facilities, and religious institutions (totaling seven) were functional, yielding a 0% failure rate. However, the limited sample size of these categories necessitates caution in deriving broad conclusions. More comprehensive data on borehole functionality across different ownership categories is available in Supplementary Table S1.

3.5.1. Implications of ownership on borehole functionality

The comparative analysis of borehole functionality indicates that ownership type might influence operational outcomes. Community-owned boreholes, which are often built in direct response to local needs and water demands, exhibit relatively lower failure rates. This could be indicative of the higher efficacy of local management and the direct alignment of the water projects with the actual needs of the users.

In contrast, boreholes instituted by governments or NGOs may not always align as closely with specific community needs and demands, which can lead to underutilization or neglect. The data underscores the importance of local involvement in the planning and maintenance of water infrastructure. Projects that are not closely mapped to community needs are less likely to be sustainable in the long term.

The findings from Section 3 of this article, which present a detailed mapping of water infrastructure status, further reinforce the necessity for NGOs and government bodies to consider on-ground realities, including water demand and community engagement, in the installation and management of water projects. By adopting a community-centric approach in the conceptualization and execution of such projects, governments and NGOs can enhance the functionality and longevity of boreholes, ultimately leading to improved water access and security.

4. ACTIONABLE RECOMMENDATIONS FOR ENHANCING WATER SUPPLY INFRASTRUCTURE SUSTAINABILITY

This study's insights into borehole failure trajectory, MPI relevance on actual community water condition, technical malfunction identification, and ownership impact culminate in the following recommendations for a durable water supply infrastructure:

- Adopt IoT Technology for Monitoring and Maintenance: Utilizing the Internet of Things (IoT) can significantly advance the management of rural water systems through real-time monitoring and predictive maintenance, improving the speed and efficiency of repairs.
- Precision Mapping and Community Surveys: GIS-based precision mapping and comprehensive community surveys, as illustrated in Figure 3, offer a detailed perspective on water infrastructure challenges that state-level poverty indexes may overlook. This localized assessment identifies key factors, including community engagement and specific water needs, which are essential for developing water projects that are truly aligned with on-the-ground realities.
- Invest in Quality Construction Materials: Using superior materials can increase water systems' longevity, ultimately resulting in cost savings by reducing the need for frequent repairs and maintenance.
- Encourage Community Ownership: Empowering communities to take charge of water projects promotes better maintenance and sustainability, as local stewardship leads to more conscientious care and investment in these critical resources.

In addition to the above recommendations, it is crucial to consider the geopolitical context and the political dynamics within the states and the country. The commitment of local governments to undertake such projects, which are often hindered by high costs and political influences, plays a determining role in the prioritization, establishment, monitoring, and maintenance of boreholes. While our study focuses on technical and community-based factors, the feasibility and success of these initiatives are inextricably linked to the political will and policies of the day, which may affect the allocation of resources for such essential projects. Recognizing this, our recommendations also include the need for policy advocacy and engagement with political entities to ensure that water infrastructure projects align with local government priorities and are shielded from shifting political landscapes to the extent possible.

5. FUTURE RESEARCH AND DEVELOPMENT: HYPOTHESIZED MODEL FOR A HOLISTIC APPROACH IN WATER INFRASTRUCTURE

This section presents a hypothesis to be rigorously tested through future research and real-life pilot projects, positing that a holistic approach incorporating the following three steps is critical for the development of sustainable water infrastructure in rural Nigeria:

1. *Community Mapping:* Undertake comprehensive mapping to determine community-specific needs, factoring in water demands, poverty's impact on water access, and the community's willingness to invest in water solutions.
2. *Viability Rating*: Utilize collected data to calculate a location viability rating (LVR). Future studies should define a benchmark LVR for deeming communities as viable candidates for sustainable water projects.
3. *Smart Infrastructure Implementation:* For communities meeting the LVR benchmark, the proposal is to deploy smart, durable water infrastructure with IoT capabilities for constant monitoring and data collection, enabling historical trend analysis and pre-emptive maintenance.

The proposed model for future water infrastructure interventions advocates for customization according to community needs and the latest technology, promising sustainable and community-centric project implementation. However, its success in Nigeria hinges on overcoming non-technical hurdles such as political will, funding, and local governance cooperation. These factors are crucial to transition from theory to practice. Therefore, future research and development must include policy advocacy and stakeholder engagement to ensure technical solutions resonate with both national and local development plans. A holistic approach that integrates technical, community, and political dimensions is essential for the lasting impact of water infrastructure sustainability efforts in Nigerian communities.

6. CONCLUSION

The comprehensive analysis undertaken in this study has traversed the multifaceted aspects of water infrastructure in rural communities, examining the failure trajectories of boreholes, the interplay between MPI and water access, the technical root causes of infrastructure failure, and the significant role of ownership in the functionality and sustainability of water projects.

The insights gleaned have informed a set of actionable recommendations. These include the adoption of IoT technology for improved monitoring and predictive maintenance, the use of high-quality construction materials, and the implementation of detailed community mapping to ensure that local water demands are met effectively. The study also emphasizes the vital role of community engagement in enhancing the sustainability of water projects.

On this groundwork, the article proposes a direction for future research and development projects, hypothesizing that a comprehensive approach – encompassing community mapping, viability rating evaluations, and the installation of intelligent, robust infrastructure – is essential for sustainable development. This proposed approach awaits rigorous validation through future research and practical pilot implementations.

While centered on rural Nigeria's distinct challenges, the research carries broad-reaching implications. Stakeholders across sub-Saharan Africa and beyond in developing regions can leverage these insights as a blueprint for advancing solid, effective, and long-lasting water infrastructure initiatives. In this endeavor, our study adds depth to the global research on finding solutions to water infrastructure sustainability challenges, a critical step toward realizing SDG 6.1.

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DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories: https://osf.io/v4jk2/?view_only=1004b586c66e40ea9106f355f5be5b04.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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