UTS UNIVERSITY OF TECHNOLOGY SYDNEY

Developing a Transdisciplinary Framework for Sustainable Water Infrastructure Solutions in Nigeria

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Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of Emeritus Professor Saravanamuthu Vigneswaran and Associate Professor Jaya Kandasamy

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May 2026

Certificate of Original Authorship

I, Oluwagbemi Samuel Adeoti, declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research was supported by an Australian Government Research Training Program (RTP) Scholarship doi.org/10.82133/C42F-K220.

Signature: Production Note:
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Date: 18/05/2026

Acknowledgements

I express my sincere gratitude to my Principal Supervisor, Emeritus Professor Saravanamuthu Vigneswaran, for his guidance, high standards, and steady support throughout the doctorate. Beyond academic supervision, he also provided moral support in a way that reflected the care and encouragement of a father, which I deeply appreciate. I also thank my Co-Supervisor, Associate Professor Jaya Kandasamy, for his valuable academic input, clarity of advice, and consistent encouragement.

I gratefully acknowledge the University of Technology Sydney (UTS), the Faculty of Engineering and Information Technology (FEIT), and the Graduate Research School (GRS) for institutional support throughout my candidature.

This research required real-life pilot projects, extensive field data collection, sustained community engagement, and collaboration with technical and industry experts. I am deeply grateful to Fairaction International for providing the platform and resources that enabled the fieldwork, data collection, and pilot project implementation underpinning this thesis. I thank Fairaction Nigeria for operational support across field logistics, community liaison, and implementation activities in remote settings. I also acknowledge Fairaction's project partner, YSG Multi-Tasking Nigeria Limited, for support during project delivery. I thank Fairaction International's R&D partners: Clean Water for All Pty Ltd for its aligned mission and funding support, and Essential Need Project Ltd and Farmbot Monitoring Solution for enabling longitudinal data monitoring through the Target 6.1 Map algorithmic software and an IoT monitoring system, respectively.

On a personal level, I am profoundly grateful to my family. As someone who grew up in a village and experienced water poverty first-hand, I understand how deeply it shapes a child's life, family stability, and opportunity. I was fortunate to survive those conditions, and I carry that history into this work with humility and resolve. As the Yoruba proverb says, "Ti ori ba pe ni ile, a di ire", a reminder that enduring hardships and remaining hopeful and patient will ultimately yield positive outcomes. My family's resilience and support enabled the patience and perseverance I needed to endure hardship as a child and to reach where I am today, blessed. My deepest gratitude goes to my parents, Mr Olawale Adeoti and Mrs Abosede Adeoti, for their love, prayers, sacrifices, and unwavering belief

in me. I thank my siblings, Olayinka, Oluwasola, and Aderonke, for their support from primary school through university, my master's degree, and the completion of this PhD. To my wife, Oluwaseun Adeoti, your love, encouragement, prayers, and constant support mean everything to me. You continue to inspire me to go further than I thought possible. Finally, I give thanks to God Almighty, the Alpha and the Omega, the Beginning and the Ending, for strength, direction, and grace through every stage of this journey.

List of Publications

Adeoti, O. S., Kandasamy, J., & Vigneswaran, S. (2023). Water infrastructure sustainability in Nigeria: a systematic review of challenges and sustainable solutions. *Water Policy*, wp2023173. https://doi.org/10.2166/wp.2023.173

Adeoti, O. S., Kandasamy, J., & Vigneswaran, S. (2024b). Water infrastructure sustainability challenge in Nigeria: A detailed examination of infrastructure failures and potential solutions. *Water Supply*, *24*(6), 2066-2076. https://doi.org/10.2166/ws.2024.127

Adeoti, O. S., Kandasamy, J., & Vigneswaran, S. (2024a). Sustainability framework for water infrastructure development in Nigeria: A modeling approach. *Water Supply*, *24*(8), 2933–2945. https://doi.org/10.2166/ws.2024.193

Adeoti, O. S., Haremi, R., Kandasamy, J., & Vigneswaran, S. (2025c). Evaluating the effectiveness of smart water management systems in enhancing the resilience and sustainability of water infrastructure in Nigeria. *AQUA-Water Infrastructure, Ecosystems and Society*. https://doi.org/10.2166/aqua.2025.291

Adeoti, O. S., Adeniran, A., Kandasamy, J., & Vigneswaran, S. (2025b). Diagnosing water infrastructure underutilization: a planning framework for behavioral risk, smart monitoring, and SDG 6.1 alignment. *Water Supply*. https://doi.org/10.2166/ws.2025.088

Adeoti, O. S., Kandasamy, J., & Vigneswaran, S. (2025a). *Assessing water safety and treatment feasibility in Nigeria's public boreholes: Toward SDG 6.1 compliance* . Manuscript submitted for publication in Water Policy.

Professional or Industry Publications

Adeoti, O. S., & Vigneswaran, S. (2024, December). Smart solutions – a Nigerian answer to access. *The Source*, (37), 32-35. thesourcemagazine.org/smart-solutions-a-nigerian-answer-to-access/

List of Acronyms and Abbreviations

Acronym	Meaning
AWDH	Average Water Demand per Household
CFU/ml	Colony-forming units per millilitre
DE	Design Effect
E. coli	Escherichia coli
GIS	Geographic Information System
ICC	Intra-cluster Correlation Coefficient
IoT	Internet of Things
JMP	Joint Monitoring Programme (WHO/UNICEF)
LVR	Location Viability Rating
MPI	Multidimensional Poverty Index
ND	Not Detected
NGO	Non-governmental organisation(s)
NIS	Nigerian Industrial Standard
NRW	Non-Revenue Water
NTU	Nephelometric Turbidity Unit
O&M	Operations and Maintenance
PEWASH	Partnership for Expanded Water Supply, Sanitation and Hygiene
PISM	Predictive Iterative Sustainability Model
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RANAS	Risk, Attitudes, Norms, Abilities, and Self-Regulation
RO	Reverse Osmosis
RW	Revenue Water
SDG	Sustainable Development Goal(s)
SR	Sustainability Rating
SSR	Self-Sustainability Rating
SWI	Smart Water Infrastructure
TDS	Total Dissolved Solids
TPB	Theory of Planned Behaviour
TSS	Total Suspended Solids
TWPSCH	Total Water Project Supply Capacity per Household

UN	United Nations
UN-Water	United Nations Water
UNICEF	United Nations Children's Fund
UTS	University of Technology Sydney
VLOM	Village Level Operation and Maintenance
VR	Viability Rating
VWSC	Volume of Water Supply Capacity (per day)
WASH	Water, Sanitation and Hygiene
WC	Water Credit
WD	Water Dispensed
WHO	World Health Organization
WSP	Water Safety Planning

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Abstract

This thesis develops a transdisciplinary, life cycle Sustainability Framework for Water Infrastructure in Nigeria, where almost half of existing schemes are non-functional and progress toward Sustainable Development Goal 6.1, universal and equitable access to safe and affordable drinking water, remains slow. It integrates systematic review, field diagnostics, predictive modelling, smart-system evaluation, behavioural analysis and water-quality assessment into a unified, metric-driven framework.

A systematic review of 15 studies generated 265 sustainability challenges across technical, financial, environmental, social and institutional factors. These informed field diagnostics across 1,696 communities, characterising borehole failure trajectories and their association with poverty and ownership. Of these, 49.8% lacked an improved source, and among those with boreholes almost half had failed, community-owned schemes failing at roughly half the rate of externally managed schemes, indicating that ownership and local accountability are central determinants of sustainability.

The thesis introduces the Predictive Iterative Sustainability Model (PISM), integrating Viability Rating, Sustainability Rating (SR) and Self-Sustainability Rating (SSR). Tested in five water-poor communities, PISM produced viability scores of 63.95 to 67.91% and predicted SR values of 179 to 424%, enabling ex-ante risk classification before capital is committed.

Smart Water Infrastructure (SWI) performance was evaluated over 1,095 days of IoT telemetry at a kiosk serving approximately 1,000 of an estimated 2,200 residents. The kiosk averaged 1,526 L per day, 7.63% of design capacity, achieving 100% SR and 97.1% reliability but 22% SSR, revealing underutilisation as a critical constraint. Behavioural analysis of 86 households and GIS-derived walking times found 16.3% adoption, each additional minute of walking reducing adoption odds by approximately 48%. These findings informed the Water Infrastructure Underutilisation Principle.

Accredited testing of 40 parameters across 17 public boreholes showed 88.2% non-compliance, and rule-based simulation produced a low-cost proxy model for water-safety monitoring; treatment pilots at two SWIs demonstrated feasible pathways to safe drinking water in low-resource settings.

The thesis synthesises this evidence into a novel, metric-driven sustainability framework spanning pre-construction diagnostics, treatment-ready and monitorable design, and post-construction operational, behavioural and water-safety feedback. It contributes this framework as a practical decision tool for sustainable water-service delivery in Nigeria, introduces PISM as a predictive planning tool, and develops the Water Infrastructure Underutilisation Principle to explain persistent non-use of functional infrastructure. Validated through SWI deployments across five communities with capacity to serve approximately 5,000 people, the framework is transferable and can be adapted and tested in comparable low-resource settings, supporting progress toward SDG 6.1.

Chapter 1: Introduction

1.1. Contextualising Nigeria's water infrastructure challenges

Safe drinking water is essential to human life, public health, socio-economic development, and environmental sustainability, and access to it is recognised as a basic human right (UNICEF & WHO, 2021). In 2015, the United Nations adopted the Sustainable Development Goals (SDGs), with SDG 6.1 targeting universal and equitable access to safe and affordable drinking water by 2030 (United Nations, 2015). Achieving this goal requires not only adequate water resources but also infrastructure that can be developed, operated, and maintained to deliver safe water reliably and sustainably. However, progress towards this goal remains uneven, with an estimated 703 million people still lacking basic drinking water services, the majority in low- and middle-income countries (Bain et al., 2014b; UNICEF & WHO, 2024). In many of these countries, water systems frequently become non-functional due to inadequate maintenance, poor quality control, and weak institutional arrangements. These failures reflect both technical deficiencies and broader governance and financing weaknesses, and they continue to hinder progress toward SDG 6.1. As a result, millions are left without safe water, facing heightened risks of waterborne disease and constrained socio-economic development (Foster & Hope, 2017; Hope et al., 2020). Achieving SDG 6.1 therefore requires more than expanding infrastructure; it demands solutions that address the systemic drivers of sustainability.

Water infrastructure failures are a global concern, but their consequences are particularly severe in Sub-Saharan Africa, where intersecting socio-economic, environmental, and institutional vulnerabilities amplify water insecurity (Adeniran et al., 2021; Garriga & Foguet, 2013). Countries such as Kenya, the Democratic Republic of Congo, Malawi, Tanzania, and Nigeria face persistent challenges, including deteriorating infrastructure, inadequate maintenance systems, fragmented governance, and limited financial capacity (Adeniran, 2022a; UNICEF & WHO, 2021). In Nigeria, the most populous country on the continent with over 200 million people, the crisis is especially acute. An estimated 40 million people lack access to safe drinking water (UNICEF & WHO, 2024), and approximately 46% of existing water infrastructure, especially boreholes, has failed

(Foster & Hope, 2017). New systems often fail within three years of installation, reflecting weak maintenance and sustainability planning (Adeoti et al., 2024b; Andres et al., 2018a; Andres et al., 2018b; Khan et al., 2018). The socio-economic impacts are severe**,** with the burden of water collection falling disproportionately on women and children, reducing school attendance and limiting economic opportunity. This gendered labour dynamic particularly disadvantages women and girls, directly linking the crisis to SDG 5 on gender equality (Akpabio & Takara, 2014; UNICEF & WHO, 2024). Consequently, failure to achieve universal access to safe water undermines not only SDG 6.1 but also interconnected goals on poverty reduction (SDG 1), health (SDG 3), and education (SDG 4).

Yet Nigeria's water crisis is not best characterised as one of absolute national water scarcity. In aggregate, the country possesses substantial water resources, including average annual precipitation of about 1,150 mm, total internal runoff of about 244 billion m^3/year, surface water resources potential of about 333 billion m^3/year, total internal water resources potential of about 287 billion m^3/year, and renewable groundwater potential of about 156 billion m^3/year (Federal Ministry of Water Resources, 2016). Over the same planning horizon, total national water demand was estimated at 5,933 million m^3/year in 2010 and projected to rise to 16,585 million m^3/year by 2030 (Federal Ministry of Water Resources, 2016). The central challenge, therefore, is not simply the national presence of water, but the uneven spatial distribution of resources, the mismatch between local demand and dependable supply, and the institutional and infrastructural failures that prevent available resources from being translated into sustained service delivery. This wider context is also relevant to the three study states examined in this thesis. Oyo, Osun, and Ekiti are located in south-west Nigeria, a region with the highest proportion of improved water sources in the country at 71.5%, where public boreholes are especially prominent (World Bank, 2017). This makes the three states analytically important, because they allow the thesis to examine why serious failures in functionality, sustainability, and service quality persist even in a region that performs relatively better on improved-source access and where borehole-based communal supply is widespread (Adeoti et al., 2024b; World Bank, 2017).

While much of the existing discourse focuses on technical, institutional, and financial explanations, Nigeria's water infrastructure crisis is also shaped by long-standing historical and structural legacies. During the colonial period, infrastructure investment prioritised urban administrative centres, neglecting rural and marginalised areas and entrenching inequities that persist today (Adeniran et al., 2021). These patterns continued after independence as post-colonial planning remained centralised and top-down. National Development Plans and Agricultural Development Programs (ADPs), though ambitious, were driven more by political and donor interests than by sustainability or inclusiveness. Between 1974 and 1997, over 190 dams and 12,651 boreholes were constructed under the ADPs, yet many failed rapidly due to weak community engagement and fragmented implementation frameworks (Adeniran et al., 2021; Hazell, 2004). The classification of rural water supply as a "social amenity" rather than a developmental asset further entrenched underinvestment, weak accountability, and the marginalisation of rural systems (Adeniran et al., 2021; Utietiang, 2015). This policy framing deprioritised strategic investment, leaving rural communities with limited access to safe water and disproportionately high rates of failure. These historically embedded disparities continue to shape the geography of water access and the persistence of infrastructure breakdowns across Nigeria.

Nigeria's water infrastructure challenges also expose the limitations of conventional development models. Many dominant approaches, particularly those shaped by "what works" narratives, rely on evidence from externally controlled settings that cannot easily be generalised. As Deaton and Cartwright (2018) argue, even rigorous intervention trials only guarantee outcomes within the specific contexts where they are conducted, and broader application requires reasoning grounded in local theory and conditions. Cornish (2015) similarly critiques systematic reviews in international development for oversimplifying evidence by neglecting the relational and dynamic nature of implementation. In the water sector, Crocker et al. (2024) demonstrate that inadequate reporting of contextual variables in WASH evaluations restricts adaptation and replication, ultimately undermining long-term sustainability. Without a context-specific and holistic framework that responds to Nigeria's complex sustainability challenges, infrastructure systems are likely to continue underperforming and failing prematurely.

1.2. Problem Statement

In rural and peri-rural Nigeria, communal borehole-based water systems often suffer persistent underperformance and premature failure, leaving millions without reliable access to safe drinking water despite decades of investment from government agencies, development partners, and non-governmental organisations. These outcomes reflect not only technical challenges but also the combined effects of institutional weakness, political and governance shortcomings, socio-cultural dynamics, environmental pressures, and systemic inefficiencies that prevent conventional project delivery models from achieving long-term sustainability.

Current approaches to infrastructure delivery remain fragmented, with little integration of these interrelated sustainability dimensions into planning, implementation, and long-term management. Projects are frequently based on externally developed or standardised models that are poorly adapted to Nigeria's governance structures, resource limitations, and community realities. Although national policies such as the Partnership for Expanded Water Supply, Sanitation and Hygiene (PEWASH) framework and numerous academic studies have acknowledged aspects of these challenges, their outputs remain largely high-level or fragmented. They have not translated into practical, field-validated mechanisms capable of guiding sustained service delivery.

As a result, infrastructure practice remains largely unguided by robust, empirically validated models, and many rural and peri-rural communities continue to experience recurrent system failures. Figure 1-1 illustrates examples of abandoned and non-functional community water infrastructure in Nigerian settings similar to those examined in this thesis. These failures reflect the recurring breakdown of communal water systems that motivates the study and underscore the need for a context-specific sustainability framework capable of improving long-term service delivery. Without a more integrated and contextually grounded approach, efforts to improve Nigeria's water infrastructure are likely to continue falling short, making achievement of SDG 6.1 increasingly uncertain. This persistent pattern of systemic failure underscores the urgent need for a holistic, context-specific, and empirically validated sustainability framework that can provide the structured guidance currently missing in Nigeria's water sector.



1a. Failed Borehole in Olori Oko Community
GPS: 7.395238, 5.018400



1b. Failed Borehole in Basiri, Ado-Ekiti
GPS: 7.638361, 5.209389



1c. Failed Standpipe in Ipetu Ijesa
GPS: 7.470852, 4.893111



1d. Failed Borehole project in Ado-Ekiti
GPS: 7.633167, 5.205861

Figure 1-1: Examples of abandoned and non-functional water infrastructure in Nigerian communities

1.3. Rationale

The persistent underperformance of Nigeria's water infrastructure highlights a critical gap: the absence of a field-ready, empirically validated, and context-specific framework that can translate sustainability concepts and research insights into practical application. Existing initiatives, such as the PEWASH Policy, the National Action Plan, and state WASH master plans, articulate important strategic directions but remain largely at the

policy level, without providing the operational procedures, performance thresholds, or feedback mechanisms needed to guide day-to-day delivery and long-term management. Academic scholarship since the Millennium Development Goals (MDGs) and into the SDG era has offered valuable insights into governance, ecological pressures, community participation and institutional reform. Studies such as those by Adepoju and Obademi (2023), Akpabio and Subramanian (2012), and Adeniran (2022a) have enriched understanding of sector dynamics, but most remain conceptual, focused on particular issues, and rarely applied or tested in real-world delivery contexts.

This research is motivated by the need to bring these strands together through a transdisciplinary approach that combines academic evidence, practitioner expertise, engineering diagnostics, and community perspectives into a unified framework. By integrating insights across domains and validating them empirically, the study aims to advance a sustainability framework that (i) integrates engineering diagnostics with governance and behavioural realities, (ii) incorporates life cycle metrics and decision rules across planning, implementation, and management stages, and (iii) is tested through implemented projects supported by longitudinal monitoring.

Nigeria provides a critical context for this work: the scale of need, diversity of challenges, and repeated cycles of infrastructure failure make it both an urgent national priority and a setting where lessons can generate insights of wider relevance. In this way, the study seeks to provide practical guidance, contribute to reducing systemic failures, and support measurable progress toward SDG 6.1.

1.4. Research Gap

Despite ongoing policy efforts and an emerging body of scholarship, practice in Nigeria still lacks a systematically organised, empirically validated sustainability framework that spans pre-construction, construction, and post-construction, and that can translate conceptual insights into operational procedures supported by decision rules, measurable thresholds, and feedback loops where monitoring data trigger predefined actions, inform reviews, and enable iterative improvement.

In the pre-construction stage, there is no empirically validated toolset currently in use to predict site-specific viability and expected use (Adeoti et al., 2024a). Eligibility and siting rules seldom incorporate behavioural predictors of uptake, such as walking time to a communal water point, perceived safety of existing sources, and household preferences (Adeoti et al., 2025b). As a result, infrastructure is often underutilised, with use remaining low relative to capacity and, in some cases, leading to abandonment.

During construction, available guidance does not provide context-specific design and quality-control rules that integrate water safety, feasible treatment pathways to meet standards, and affordability and cost-recovery constraints (Adeniran, 2022a; Adeoti et al., 2024b, 2025a). Build quality is rarely aligned with realistic operating budgets or reliable spare parts supply chains, and commissioning protocols to verify performance and water quality are inconsistently applied.

In the post-construction stage, longitudinal data collection, including smart monitoring, is not consistently structured into feedback loops with thresholds that guide operations, preventative maintenance, rehabilitation, or redesign (Adeoti et al., 2025c). Key metrics such as sustainability rating, reliability rating, utilisation rate, non-revenue water, water credit, and user behaviour are recognised in principle but remain insufficiently operationalised to drive routine decision-making. As a result, valuable insights that could improve equity, safety, and financial sustainability are not embedded in practice.

Targeting remains imprecise and coordination fragmented, so practice, policy, and evidence do not converge effectively in delivery (Adeniran, 2022b; Adeniran, 2022a; Adeoti et al., 2023). The resulting research gap is the absence of a transdisciplinary, life cycle framework that is empirically validated, context-specific, and metric-driven, providing a shared basis for evaluation and systematised operating procedures to support sustainable service delivery. While this gap is most visible in Nigeria, its characteristics are shared across many resource-constrained settings. Nigeria therefore provides a critical context for developing and validating such a framework in ways that can also generate lessons of wider global relevance.

1.5. Research Aim and Objectives

1.5.1. Research Aim

The overarching aim of this research is to develop and empirically validate a transdisciplinary sustainability framework for water infrastructure in Nigeria, structured to strengthen planning processes, enable adaptive monitoring, and ensure long-term performance under complex socio-technical and environmental conditions.

1.5.2. Research Objectives

1. To systematically investigate the technical, institutional, political, environmental, behavioural, and social factors influencing the sustainability of water infrastructure in Nigeria, and to evaluate how these dimensions interact across the project life cycle.

2. To conduct diagnostic and field-based research integrating community perspectives and behavioural insights to identify barriers to sustainable infrastructure performance.

3. To design, implement, and empirically evaluate pilot interventions that generate real-time evidence on infrastructure utilisation, system reliability, and the socio-technical conditions influencing long-term functionality.

4. To develop and validate sustainability metrics and diagnostic tools capable of supporting adaptive planning, real-time monitoring, and comprehensive evaluation of water infrastructure performance.
5. To evaluate water quality as a core dimension of sustainability by assessing compliance risks, treatment performance, and the integration of water-quality assurance metrics into the sustainability framework for reliable and safe service delivery.

6. To integrate findings from research, field practice, and implementation into a comprehensive framework applicable across pre-construction, construction, and post-construction phases, ensuring its adaptability to diverse Nigerian contexts.

7. To formulate evidence-based recommendations for engineering practice, governance, and policy that enable the adoption and scaling of the framework across Nigeria and comparable low-resource settings, thereby contributing to progress towards SDG 6.1.

Taken together, the objectives organise the thesis as a cumulative enquiry into the conditions under which water infrastructure can remain functional, safe, and sustainable in Nigeria. The study moves from identifying the determinants and manifestations of failure, through the development and testing of predictive, evaluative, and monitoring tools, to the incorporation of utilisation dynamics, water quality, and treatment feasibility within a single analytical frame. Objective 6 is realised in Chapter 9, where these strands are synthesised in the integrated life cycle framework developed from the accumulated evidence of the preceding chapters. Chapter 10 then extends that synthesis by drawing out its implications for engineering practice, governance, policy, and future research.

1.6. Research Questions

I began this research with a critical question rooted in both personal and industry experience: why does water infrastructure in Nigeria continue to experience persistent underperformance and failure despite decades of investment, technical effort, and national and international development programming? As outlined in the preceding sections, these failures are not the result of a single issue but rather stem from a complex interplay of factors that influence sustainability over the long term.

My initial enquiry into this question led to the development of a comprehensive systematic literature review on water infrastructure sustainability in Nigeria (Adeoti et al., 2023), presented in Chapter 2. This review synthesised evidence from a wide range of studies and identified 265 distinct challenges affecting sustainability. While various solutions had been proposed in the literature, the complexity and interconnectedness of these challenges confirmed that the problem cannot be resolved through a simple list of proposed interventions. This finding supports the earlier discussion on the need for a

unifying framework, tailored to the Nigerian context, that can address these challenges in a systematic and integrated manner.

Accordingly, the thesis is guided by the following overarching research question:

How can a transdisciplinary sustainability framework be developed and empirically validated to strengthen the planning, implementation, adaptive monitoring, and long-term performance of water infrastructure in Nigeria?

To answer this overarching question, the study investigates five interrelated sub-questions, as detailed in Table 1-1. Reflecting the iterative and transdisciplinary nature of the research design (outlined in Chapter 3), each sub-question is addressed through multiple interlinked but thematically distinct investigations, presented across the thesis chapters and associated publications. Table 1-1 illustrates how each sub-question is explored by drawing on findings from the research publications, pilot implementations, and corresponding thesis chapters. Collectively, these sub-questions and their associated outputs contribute to addressing the overarching research question.

Table 1-1: Sub-research questions and corresponding chapters and author's publications contributing to the overarching inquiry

Sub-research Question	**Chapters and associated publications**	**Key contributions of relevant chapters**

1. What are the key factors impacting the sustainability of water infrastructure in Nigeria, and how do these factors interact across the infrastructure life cycle?	Chapter 2 (Adeoti et al., 2023), Chapter 4 (Adeoti et al., 2024b), Chapter 5 (Adeoti et al., 2024a), Chapter 7 (Adeoti et al., 2025b), Chapter 8 (Adeoti et al., 2025a)	Across these chapters the thesis identifies 265 sustainability challenges, quantifies large-scale failure patterns, develops pre-construction sustainability metrics, reveals underutilisation and aid overlap as new failure drivers, and incorporates water-quality and regulatory compliance risks into a life cycle view of sustainability.
2. How can infrastructure diagnostics, community engagement, and behavioural insights be applied to design and refine a sustainability framework for water infrastructure in Nigeria?	Chapter 4 (Adeoti et al., 2024b), Chapter 5 (Adeoti et al., 2024a), Chapter 7 (Adeoti et al., 2025b).	These chapters translate field diagnostics, GIS mapping, community perspectives and behavioural evidence into concrete planning rules and eligibility criteria embedded within the sustainability framework.
3. How can real-world pilot implementations support the validation and refinement of sustainability metrics and tools for adaptive water infrastructure management?	Chapter 5 (Adeoti et al., 2024a), Chapter 6 (Adeoti et al., 2025c), Chapter 8 (Adeoti et al., 2025a).	Chapter 5 develops predictive and planning metrics as part of framework design. Chapter 6 evaluates the effectiveness of smart water solutions using real-time IoT-based performance data collected over 1,095 days. Chapter 8 develops and applies water quality-specific metrics through treatment technology integration.

4. What behavioural, perceptual, and spatial barriers hinder sustained use of water infrastructure, and how can these be integrated into design and evaluation?	Chapter 4 (Adeoti et al., 2024b) Chapter 6 (Adeoti et al., 2025c) Chapter 7 (Adeoti et al., 2025b)	Chapter 4 identifies gaps in traditional planning assumptions. Chapter 6 measures usage trends and reliability through smart kiosk monitoring. Chapter 7 introduces the Water Infrastructure Underutilisation Principle, highlighting perception, proximity, and low perceived health risk as barriers to sustained use.
5. How can water-quality compliance and treatment performance be incorporated into the sustainability framework to ensure long-term reliability and safe service delivery?	Chapter 8 (Adeoti et al., 2025a)	Chapter 8 identifies and assesses low-cost proxy indicators against certified datasets, estimates non-compliance and dominant contaminants, pilots treatment options, and defines a phased compliance pathway that integrates water-quality assurance into the sustainability framework.

1.7. Scope

The scope of this research is defined by the parameters within which the sustainability framework was developed and validated. The scope is defined as follows:

- **Geographic focus:** Rural, peri-rural, and peri-urban communities in Nigeria, where infrastructure challenges are most acute and complex

- **Technical focus and infrastructure type:** The study examines communal water supply systems, specifically borehole-based schemes and a piloted smart water infrastructure (SWI) configured as a borehole with standpipe outlets. These communal arrangements reflect the predominant service model in rural and peri-urban Nigeria, where household piped connections are rarely feasible due to prohibitive capital and maintenance costs. Analysing communal SWI captures the practical infrastructure realities of water-poor communities and enables evaluation directly relevant to their prevailing service conditions.

- **Resource focus:** Groundwater as the primary water source, selected due to its climate resilience, reliability, and critical role in rural water provision. Globally, groundwater supplies nearly half of the world's drinking water and serves as a vital resource in many water-scarce regions (Margat & Van der Gun, 2013). Its relative protection from surface evaporation and short-term climatic variability allows for more stable supply during prolonged dry seasons and under increasing climatic uncertainty (Treidel, 2013). In Nigeria, over 60% of the rural population relies on groundwater withdrawn through boreholes and wells for daily drinking water needs (Akpabio & Takara, 2014; UNICEF & WHO, 2021). Despite its prevalence, boreholes in Nigeria frequently fail within a few years, making them a particularly relevant focus for sustainability research. This emphasis also defines the empirical boundaries of the thesis, which is developed and validated primarily in relation to groundwater-centred communal infrastructure, particularly borehole-based systems.

- **Adaptability:** While centred on groundwater systems, the research is structured around the life cycle stages of water infrastructure and associated sustainability criteria, which are also applicable to other configurations, including rainwater harvesting and dam-fed piped networks. However, those configurations are not examined here in equivalent empirical depth, and their direct application would therefore require further context-specific testing.

- **Strategic alignment:** Focus areas are consistent with national and global development goals targeting reduced disparities in basic service access (Popoola et al., 2021).

1.8. Methodological Orientation and Transdisciplinary Positioning

The research gap identified in Section 1.4 highlighted the absence of a transdisciplinary, life cycle framework that is empirically validated, context-specific and metric-driven, providing a common set of criteria and metrics for evaluating sustainability and underpinning systematised operating procedures to support sustainable service delivery. To address this gap, the thesis adopts a transdisciplinary methodological orientation.

Transdisciplinary approaches recognise that sustainability challenges require integration of diverse forms of knowledge and practice across disciplinary boundaries (Bammer et al., 2020; Robinson, 2008; Wickson et al., 2006). In the context of water infrastructure, outcomes are shaped by technical performance, institutional arrangements, financial viability, political context, social behaviour and environmental conditions. The thesis therefore combines academic research, engineering practice, policy perspectives and community knowledge within a coherent program of interlinked studies that are aligned with shared constructs of sustainability and evaluation. The specific methodological design, including the iterative research cycle through which the transdisciplinary stance is operationalised, and the associated data sources, analytical techniques and theoretical frameworks, is presented in detail in Chapter 3.

1.9. Thesis Structure

This thesis is presented in ten chapters and draws on five peer-reviewed publications, and one submitted manuscript awaiting publication (Chapters 2, 4, 5, 6, 7 and 8), as well as one professional dissemination article that illustrates the iterative research cycle discussed in Chapter 3. Each publication is embedded within the thesis and accompanied by contextual framing and critical reflection to ensure coherence. The chapters are arranged so that each builds logically on the previous, reflecting the iterative progression

of the research, culminating in a synthesis chapter (Chapter 9) and a conclusions and recommendations chapter (Chapter 10).

- **Chapter 1: Introduction**
  Sets out the research problem, contextual background and motivation. It outlines the aim, objectives and research questions, and establishes the scope and methodological orientation of the study.

- **Chapter 2: Systematic Review of Water Infrastructure Sustainability in Nigeria**
  Publication 1 – *Water infrastructure sustainability in Nigeria: A systematic review of challenges and sustainable solutions* (Adeoti et al., 2023). Synthesises existing knowledge and identifies 265 distinct challenges affecting water infrastructure sustainability across technical, institutional, environmental, financial and social dimensions.

- **Chapter 3: Methodology**
  Presents the overarching methodological architecture of the thesis, including the transdisciplinary orientation, theoretical framework, iterative research cycle, mixed methods and multi scale design, and core analytical approaches. Discusses the iterative research cycle through smart water infrastructure pilots, drawing on the industry article *Smart solutions – a Nigerian answer to access* (Adeoti & Vigneswaran, 2024)

- **Chapter 4: Field Diagnostics of Water Infrastructure Sustainability in Nigeria**
  Publication 2 – *Water infrastructure sustainability challenge in Nigeria: A detailed examination of infrastructure failures and potential solutions* (Adeoti et al., 2024b). Presents field diagnostics across 1,696 communities to identify patterns of borehole failure and underlying risk factors.

- **Chapter 5: Predictive Modelling for Sustainable Water Infrastructure**
  Publication 3 – *Sustainability framework for water infrastructure development in*

Nigeria: A modelling approach (Adeoti et al., 2024a). Introduces the Predictive Iterative Sustainability Model (PISM), tested in five communities for pre-construction viability and sustainability assessment.

- **Chapter 6: Smart Water Infrastructure for Resilience and Sustainability** Publication 4 – *Evaluating the effectiveness of smart water management systems in enhancing the resilience and sustainability of water infrastructure in Nigeria* (Adeoti et al., 2025c). Reports findings from a 1,095-day pilot of IoT enabled smart water kiosks, evaluating service reliability, usage patterns and non-revenue water.

- **Chapter 7: Behaviour and Sustainable Infrastructure Utilisation** Publication 5 – *Diagnosing water infrastructure underutilisation: A planning framework for behavioural risk, smart monitoring and SDG 6.1 alignment* (Adeoti et al., 2025b). Investigates behavioural, perceptual and spatial barriers to infrastructure use, introducing the Water Infrastructure Underutilisation Principle.

- **Chapter 8: Water Safety, Treatment Feasibility and Sustainability Pathways** Publication 6 (manuscript submitted for publication) – *Assessing water safety and treatment feasibility in Nigeria's public boreholes: Toward SDG 6.1 compliance* (Adeoti et al., 2025a). Analyses borehole water quality, tests treatment interventions and evaluates regulatory feasibility under resource constraints

- **Chapter 9: Synthesis and Integrated Framework for Sustainable Water Infrastructure**
  Synthesises findings across all empirical chapters and presents an integrated, life cycle sustainability framework for water infrastructure in Nigeria.

- **Chapter 10: Conclusion and Recommendations**
  Presents the conclusions drawn from each empirical chapter and the thesis as a whole, and sets out recommendations for future research directions.

Chapter 2: Systematic Review of Water Infrastructure Sustainability in Nigeria

This Chapter is based on the following Publication:

Adeoti, O. S., Kandasamy, J., & Vigneswaran, S. (2023). *Water infrastructure sustainability in Nigeria: a systematic review of challenges and sustainable solutions. Water Policy*, 25(11), 1094–1111. https://doi.org/10.2166/wp.2023.173

Overview

This chapter presents a systematic literature review that establishes the conceptual and measurement framework for the research enquiry. It assembles a coherent, evidence-based understanding of water infrastructure sustainability in Nigeria to frame and address the research questions. The review clarifies core constructs and outcome measures for functionality and sustainability, delineates the scope of the challenge across technical, institutional, financial, social, political and environmental domains, and identifies the principal solution pathways reported in the literature. It initiates enquiry into the first sub-research question by organising what is known about the factors that affect sustainability and how these factors are reported to interact across the pre-construction, construction and post-construction stages. The analysis also appraises prevailing theoretical and methodological approaches, identifies methodological gaps and research trends, and sets out the terminology, indicator selection and measurement choices adopted in the thesis.

The review maps factor interactions to life cycle stages, identifies where studies agree and where they conflict, and specifies where knowledge is thin, inconsistent or absent. These clarifications define the boundaries of current understanding, indicate where new empirical data are required, and set out the assumptions and definitions that will be applied consistently. As such, the chapter provides the foundation on which subsequent analysis builds, ensuring that the thesis proceeds from a well-specified problem space, established indicators and clearly articulated evidence gaps.

2.1. Introduction

Access to safe and affordable drinking water is a fundamental human right and central to sustainable development (Bain et al., 2014b). Sustainable Development Goal 6.1 commits countries to achieve universal and equitable access by 2030 (United Nations, 2015), with well-documented co-benefits for public health, poverty reduction, gender equality and economic growth (Aly et al., 2022; Satterthwaite et al., 2020; UN-Water, 2016). Safe water reduces waterborne disease, supports food, energy and industrial systems, and reduces the time spent collecting water, which disproportionately burdens women and girls (Prüss-Ustün et al., 2019; Ray, 2007; Sorenson et al., 2011). Despite recent progress, significant disparities persist within and between countries, particularly in rural and disadvantaged areas (WHO, 2017, 2019). Addressing these disparities requires a robust synthesis of the evidence to clarify concepts, organise determinants and identify effective solution pathways for policy and practice (Adeniran, 2022b; Adeniran et al., 2021).

Globally, more than 90% of people now use improved sources (WHO, 2019), yet about 785 million still lack basic services and many systems fail to deliver sustained benefits (Bain et al., 2014b; WHO, 2019). In low-resource settings, high rates of infrastructure failure are linked to weaknesses in planning, finance and maintenance (Bonsor et al., 2015; Whaley & Cleaver, 2017). These pressures are acute in Sub-Saharan Africa, where rapid urbanisation, population growth, climate variability and governance constraints compound service gaps, and where up to 40% of water points have been reported non-functional (Dos Santos et al., 2017; Foster & Hope, 2017; Onda et al., 2012). Failures have significant local consequences, including water scarcity, adverse health outcomes and entrenched poverty (Prüss-Ustün et al., 2019; Whaley & Cleaver, 2017).

Nigeria, Africa's most populous country, continues to face persistent shortfalls in safe water service despite sustained investment. Boreholes and other groundwater systems are central to supply, yet performance remains weak: in 2024, 82% of the population used at least basic drinking water services, but only 30% used safely managed drinking water services, while field diagnostics across 1,696 communities in south-west Nigeria identified 852 public boreholes, of which 418 were non-functional (Adeoti et al., 2024b; WHO & UNICEF, 2025). These figures indicate that progress in nominal access has not been matched by equivalent improvements in service reliability, water safety, and long-

term functionality. Failures arise from interacting technical, institutional, financial, social, political and environmental factors amid substantial geographic variation (Adeniran et al., 2021; Andres et al., 2018a). These conditions underscore the need for a comprehensive review to clarify constructs, synthesise evidence on drivers and responses, and identify actionable solution pathways relevant to SDG 6.1. Accordingly, this systematic literature review seeks to address the following objectives:

- Critically review and synthesise the existing literature on water infrastructure challenges and sustainability in Nigeria, examining the employed theoretical frameworks, methodologies, and empirical findings, and understanding how the current research addresses the factors contributing to failure.
- Identify evidence-based sustainable solutions that have been proposed or implemented to address the challenges contributing to water infrastructure failure and promote sustainable development in Nigeria's water sector.
- Discuss the implications of the findings for policy, practice, and future research, highlighting the areas where further research is needed to advance the understanding of water infrastructure sustainability in Nigeria.
- Propose actionable recommendations for policymakers, practitioners, and researchers to address the identified challenges and contribute to achieving SDG 6.1 in Nigeria and other developing countries.

The review focuses on studies conducted within Nigeria and published in English between 2000 and 2023, spanning the Millennium Development Goals and the Sustainable Development Goals, and follows a reproducible protocol with predefined inclusion and exclusion criteria (Adeniran, 2022b). It also notes where studies agree and where they conflict, and recognises limitations arising from study quality, inconsistent reporting and the Nigeria-specific focus.

2.2. Methodology

The methodology adopted for this systematic literature review is summarised below, with additional details provided in Appendix 1.

2.2.1. Search Strategy

The study adheres to the PRISMA guidelines, ensuring a transparent, rigorous, and replicable review process (Moher et al., 2009; Page et al., 2021). The primary electronic database used for the search was Scopus, selected for its extensive collection of publications, large peer-reviewed library (Burnham, 2006; Falagas et al., 2008), and ability to capture publications from various developing countries, including Nigeria (Mongeon & Paul-Hus, 2016; Zhu & Liu, 2020). Details of the search strategy are available in Appendix 1.

Table A1.1 in Appendix 1 provides details of the search strings used across the search databases. Full-text review for eligibility was conducted on the selected articles. In addition to the electronic database search, hand-searching of relevant article references and grey literature was also performed. This comprehensive search strategy ensured the inclusion of a diverse range of literature and minimised bias in the review.

2.2.2. Inclusion and Exclusion Criteria

A predefined set of inclusion and exclusion criteria was established to ensure relevance and consistency. These criteria specified eligibility for the systematic review. Mandatory and additional criteria provided a robust, adaptable framework for study selection. Table 2-1 summarises the inclusion and exclusion criteria; further details are provided in Appendix 1.

Table 2-1: Inclusion and Exclusion Criteria

Criteria	**Inclusion**	**Exclusion**
1. Academic Database	Articles indexed in Scopus and Google Scholar.	Articles from databases other than Scopus and Google Scholar.
2. Type of Research	Published journal articles, book chapters, conference papers, postgraduate research outputs, and government publications.	Review articles, book reviews, conference reviews, newspapers, and personal correspondences.

3. Publication Status	Published articles and articles in the press.	Unpublished articles.
4. Year of Publication	Articles published from 2000 to 2023.	Articles published before 2000.
5. Access Type	Access to the full text of the article	Articles whose access is restricted to their titles and abstract.
6. Language	Articles published in the English language.	Articles published in languages other than English.
7. Research Area	Studies focused on water infrastructure sustainability, access, maintenance, and challenges in Nigeria, with particular emphasis on both groundwater sources and other water systems.	Studies on infrastructure sustainability unrelated to water or not focused on Nigeria.
8. Article Content	Articles that discuss factors, including (but not limited to) community participation, that are responsible for water infrastructure failure or sustainability challenges in Nigeria, and that propose or assess sustainable solutions to these challenges.	Articles that do not discuss any of the factors responsible for water infrastructure failure or sustainability challenges in Nigeria, or articles that neither propose nor assess sustainable solutions to these issues. This includes studies that may touch on water issues in Nigeria but lack a direct link to infrastructure sustainability, or those that solely focus on a single factor without considering the context of water infrastructure challenges or sustainability.
9. Water Resources Management	Articles discussing water resources management in relation to the sustainability and maintenance of water supply infrastructure in Nigeria. This includes articles	Articles focusing solely on water resources management without addressing its relationship to water supply infrastructure sustainability and maintenance in Nigeria.

	discussing governance, policy impacts, and community involvement

2.2.3. Data Extraction and Synthesis

Systematic data extraction was carried out using a custom-made Microsoft Excel form, focusing on significant details from each study related to the factors contributing to water infrastructure failure in Nigeria. An integrated approach combining thematic analysis, narrative synthesis, and content analysis was employed to synthesise the extracted data. This approach facilitated the identification of common themes, exploration of relationships and findings across studies, and quantification of the frequency of certain responses or factors. Further details on data extraction and synthesis are provided in Appendix 1

2.2.4. Quality Assessment

The quality of each selected study was assessed using a customised checklist based on key criteria essential for evaluating the validity and reliability of research findings. This quality assessment tool was developed with reference to sources such as the Critical Appraisal Skills Programme (CASP) tools and literature on research methodology (e.g., (Long et al., 2020; Mengist et al., 2020). More details about the quality assessment are provided in Appendix 1. However, it is important to note that this quality assessment method, while robust, has some limitations. It may not capture all aspects of a study's quality, and the binary 'yes/no' responses may oversimplify complex issues. Therefore, the quality assessment should be interpreted in conjunction with other considerations, such as the relevance of the study to the research questions and its overall contribution to the knowledge of water infrastructure sustainability in Nigeria.

2.2.5. Overview of the Selected Studies

The procedure used to select studies for inclusion in the review is outlined in the flow chart presented in Figure 2-1. Based on this process, a total of 15 studies were selected for data extraction and synthesis. The details of these studies are provided in Table A1.2 in Appendix 1.

The resulting set of studies is intentionally focused. This review was designed as a thematic synthesis of literature dealing directly with water infrastructure sustainability in Nigeria, rather than as a meta-analysis aimed at large-sample statistical aggregation. Studies were retained only where they engaged substantively with infrastructure functionality, sustainability challenges, and relevant solutions or interventions within the Nigerian context. Studies addressing water access more broadly, but without a clear connection to infrastructure sustainability, were excluded. The selected studies therefore provide a focused evidentiary base for tracing recurring determinants of failure, examining how these issues are conceptualised across the literature, and locating the principal gaps that shape the analysis developed in the chapters that follow. Further detail on the search strategy, inclusion and exclusion criteria, and the characteristics of the selected studies is provided in Appendix 1 and Table A1.2.

The search period for this systematic literature review encompassed the years 2000 to 2023, providing a comprehensive understanding of the topic's evolution over two decades. The earliest article included in this review was published in 2008 by Adeoti, Adetola I., while the most recent publication was in 2022 by Ugwu, Paschaline Nkeiruka, and colleagues. Notably, a significant portion of the articles (7 out of 15, 47%) were published in the last five years, between 2018 and 2023, indicating a growing interest and increased research activity on the subject during this period. A detailed year-wise distribution of the included articles is presented in Figure 2-2.

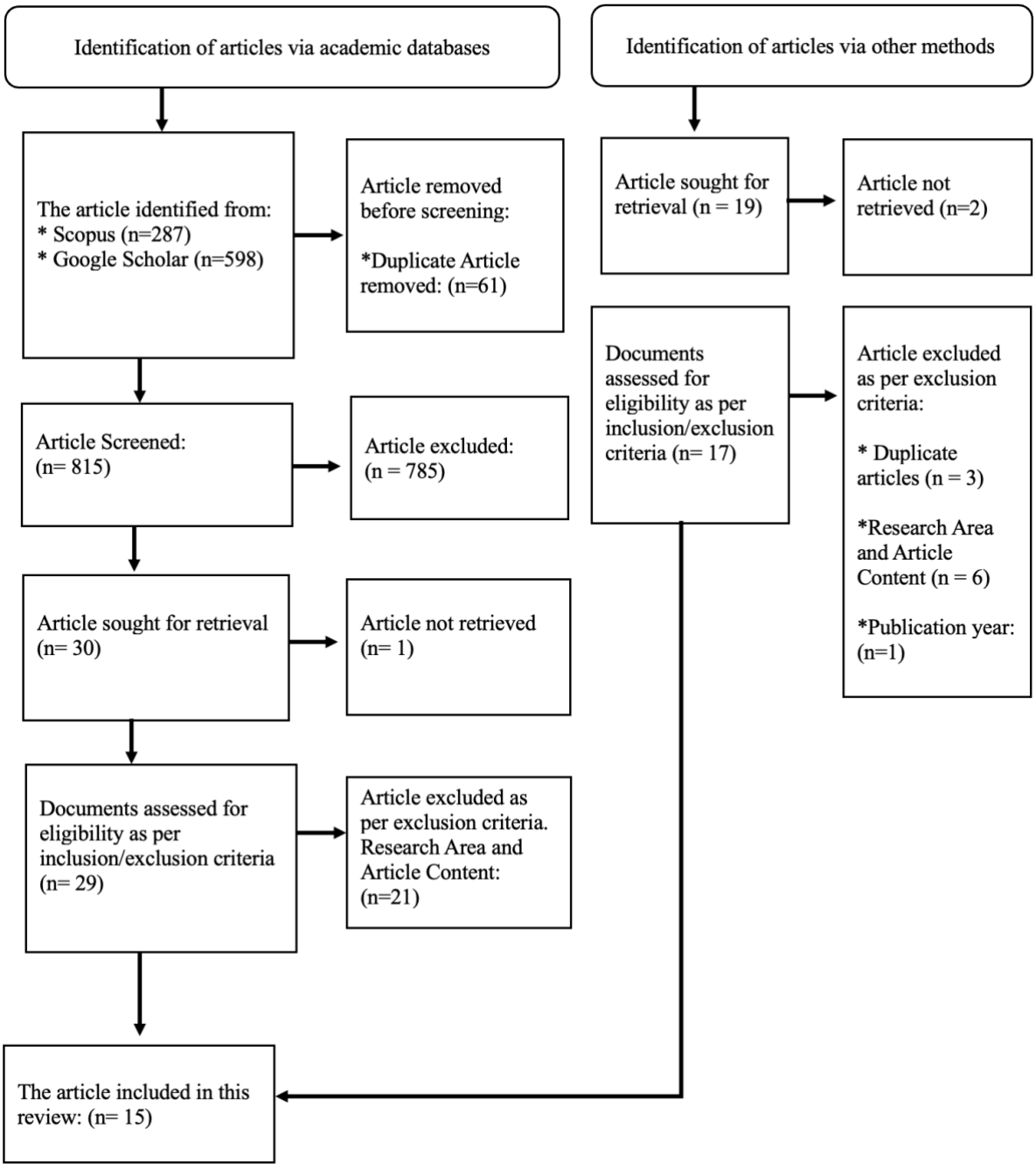


Figure 2-1: Selection process flow chart adapted from Page et al. (2021)

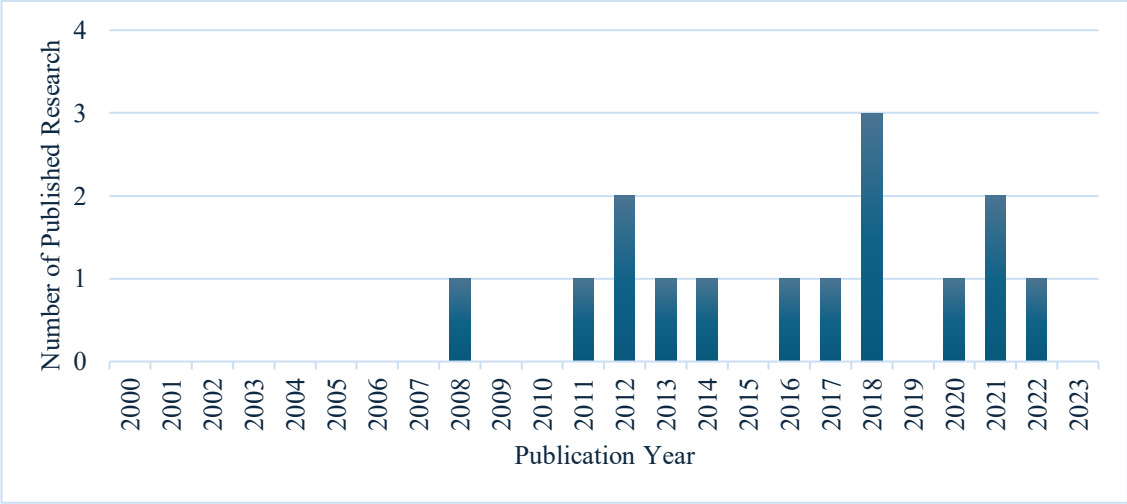


Figure 2-2: Yearly Research Publication on Nigerian Water Infrastructure Sustainability and challenges

2.3. Result

2.3.1. Overview of Analysed Water Infrastructure in Selected Studies

The diverse landscape of Nigeria's water infrastructure is thoroughly examined in the 15 studies included in this review. Boreholes are a dominant focus consistently discussed across all 15 studies, underscoring their paramount significance in Nigeria's water supply framework. Wells, a primary water source for many households, are featured in over half of the studies, specifically 8 out of the 15. Pipe distribution systems, crucial for a seamless water supply across urban and rural areas, were highlighted in 6 studies. Dams, which play a pivotal role in bulk water supply and reservoir creation, were mentioned in three studies. Other sources such as standpipes and rainwater collection were discussed in two studies each. Streams and protected springs, though less common, were each reported in only one study.

Adeniran et al. (2021) conducted a comprehensive analysis encompassing various dams and reservoirs, providing valuable insights based on data spanning from 1923 to 2007. On a more micro-level, Andres et al. (2018a) focused on 43,443 water points, primarily wells and boreholes, to comprehend their crucial role in community water supply. The

significance of groundwater, especially in areas adjacent to landfill sites, was emphasised by Shiru et al. (2020), indicating potential environmental and health concerns.

Active stakeholder participation is fundamental to any water project. An integral component of the selected literature for this review was the extensive use of questionnaires to understand the perspectives of local communities, a strategy predominantly employed by Popoola et al. (2021) and Olajuyigbe (2016). These grassroots insights, gathered from a wide spectrum of respondents, provide a detailed understanding of localised water challenges and underscore the pivotal role community engagement plays in the success of water projects. On a broader scale, Andres et al. utilised the 2015 Nigeria National Water and Sanitation Survey to identify patterns in the failure of water initiatives across Nigeria (Andres et al., 2018b).

Following this overview, the subsequent sections delve deeper into the myriad factors influencing the functionality and sustainability of these diverse water infrastructure assets.

2.3.2. Factors Contributing to Water Infrastructure Failure in Nigeria

This systematic literature review provides a comprehensive understanding of the multitude of factors contributing to water infrastructure failure in Nigeria. Based on the analysis of the 15 selected studies, these influential factors are methodically divided into technical, financial, environmental, social, political, institutional factors, and "other". The factors are further categorised into 52 distinct themes. A consolidated summary of these themes and the associated issues identified across the reviewed studies is provided in Table A1.5 in Appendix 1. In total, 265 issues influencing the sustainability of water infrastructure in Nigeria were identified, and their distribution across the major categories is summarised in Figure 2-3.

Among the identified issues, the technical factor holds the highest proportion with 59 issues (22.3%) spread across 11 themes. Institutional factors account for 56 issues (21.1%) categorised under nine themes. Social factors contain 48 issues (18.1%) falling under nine themes, while financial factors contribute 37 issues (14%) distributed among

six themes. Political factors, representing five themes, account for 32 issues (12.1%). Environmental factors, allocated into seven themes, encompass 22 issues (8.3%). Lastly, the category labelled "Other" captures 11 issues (4.2%) that could not be neatly placed within the six principal categories and is separated into five unique themes.

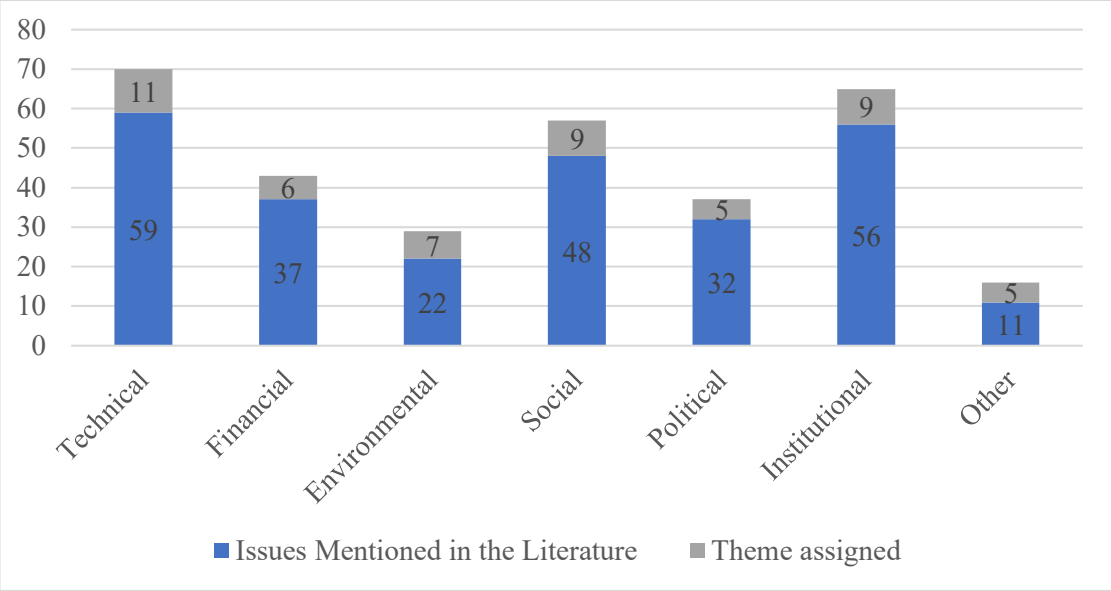


Figure 2-3: Overview of Issue Counts and Thematic Categories of Factors Contributing to Water Infrastructure Failure - A Synthesis from 15 Selected Publications

In the subsequent sections, each factor will be explored in detail, providing a comprehensive understanding of the complex challenges confronting water infrastructure functionality and sustainability in Nigeria.

2.3.3. Technical Factors

The review identifies a total of 59 issues under the technical factors contributing to water infrastructure functionality in Nigeria. These factors are grouped into eleven categories. The categorisation and count of the technical issues are shown in Figure 2-4.

The most frequently occurring category, with ten instances (17%), is related to the *"Deterioration of Infrastructure"*. It encompasses aspects like systemic malfunctioning

(Adeniran et al., 2021), aging water schemes, and poor infrastructure development and management (Adeniran et al., 2021; Otun et al., 2011), among others.

"Poor Material and Construction Practices", occurring four times (7%), involve instances of poor workmanship (Oyekale & Ogunsanya, 2012), poor construction materials, (Popoola et al., 2021), and design failures (Oloruntade et al., 2014).

Nine instances (15%) pertain to *"Poor Operation and Maintenance".* This category includes issues such as lack of preventive maintenance knowledge (Khan et al., 2018), poor maintenance of water sources (Popoola et al., 2021), and technical issues related to management (Andres et al., 2018a).

Six instances (10%) were identified related to the *"Choice of Technology and Equipment"*, emphasising the importance of the technological dimension (Adeoti, 2008; Andres et al., 2018b), equipment failure (Andres et al., 2018a), and the wrong choice of pump types (Khan et al., 2018).

"Water Supply Issues" were identified five times (8%), covering topics like groundwater overdraft (Shiru et al., 2020), uneven water distribution (Shiru et al., 2020), and shallow wells that cannot provide an all-year-round water supply (Oloruntade et al., 2014).

"Spare Parts Availability and Quality" were raised seven times (12%), focusing on the availability and quality of spare parts and supplies (Andres et al., 2018a; Khan et al., 2018; Otun et al., 2011).

The *"Impact of External Factors",* like vandalism impacting water infrastructure, leading to technical challenges, contamination, and lack of electricity, was reported five times (8%) (Andres et al., 2018a; Khan et al., 2018; Shiru et al., 2020).

Three instances (5%) related to *"Overuse and Lack of Proper Planning"* were identified, including exceeding the intended use of the infrastructure (Andres et al., 2018a) and wear and tear due to aging (Oloruntade et al., 2014).

"Inadequate Knowledge and Resources", such as poor knowledge of the Nigerian geological terrain and non-existent literature on water infrastructure functionality (Andres

et al., 2018a), and large maintenance backlogs (Otun et al., 2011), were highlighted six times (10%).

"Specific Technology Issues", like the functionality of manual pumps versus hand pumps and pump failures (Oloruntade et al., 2014), were reported three times (5%).

Lastly, there was one instance (2%) of *"Infrastructure Collapse"* due to poor drilling (Popoola et al., 2021).

In summary, technical factors constitute a substantial proportion of the identified challenges, highlighting the need for technical capacity building, improved practices, and better management of water infrastructure in Nigeria.

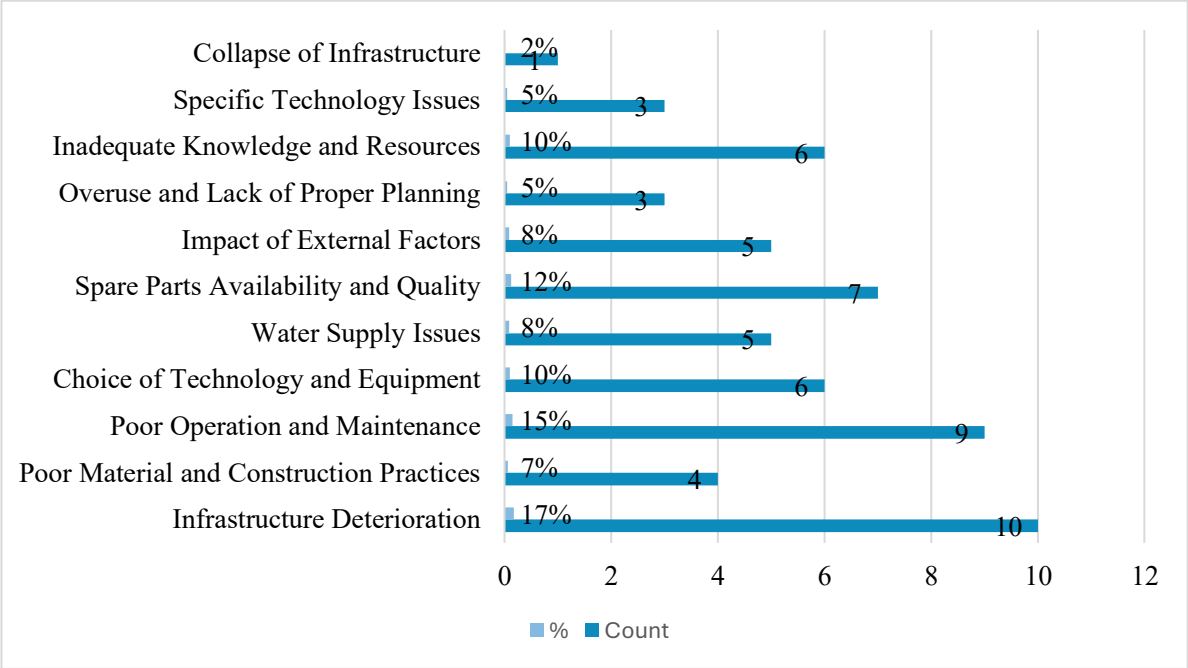


Figure 2-4: Distribution of Identified Technical Factors Impacting Water Infrastructure Functionality in Nigeria

2.3.4. Financial Factors

The analysis identifies 37 issues pertaining to the financial factors affecting water infrastructure functionality in Nigeria, classified into six main groups. The distribution of these factors is shown in Figure 2-5.

The most frequently mentioned category, with 8 instances (22%), accounts for issues related to the *"Cost of Infrastructure and Maintenance"*. This category captures increased costs of water production and distribution due to power supply issues (Shiru et al., 2020), the high cost of laying pipes to rural communities (Adeoti, 2008), the cost of maintenance (Andres et al., 2018a), and the substantial cost of solar panels, making it difficult for communities to afford repairs (Oloruntade et al., 2014).

The second category, *"Insufficient Funding/Budget Allocation",* identified in 7 instances (19%), discusses challenges around infrastructure financing, dwindling finances, and deprioritising Water Supply (Adeniran et al., 2021), as well as insufficient funding (Oyegoke et al., 2012) and decrease in the total budgetary allocation for water supply (Adeoti, 2008).

"User Fees and Willingness to Pay" is the third category with 7 instances (19%), addressing issues such as the absence of user fee collection (Andres et al., 2018b), inability to pay for water (Popoola et al., 2021), and users' unwillingness to pay charges (Khan et al., 2018).

The fourth category is *"Government Funding and Allocation",* highlighted in 5 instances (14%). This category includes issues such as the type of funding organisation, absence of fund allocations from the state or local government (Khan et al., 2018), and unsustainable public sector spending (Ugwu et al., 2022).

"Household Income and Poverty" has been listed 6 times (16%), focusing on issues such as increased household expenses in purchasing potable water (Popoola et al., 2021), community members' inability to meet full financial responsibility (Olajuyigbe, 2016), and the lack of financial means to connect to government water services (Oyekale & Ogunsanya, 2012).

Finally, *"External Funding"* was discussed in 4 instances (11%), including points such as lack of infrastructure facilities due to funding (Andres et al., 2018b), dependence on communities for financial responsibility (Emmanuel & Bamidele, 2013), and inefficient use of over 3 billion dollars in funds (Otun et al., 2011).

Overall, the financial aspects of maintaining functional water infrastructure are multifaceted, involving a complex mix of user fees, government spending, external funding, and the socioeconomic status of the households that ultimately depend on these services

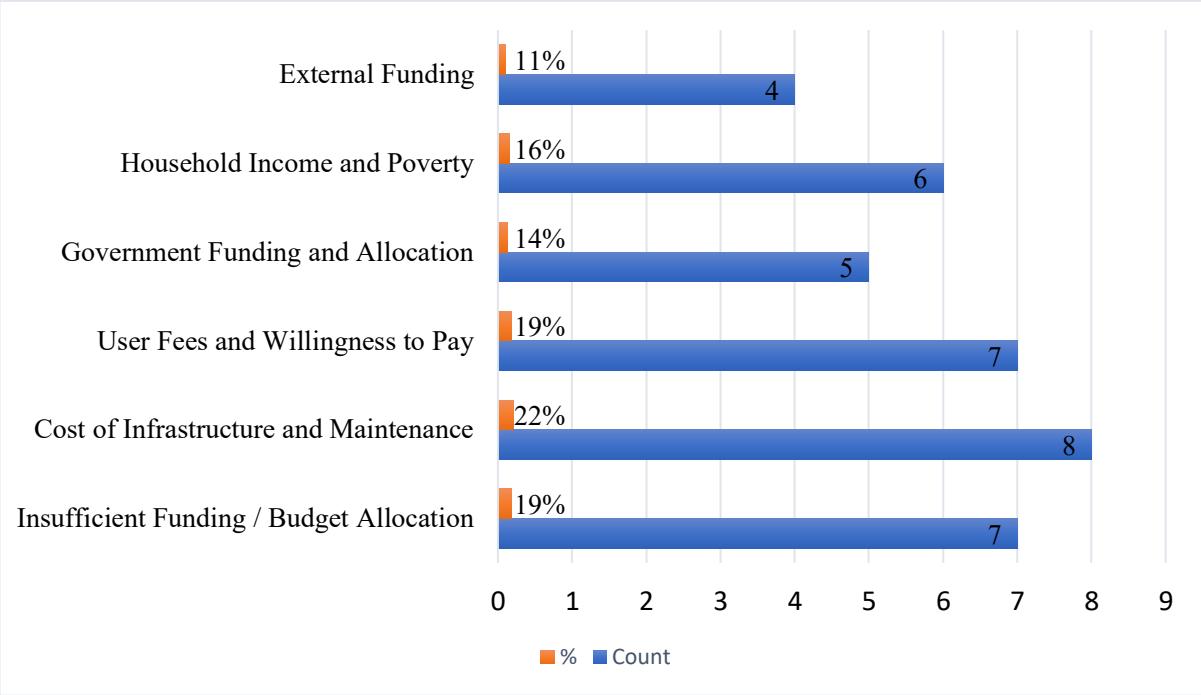


Figure 2-5: Distribution of Identified Financial Factors Impacting Water Infrastructure Functionality in Nigeria.

2.3.5. Environmental Factor

This review identifies 22 environmental issues that influence the functionality of water infrastructure in Nigeria, organised into seven key categories. The distribution of these issues across the reviewed literature is shown in Figure 2-6.

The most frequently discussed issue, featured in five instances (23%), pertains to *"Hydrogeology"*. It includes factors like sparse geographical locations of villages, morphological issues such as clay soil or rocky terrain (Popoola et al., 2021), the importance of hydrogeology to the functionality of water points (Andres et al., 2018b).

"Water Scarcity" and *"Climate Change Impacts"* were the next two prominent categories, each raised in four instances (18%) and addressing global water scarcity due to poor water management, increasing urbanisation (Popoola et al., 2021), climate change impacts on water resources (Shiru et al., 2020), and variability by climate zone (Cronk & Bartram, 2017).

Three issues (14%) fell under the *"Pollution"* category, exploring problems like environmental pollution and deforestation (Adeniran et al., 2021).

"Population Growth" was raised in two instances (9%), addressing the strain on water infrastructure due to population growth and internal migration (Oyegoke et al., 2012; Ugwu et al., 2022).

"*Insufficient Ground Water*" featured in two instances (9%), pertaining to decline in groundwater storage (Shiru et al., 2020) and insufficiency of the groundwater in the aquifer serving specific boreholes (Oloruntade et al., 2014).

Lastly, the category *"Drought"* was highlighted by two (9%) authors, emphasising issues related to drought's impact on water infrastructure (Adeniran et al., 2021; Oyekale & Ogunsanya, 2012).

Overall, environmental factors affecting water infrastructure in Nigeria are complicated, underscoring the need for comprehensive environmental management and protection measures in the planning and operation of water supply systems.

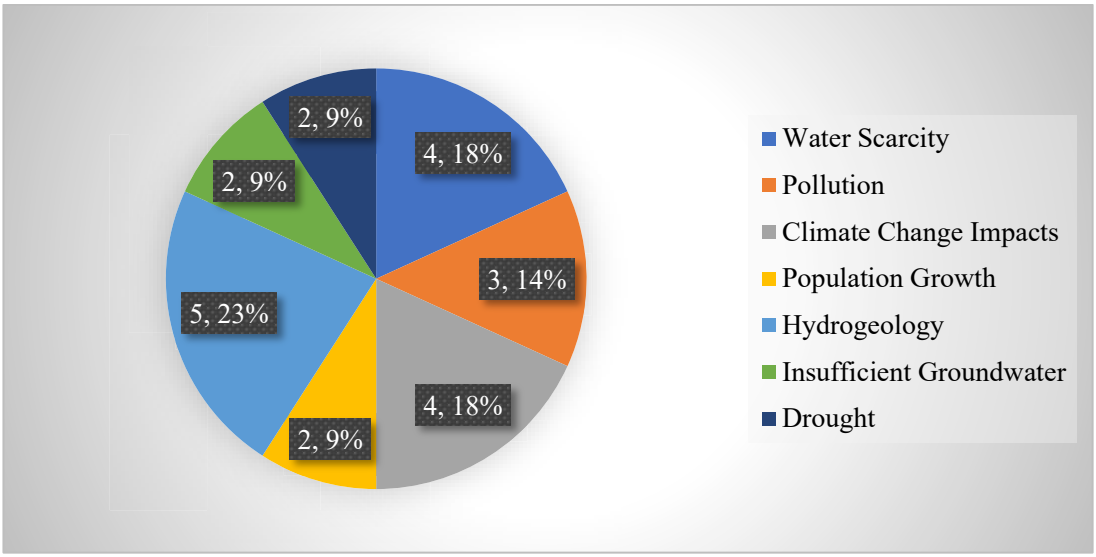


Figure 2-6: Distribution of Identified Environmental Factors Impacting Water Infrastructure Functionality in Nigeria.

2.3.6. Social Factor

The social factors influencing the functionality and sustainability of water infrastructure in Nigeria, as identified by the selected articles, are diverse and interconnected. 48 issues were identified in the studies, grouped into nine categories. Figure 2-7 shows the frequency and distribution of each social factor.

The most frequently cited category is *"Community Involvement",* with 13 instances (27%). This category includes issues like the neglect of rural water supply (Adeniran et al., 2021), low functionality with local management (Andres et al., 2018b), poor community cooperation (Popoola et al., 2021), and lack of public participation in water infrastructure management (Adeoti, 2008). It is apparent from this data that the level and quality of community involvement significantly impact the performance and sustainability of water infrastructures.

Another prevalent category is *"Population and Migration",* with eight mentions (17%). This category concerns the strain on water infrastructure due to population growth and internal migration, with a particular emphasis on issues in Lagos where the population continues to grow rapidly, causing an insurmountable water and environmental crisis (Adeniran et al., 2021; Andres et al., 2018a; Shiru et al., 2020).

"Socio-Economic Factors" also emerged as a significant category with ten instances (21%), encapsulating issues such as the influence of the household head's sex, education, and age on water access (Oyekale & Ogunsanya, 2012), as well as how socio-economic characteristics can affect the maintenance and sustainability of water schemes (Emmanuel & Bamidele, 2013).

The *"Ownership and Management"* category, highlighted in nine instances (19%), includes issues like the advantages of private sector management, the benefits of women in water committees (Andres et al., 2018b), and the importance of community organisation for system improvements (Cronk & Bartram, 2017).

Other categories with fewer instances include *"Rural-Urban Inequality", "Water Conflict", "Access to Water Sources", "Attitude and Corruption", and "Environmental Considerations"*. Despite their lower frequency, these factors still play a critical role in the overall picture of social determinants affecting water infrastructure functionality and sustainability. *Rural-Urban Inequality* describes the unequal water access in rural and urban areas. *Water Conflict* refers to disputes over water use and management. *Access to Water Sources* highlights the idea that social factors like community needs, usage patterns, and logistical constraints (like distance to the source and availability of water systems) can significantly influence water system functionality (Cronk & Bartram, 2017; Oyekale & Ogunsanya, 2012). *Attitude and Corruption* category refers to behavioural and socio-political issues like corruptive attitudes and tendencies (Otun et al., 2011) and theft of infrastructure parts. These issues highlight the importance of social engagement and attitudes in maintaining water infrastructure sustainability. *Environmental Considerations* involve the influence of environmental factors on social dynamics around water infrastructure.

Taken together, these results demonstrate the importance of considering a wide range of social factors in the planning, implementation, and management of water infrastructure projects in Nigeria.

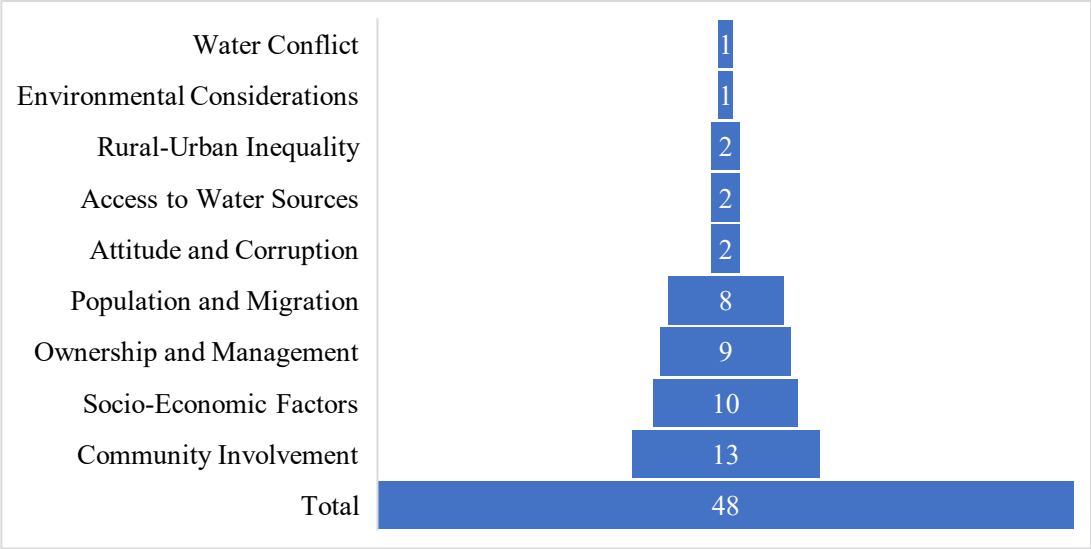


Figure 2-7: Distribution of Identified Social Factors Impacting Water Infrastructure Functionality in Nigeria

2.3.7. Political Factor

The political factors contributing to the failure of water infrastructure in Nigeria are complex and multifaceted, ranging from the politicisation of infrastructure projects to the lack of effective regulation and corruption. This review has identified a total of 32 issues related to the political factors, categorised into five broad themes. Figure 2-8 illustrates the frequency and proportion of each political factor.

The *"Government Commitment"* category emerged as the most frequent, with eight instances, contributing 25% to the overall political factors. Key issues in this category include the lack of government commitment to water infrastructure (Popoola et al., 2021), poor government attitude towards project continuity (Olajuyigbe, 2016), and the lack of political will to fix prevalent issues (Oyegoke et al., 2012).

"Geographical Politics", with eight mentions (25%), ties in frequency with the *"Government Commitment"* category. Issues under this category entail how geographical location, whether strategic or based on local government policies, impacts the access, availability, and functionality of water infrastructure (Andres et al., 2018a; Cronk & Bartram, 2017; Popoola et al., 2021).

"Policy Misalignment" and *"Political Instability"* were observed with six (19%) and five (16%) instances, respectively, indicating their notable influence. They cover issues like functional misfits at policy implementation levels and the instability arising from complex political structures (Adeniran et al., 2021).

Lastly, the *"Corruption & Noncompliance"* category, with five instances (16%), covers issues such as substantial increases in executive corruption and lack of accountability (Oyekale & Ogunsanya, 2012), and policy non-compliance (Ugwu et al., 2022). Despite its fewer instances, its role in shaping water infrastructure functionality should not be underestimated.

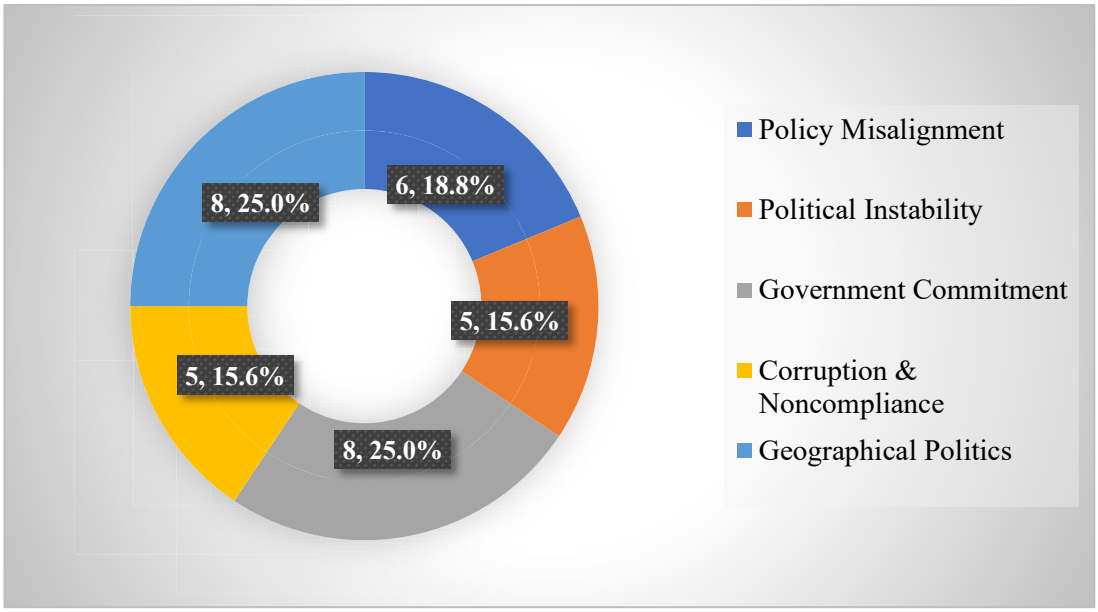


Figure 2-8: Distribution of Identified Political Factors Impacting Water Infrastructure Functionality in Nigeria

2.3.8. Institutional Factors

The review identified a total of 56 issues falling under the umbrella of Institutional Factors contributing to the functionality of water infrastructure in Nigeria, categorised into nine categories. Figure 2-9 depicts the frequency of each category.

The most prevalent category, with 10 instances (18%), pertains to *"Infrastructure Planning and Management."* This category covers various concerns such as decentralisation of infrastructure types (Adeniran et al., 2021), lack of thorough planning (Oyekale & Ogunsanya, 2012), infrastructural challenges due to ad hoc and unsustainable initiatives (Oyegoke et al., 2012), and poor service delivery coverage and performance (Otun et al., 2011).

The *"Policy and Regulation"* category, mentioned in 6 instances (11%), highlights the incomplete or unsustainable water infrastructure projects (Popoola et al., 2021) and the lack of clear policies and guidelines on operation and maintenance (Khan et al., 2018).

The *"Institutional Capacity"* category, found in 8 instances (14%), emphasises issues such as disjointed responsibility (Ugwu et al., 2022), low institutional capacity (Otun et al., 2011), and the lack of availability of trained mechanics (Khan et al., 2018).

The *"Monitoring and Quality Control"* category, mentioned 7 times (13%), addresses inadequate monitoring of water-related projects, poor quality control (Oyegoke et al., 2012), and inefficient monitoring systems (Andres et al., 2018a).

"Community Engagement and *Transparency"* is another significant category, highlighted in 6 instances (11%), stressing community participation in water programs (Olajuyigbe, 2016) and poor government motivation (Oloruntade et al., 2014).

"Corruption and mismanagement" category, with 7 instances (13%), includes issues such as substantial increases in executive corruption (Ugwu et al., 2022) and lack of accountability (Andres et al., 2018a).

The *"Resource Allocation"* and *"Definition and Research"* categories, appearing in 6 (11%) and 2 (4%) instances, respectively, encapsulate issues ranging from state spatial inequalities due to investment (Adeniran et al., 2021) to the lack of a widely agreed-upon definition for water infrastructure and sustainability functionality (Andres et al., 2018b).

Lastly, the *"Overarching Problems"* category, with 4 instances (7%), underlines broad issues like modernisation and urbanisation leading to the neglect of rural areas (Popoola et al., 2021).

In summary, these findings underscore the multifaceted nature of institutional factors impacting water infrastructure functionality in Nigeria, necessitating comprehensive institutional reforms to address these challenges.

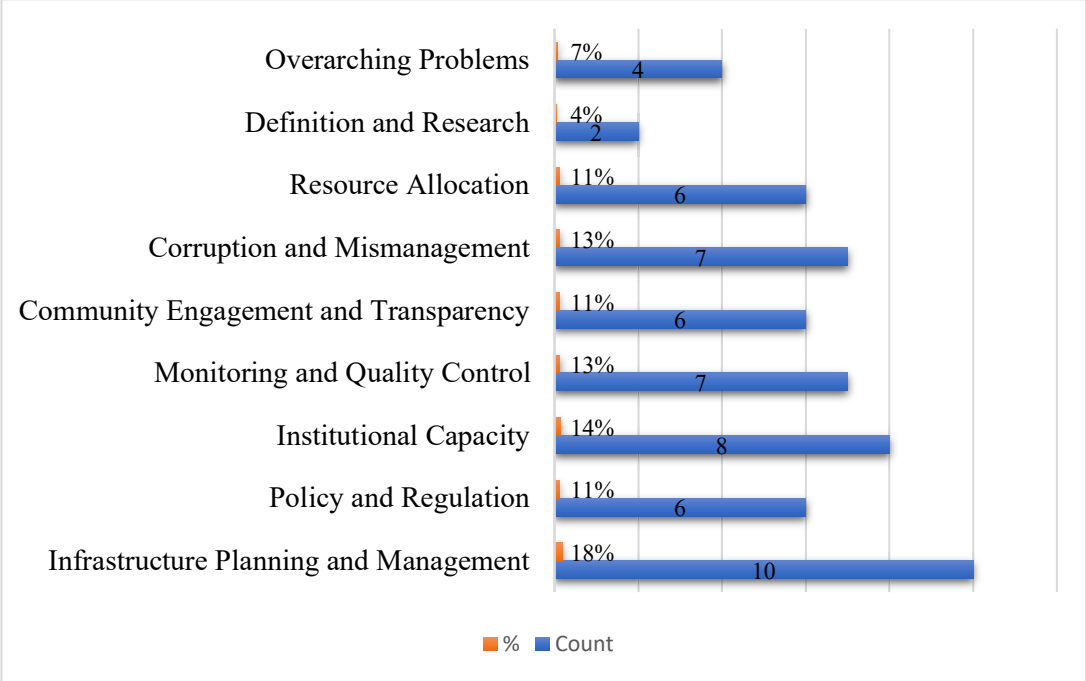


Figure 2-9: Distribution of Identified Institutional Factors Impacting Water Infrastructure Functionality in Nigeria

2.3.9. Other Factors

The review categorises 11 issues as "Other Factors" that affect the functionality of Nigeria's water infrastructure. These factors, which do not fit neatly into the conventional categories of technical, financial, environmental, social, institutional, or political, are grouped into five distinct themes. Geographical factors, accounting for 5 out of 11 instances (45%), concern distance challenges, such as proximity to administrative centres and water sources (Adeoti, 2008; Andres et al., 2018b; Cronk & Bartram, 2017; Popoola et al., 2021). Vandalism/Theft, making up 3 out of 11 (27%), denotes concerns like damage and theft of infrastructure (Oloruntade et al., 2014). Demographic and Age Factors, both at 1 out of 11 (9%), touch on the influence of population growth and

household head age on financial contributions (Adeoti, 2008). Lastly, Methodological Factors, at 1 out of 11 (9%), reflect on the approaches used by certain developers and a deficiency in thorough feasibility studies (Olajuyigbe, 2016). Collectively, these highlight the intricate challenges facing Nigeria's water infrastructure, underscoring the need for multifaceted solutions. Figure 2-10 illustrates the count of issues assigned to each theme within the "Other Factors" category.

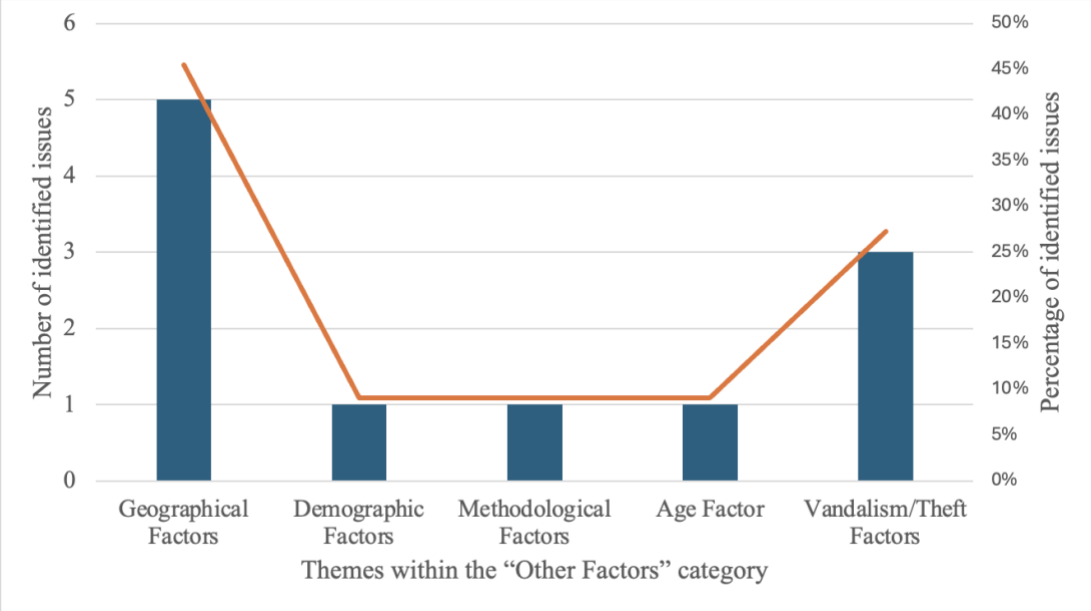


Figure 2-10: Breakdown of Identified "Other Factors" Influencing the Functionality of Water Infrastructure in Nigeria

2.3.10. Theoretical Frameworks, Methodology and Empirical Findings of Selected Studies

2.3.10.1. Theoretical Frameworks of Selected Studies

In the evaluation of 15 selected articles on water infrastructure sustainability in Nigeria, varied theoretical approaches are evident. Only one article provides a clear theoretical framework, necessitating an inference on the rest based on content and methodology. Adeniran et al. (2021) and others gravitate towards the Integrated Water Resources Management (IWRM) framework, stressing the interplay of several factors affecting water resources. Andres et al. (2018b) utilise data-driven analyses, though the

underpinning theoretical model isn't explicitly mentioned. Popoola et al. (2021) and Olajuyigbe (2016) lean towards socio-ecological methods, with the latter specifying the Community Management Model (CMM). Oyegoke et al. (2012) adopt a systems theory perspective, understanding the many interconnected issues in water supply. Both Ugwu et al. (2022) and Adeoti (2008) weave economic and socio-economic considerations into their works. Andres et al. (2018a) and Cronk and Bartram (2017) use advanced econometrics, inferred from their methodologies. Perspectives of community participation, decentralised management, and asset management emerge from Emmanuel and Bamidele (2013), Khan et al. (2018), and Otun et al. (2011). In summary, although most articles don't explicitly mention their theoretical approaches, the diverse methods deduced underscore the complexity of understanding water infrastructure sustainability in Nigeria.

2.3.10.2. Methodology of Selected Studies

Various methodologies were employed across the analysed articles, encompassing qualitative, quantitative, and mixed methods designs. Quantitative methodologies were used in 7 articles (47%), utilising statistical techniques to analyse data. Four studies adopted mixed methods (27%), combining quantitative and qualitative techniques to offer a comprehensive perspective. Additionally, two articles employed a qualitative approach (13%), providing in-depth insights into the subject matter. However, in two articles (13%), namely Oyegoke et al. (2012) and Khan et al. (2018), the methodology was not explicitly stated. Nevertheless, Khan et al. (2018) provided a detailed account of their approach implementation. This diverse array of methodologies, often aligned with each article's theoretical framework, enriches the understanding of Nigeria's water infrastructure sustainability.

2.3.10.3. Empirical Findings of Selected Studies

The reviewed articles on water infrastructure sustainability in Nigeria present a diverse set of empirical findings that illuminate the complexity of access, functionality, and long-

term service provision. These findings highlight issues ranging from household-level access and participation, through design and management influences on functionality, to broader challenges of urbanisation, climate variability, and governance. A detailed study-by-study summary is provided in Appendix 1, Table A1.3 for ease of reference.

Overall, the evidence underscores the multifaceted challenges of sustaining water infrastructure in Nigeria and points to the need for continued investigation and more integrated approaches to intervention.

2.3.11. Evidence-Based Sustainable Solutions for Water Infrastructure in Nigeria

In this systematic literature review, the reviewed articles propose a wide array of solutions to address the complex issue of water infrastructure sustainability in Nigeria. These solutions encompass improvements in the design, implementation, and maintenance of water points, as well as increased community and government involvement. Additionally, better monitoring, funding, and strategic planning are identified as vital components for enhancing water infrastructure sustainability. Table A1.4 in Appendix 1 presents a summary of the proposed and implemented solutions discussed in each article.

The proposed solutions from the selected studies were systematically analysed and categorised under appropriate themes for quantitative assessment. The frequency of proposed solutions varied across the themes, indicating the research intensity within each topic.

"Technological Innovations and Infrastructure Optimisation" (15% of solutions): This theme proposes strategies such as appropriate extraction technology choice and the use of various modelling techniques to optimise water infrastructure utilisation (Adeniran et al., 2021; Andres et al., 2018b; Otun et al., 2011).

"*Financial Mechanisms, Monitoring, Funding, and Partnerships"* (11% of solutions): This theme advocates for increased private sector involvement, robust financial planning

within the Village Level Operation and Maintenance (VLOM) strategy, and proper monitoring of WASH projects (Khan et al., 2018; Oyegoke et al., 2012).

"*Environmental Management Strategies, Regulation and Policy Improvement"* (11% of solutions): This theme underscores the implementation of stricter regulations, integrated water resource management, and infrastructural development (Oyegoke et al., 2012; Shiru et al., 2020).

"Social Inclusiveness Approaches, Community Involvement and Education" (22% of solutions): This theme focuses on community involvement in water resource management, awareness programs for rural households, and adult education (Adeoti, 2008; Olajuyigbe, 2016; Oyekale & Ogunsanya, 2012).

"Institutional Reforms, Governance, Political Considerations, and Capacity Building" (22% of solutions): This theme suggests governmental intervention, understanding the political dimensions in water infrastructure, and implementing the VLOM strategy (Adeniran et al., 2021; Khan et al., 2018).

"Project Management Strategies" (11% of solutions): This theme calls for better project management, prioritising design, implementation, and operational stages (Andres et al., 2018a; Popoola et al., 2021).

"Strategic Planning and Flexibility" (7% of solutions): This theme emphasises flexible infrastructure development and data-driven decision-making (Adeniran et al., 2021; Cronk & Bartram, 2017).

Figure 2-11 is a Treemap chart that visually presents the various solutions for Nigeria's water infrastructure challenges, organised by theme. The size of each rectangle indicates the solution count per theme, making it easy to compare research intensity and identify potential gaps.

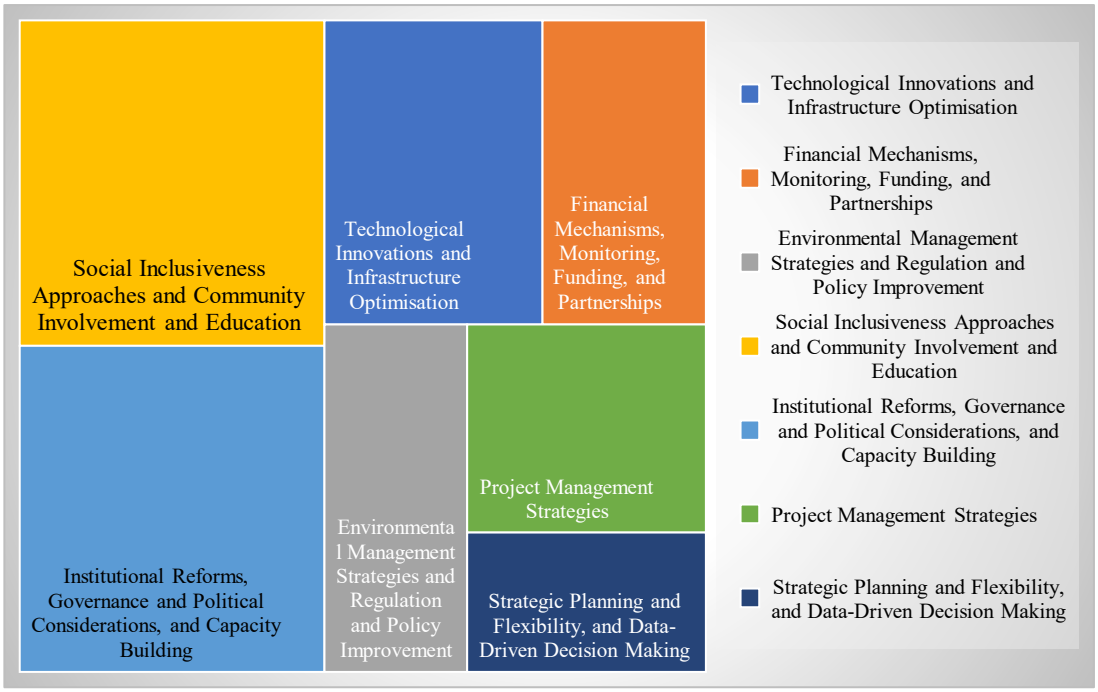


Figure 2-11: Distribution of proposed solutions for water infrastructure challenges in Nigeria

2.4. Discussion

Sustainability shortfalls emerge systemically. Technical performance depends on design quality, construction standards, and disciplined operations and maintenance, yet it endures only when institutional arrangements reliably finance maintenance, enforce standards, maintain supply chains, and assign clear accountability for service levels. The distribution of issues across domains indicates that sustainability is a life cycle property arising from decisions taken before, during, and after construction rather than from hardware choices alone. It also indicates that some pressures appear more immediate than others. Technical and institutional factors account for the largest shares of the issue distribution presented in Figure 2-3 and bear most directly on whether infrastructure can function, be maintained, and remain accountable over time. Financial and social factors are similarly consequential because they shape affordability, ownership, participation, and continued use. Political and environmental factors may appear less immediate in frequency terms, but they define the governance, regulatory, fiscal, and ecological conditions within which all other interventions operate. Priority

can therefore be sequenced, but sustainability cannot be secured through partial intervention.

Infrastructure failure emerges through the accumulation and interaction of weaknesses across the system. Environmental and social contexts shape how these constraints manifest; they rarely operate independently of technical and institutional conditions. Climate variability increases risks to assets and budgets, raising the value of resilient design, water-safety measures, and proactive asset management. Community participation, perceived quality and convenience, and affordability influence whether infrastructure is used and maintained as intended. Political direction sets priorities and allocates resources, and institutional capacity translates policy into execution; where roles are unclear or incentives weak, technical improvements are not sustained. Taken together, the evidence supports integrated, adaptive pathways that coordinate decisions across technical, financial, environmental, social, political, and institutional domains while responding to the distinct risks that vary by location, including hydrogeological conditions, settlement patterns, governance capacity, and local resource constraints.

The literature's theoretical intent is broadly integrative, but operationalisation is uneven. Quantitative designs dominate; limited qualitative work illuminates socio-political processes and implementation realities. Outcome definitions for functionality and sustainability vary, life cycle costing is often incomplete, and repeated or longitudinal performance data are scarce. These features reduce comparability and weaken inference about what works, making it difficult to trace cross-domain effects or to compare intervention pathways on common terms.

Proposed solutions are consistent with the multi-domain nature of the problem. Technological upgrades, stronger finance and governance, environmental risk management, community engagement and education, improved project management, and strategic planning form a coherent pathway when aligned. Their effectiveness depends on cross-domain alignment and on verification through routine measurement and post-implementation review. Recommendations should therefore be specified as coordinated packages and assessed against standardised measures of service, cost, and use.

Within the broader theme of technological innovations and infrastructure optimisation, decentralised options such as household-level rainwater tanks also warrant consideration. In principle, such systems can improve household storage, diversify supply, and reduce pressure on communal sources during periods of intermittent service. Their feasibility, however, is highly context-dependent. In the Nigerian settings examined in this review, household-level rainwater storage is constrained by rainfall seasonality, storage capacity, roof catchment conditions, household ability to finance and maintain tanks, and the water-quality risks associated with collection and storage where treatment is absent. These constraints mean that rainwater tanks are more credible as a supplementary measure within a mixed water-supply strategy than as a dependable standalone solution for year-round safe water access.

2.5. Summary and Synthesis

This systematic literature review expands the scope of water infrastructure challenges presented in Chapter 1. Using a PRISMA-based screening process, 15 empirical studies on water infrastructure in Nigeria were selected. The synthesis identified 265 distinct sustainability challenges, grouped into seven thematic categories: six core domains (technical, financial, environmental, social, political and institutional) and an additional "other" category for issues that did not fit neatly into these domains. These categories were mapped across the pre-construction, construction and post-construction stages

Across these studies, the review examined the theoretical frameworks, methodological approaches, empirical findings and proposed solutions. The findings provide a comprehensive theoretical understanding of the drivers of infrastructure failure and sustainability constraints in Nigeria's water sector, clarifying what has been achieved and where gaps persist in both academic research and industry practice. This evidence underpins the need for a transdisciplinary enquiry that can integrate engineering, financial, environmental, social, political and institutional perspectives into a coherent sustainability framework, aligned with the overarching aim of this thesis. However, while the review delineates the problem space in theory, it does not show how combinations of

these 265 challenges play out in specific communities or how they should inform concrete decisions about project siting, design, implementation and management.

Two main limitations constrain the practical utility of the existing evidence. First, a methodological approach suited to conducting such a transdisciplinary enquiry in the Nigerian context is essentially absent from the literature. Second, the evidence base is dominated by secondary and cross-sectional data and contains very limited longitudinal or system-level performance metrics. Consequently, the review cannot quantify how frequently the identified challenges occur in particular locations, how they interact in practice or how they combine to influence project outcomes over time.

Chapter 3 responds to these gaps by setting out the transdisciplinary, mixed-methods and multi-scale methodological approach used in the thesis to design and test the sustainability framework, including the core metrics, data sources and analytical strategies. Chapter 4 then extends the evidence base through standardised field diagnostics across 1,696 communities in Oyo, Osun and Ekiti States, combining technical assessment, GIS analysis and community engagement to quantify how the challenges identified in this chapter manifest in practice and to generate the context-specific variables that later underpin the thesis' predictive and planning tools.

Chapter 3: Methodology

The iterative research cycle described in this chapter is based on the following publication:

Adeoti, O. S., & Vigneswaran, S. (2024, December). Smart solutions – a Nigerian answer to access. *The Source*, (37), 32-35. thesourcemagazine.org/smart-solutions-a-nigerian-answer-to-access/

Overview

This chapter sets out the overarching methodological architecture of the thesis. It explains how a transdisciplinary, mixed-methods and multi-scale research design is configured to develop and test a context-specific, metric-driven framework for sustainable water infrastructure in Nigeria. It also positions the individual studies within an interdependent programme of enquiry, showing how evidence generated through systematic review, field diagnostics, predictive modelling, pilot implementation, behavioural analysis, and water-quality assessment is progressively assembled into the framework developed later in the thesis. The chapter first outlines the methodological orientation of the research, including the transdisciplinary stance, the iterative research cycle and the mixed-methods, multi-scale design. It then presents the theoretical framework that underpins the analysis and describes the primary and secondary data sources and data-collection procedures used across the empirical work.

The main analytical approaches are summarised, including descriptive and inferential statistics, equation-based modelling of the Viability Rating, Sustainability Rating and Self-Sustainability Rating, spatial and Geographic Information Systems (GIS) analysis, and qualitative techniques, followed by a brief account of ethical considerations. The chapter concludes with a discussion of methodological scope, limitations and contribution. Operational details of specific methods are presented in the chapters reporting each empirical study; the purpose of this chapter is to demonstrate how these components combine to form a coherent and integrated research design suited to the

technical, institutional, behavioural, environmental, and governance complexity of water infrastructure sustainability in Nigeria.

3.1. Methodological Orientation

3.1.1. Transdisciplinary and problem-driven stance

Chapter 1, Section 1.8 introduced the transdisciplinary methodological orientation adopted in this thesis in response to the complexity of water infrastructure sustainability in Nigeria. This chapter elaborates that orientation and establishes it as the organising principle guiding the research design.

Transdisciplinary approaches recognise that sustainability challenges require integration of diverse forms of knowledge and practice across disciplinary boundaries. Wickson et al. (2006) emphasise problem focused research in which academic researchers work collaboratively with those directly affected by the problem, including practitioners, decision makers and communities. Stokols (2006) and Robinson (2008) argue that transdisciplinary work is needed to address complex environmental and societal challenges and to link knowledge production with decision making and implementation. Bammer et al. (2020) further develop this position by formalising integration across disciplines, sectors and stakeholder perspectives as a core requirement for tackling real world problems.

In the context of water infrastructure, outcomes are shaped by the interaction of technical performance, institutional arrangements, financial viability, political context, social behaviour and environmental conditions (Adeoti et al., 2023). Reflecting this complexity, the thesis is organised around the practical problem of extreme water poverty and infrastructure failure and adopts an integrative research design that draws on multiple disciplinary theories and methods. Academic analysis, engineering practice, policy perspectives and community knowledge are integrated within this research design. The individual studies address sub research questions that interrogate specific dimensions of sustainability, including infrastructure failure patterns, pre-construction sustainability

and viability, smart water infrastructure performance, utilisation dynamics and groundwater quality and treatment feasibility. Together, these studies contribute evidence to address the overarching research question, which seeks to establish how a transdisciplinary sustainability framework can be developed and empirically validated to strengthen the planning, implementation, adaptive monitoring and long-term performance of water infrastructure in Nigeria.

3.1.2. Iterative Design and Integration

The transdisciplinary stance is operationalised through an iterative, three cycle design in which findings from one stage inform subsequent stages and, where necessary, reframe earlier assumptions:

- **Cycle 1:** identification and scoping of sustainability challenges through conceptual synthesis and empirical diagnostics
- **Cycle 2:** testing and operationalisation of potential solutions through implementation and structured monitoring
- **Cycle 3:** synthesis of accumulated learning into a framework that addresses pre-construction, construction and post-construction phases

This iterative stance is reflected in the thesis as a whole. Initial large scale diagnostics of water infrastructure sustainability across Nigerian communities (Adeoti et al., 2023, 2024b) informed subsequent modelling and piloting activities. An example of how these piloting activities operate within the cycle is detailed in Adeoti and Vigneswaran (2024). Empirical evidence from Cycle 1 contributed directly to the design of later stages and to the refinement of concepts and metrics across the thesis. Figure 3-1 illustrates this cycle of enquiry, showing how theoretical, empirical and experiential insights are continuously integrated and refined.

Integration across the thesis is achieved through shared sustainability concepts and evaluative criteria, which serve as common reference points for studies grounded in distinct theoretical frameworks and methodological choices. This structure enables triangulation of evidence and maintains coherence across the research design, while methodological specifics are elaborated in the chapters that present each empirical study.

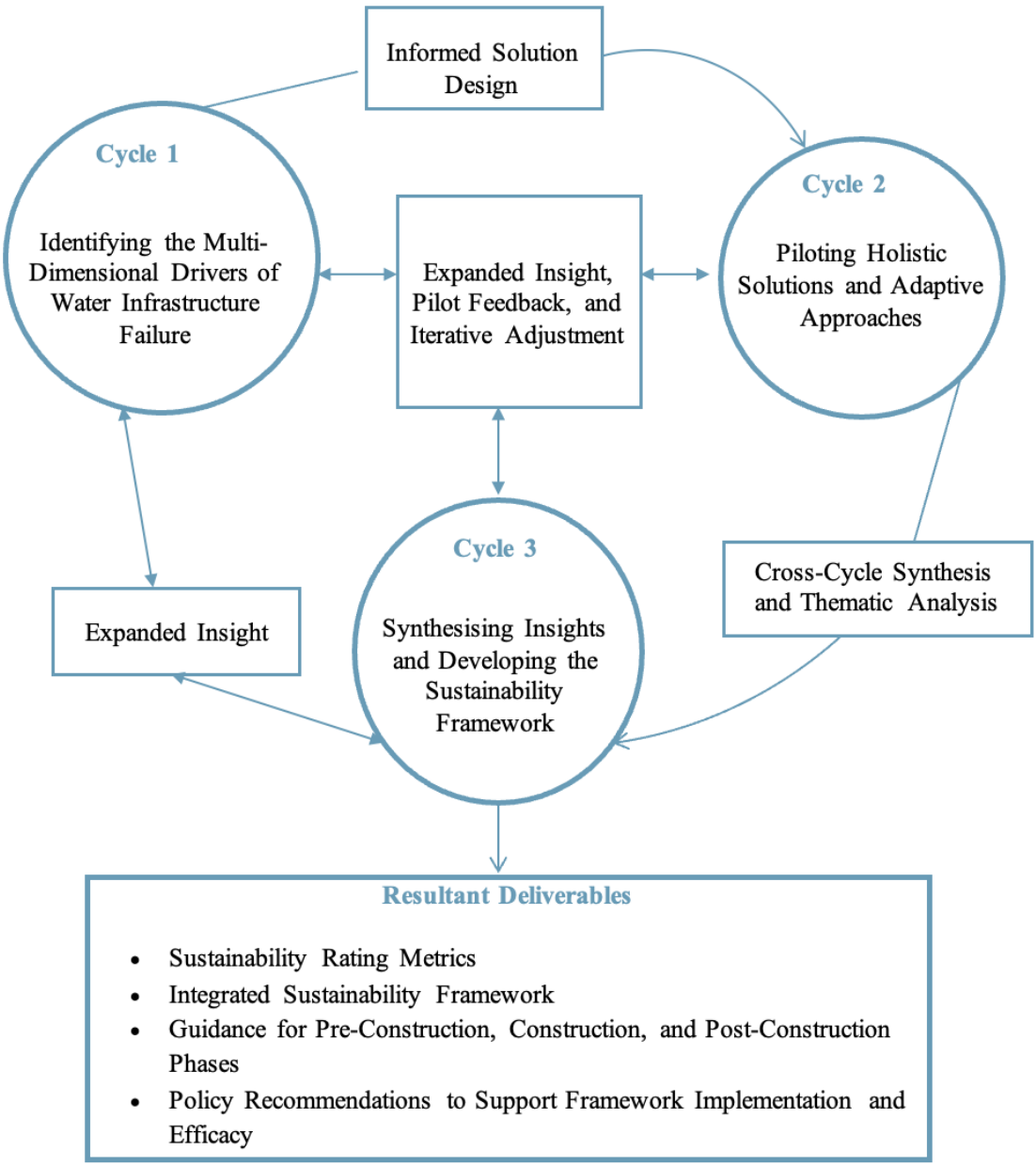


Figure 3-1: Iterative research and learning cycle underpinning the development of a transdisciplinary framework for sustainable water infrastructure in Nigeria.

3.1.3. Mixed-methods and multi-scale design

The transdisciplinary and iterative stance of the thesis is supported by a mixed methods research design applied across multiple spatial and temporal scales. Mixed methods approaches are widely used to address complex sustainability problems because they

integrate quantitative indicators with qualitative understanding of context (Plano Clark, 2017; Tashakkori & Teddlie, 2010). Applying these approaches across scales is consistent with work on social ecological and infrastructure systems that emphasises the importance of linking processes at household, community and broader governance levels (Cash et al., 2006; Ostrom, 2009). Quantitative and qualitative approaches are therefore combined in this thesis to capture both the measurable performance of water infrastructure and the contextual factors that shape its use, governance and sustainability.

Quantitative components include large scale diagnostics of borehole infrastructure across 1,696 communities in south western Nigeria (Adeoti et al., 2024b), structured household and community surveys that generate viability and sustainability metrics (Adeoti et al., 2024a) and characterise utilisation dynamics (Adeoti et al., 2025b), time series telemetry from smart water infrastructure providing longitudinal evidence on reliability, utilisation, non-revenue water and financial performance (Adeoti et al., 2025c), and laboratory based water quality measurements for public boreholes and smart water kiosks as detailed in Chapter 8. Together, these datasets generate numerical indicators of infrastructure performance, sustainability and compliance with drinking water standards.

Qualitative and contextual components include field observations, engagement with community members and local technicians, and practitioner reflections generated through the design, implementation and monitoring of pilot projects. These materials are used to interpret quantitative patterns, identify mechanisms that underpin observed failures or successes, and refine both the design of interventions and the specification of sustainability indicators.

The design is multi scale spatially and temporally. Spatially, data are collected and analysed at the level of individual water points and smart kiosks, households and communities, and across multiple local government areas and states. Temporally, the research combines cross sectional surveys and diagnostics with longitudinal monitoring, including 1,095 days of smart water kiosk telemetry and water quality sampling. This structure allows relationships to be examined between infrastructure level performance, household level behaviour, community level governance and broader patterns of

deprivation and service coverage. Detailed methodological procedures are presented in the chapters that report each empirical study.

3.2. Theoretical Framework

The development of the sustainability framework and associated metrics is informed by a set of complementary theoretical perspectives. These perspectives guide the selection of variables, the configuration of indicators and the interpretation of empirical findings across the thesis.

Systems thinking, as articulated by Meadows (2008), and complex adaptive systems perspectives (Chan, 2001; Holden, 2005) are used to conceptualise water infrastructure as part of a wider socio technical system in which technical, social, economic, institutional and environmental factors interact through feedback processes. This lens underpins the identification of multiple sustainability dimensions in the systematic review of water infrastructure sustainability in Nigeria (Adeoti et al., 2023) and the treatment of borehole and smart water infrastructure performance as emergent outcomes of interacting conditions rather than isolated technical defects (Adeoti et al., 2024a).

Ecological systems theory, drawing on Bronfenbrenner's work on nested environmental systems (Bronfenbrenner, 1979; Crawford, 2020), is used to emphasise contextual embeddedness, recognising that household and community behaviour is shaped by interacting settings, including family, community, institutional and broader policy environments. This perspective supports the design of the Predictive Iterative Sustainability Model, in which Viability Rating and Sustainability Rating draw on household level, community level and institutional level indicators (Adeoti et al., 2024b), and informs the interpretation of differences in performance and utilisation across communities exposed to similar infrastructure.

Behavioural and diffusion perspectives, particularly the Theory of Planned Behaviour (Ajzen, 1991; Ajzen & Schmidt, 2020) and diffusion of innovations theory (Kaminski, 2011; Sahin, 2006), inform the analysis of household decisions regarding source choice, willingness or ability to pay and adoption of smart water services. These perspectives

guide the specification of attitudinal, normative and perceived control variables in the household surveys and the interpretation of observed behavioural sequences, including preferences for nearby but unsafe sources and the underutilisation of monitored smart water kiosks, in the utilisation study (Adeoti et al., 2025b).

Water safety planning and risk based regulatory perspectives provide the foundation for the water quality and treatment component of the thesis. Building on World Health Organisation guidance that emphasises preventive, risk based management from catchment to consumer (Howard et al., 2020) and on analyses of determinants of water system performance (Cronk & Bartram, 2017), safe water provision is framed as a process of systematically identifying and controlling hazards along the supply chain. This framing guides the selection of parameters for groundwater quality assessment, the design of treatment pilots at smart water kiosks and the evaluation of the suitability of Nigerian Standard NIS 554:2015 and related regulatory instruments for low resource settings in Chapter 8.

Taken together, these theoretical perspectives provide the conceptual foundation for developing the transdisciplinary sustainability framework for water infrastructure in Nigeria. They guide the overall research design, including the enquiry into the overarching research question, the specification of sustainability and viability metrics, and the interpretation of evidence across the empirical chapters. The operationalisation of these perspectives, including the selection of concepts, indicators and analytical strategies, is presented in the methods and theoretical framework sections of the chapters reporting each empirical study.

3.3. Data sources and data collection

3.3.1. Primary and Secondary Data

The research draws on a combination of primary and secondary data assembled across multiple studies. Primary data include community and infrastructure diagnostics, household and community surveys, Internet of Things (IoT) monitoring and operational records from smart water infrastructure, and water quality measurements. Secondary data

include the systematic review evidence base, national and administrative datasets, and regulatory standards and guidelines. The main data sources, their purpose and key characteristics are summarised in Table 3-1, and detailed methodological procedures are presented in the chapters reporting each individual study.

Table 3-1: Summary of data sources used in the thesis

Data category	**Data type / source**	**Main purpose**	**Key features**	**Related outputs**
Primary	Community and infrastructure diagnostics across 1,696 communities in south western Nigeria	Characterise borehole functionality, failure trajectories, ownership and maintenance arrangements; relate infrastructure performance to deprivation and context	Structured field audits of public boreholes; functionality status; age; ownership; management; basic technical and contextual variables	Chapter 4 (Adeoti et al., 2024b)
Primary	Household and community surveys for PISM	Generate Viability Rating and Sustainability Rating for potential project locations; capture determinants of sustainability at multiple levels	Likert scale questionnaires on technical, financial, institutional, environmental and social dimensions at household and community level	Chapter 5 (Adeoti et al., 2024a)
Primary	Smart water infrastructure IoT data and	Assess reliability, utilisation, non-revenue water and	IoT based time series covering 1,095 days of kiosk operation;	Chapter 6

	operational records	financial performance of smart water kiosks over time	volumes dispensed; downtime and error events; sales and expenditure records	(Adeoti et al., 2025c)
Primary	Household survey and clinic data for utilisation study	Examine utilisation of smart water infrastructure and continued use of alternative sources; relate behaviour to health outcomes	Household survey on source choice, perceptions, willingness or ability to pay; clinic records on water related illness	Chapter 7 (Adeoti et al., 2025b)
Primary and secondary	Water quality data for public boreholes and smart water kiosks	Evaluate groundwater quality and performance of point source treatment at smart water kiosks	Five primary samples collected in the field and twelve sample results obtained from accredited laboratories; chemical, physical and microbiological parameters; used to assess compliance and treatment effectiveness	Chapter 8
Secondary	Systematic review evidence base	Identify sustainability challenges and existing approaches to water infrastructure in Nigeria	Peer-reviewed and grey literature synthesised to derive categories of sustainability challenges and existing practice	Chapter 2 (Adeoti et al., 2023)

Secondary	National and administrative datasets	Provide contextual indicators of poverty, population, health and service access	Official statistics and survey data used as background for interpreting infrastructure performance and utilisation patterns	Chapters 4–8
Secondary	Regulatory standards and policy documents (for example, NIS 554:2015, WHO guidelines)	Define compliance benchmarks for water quality and service standards; inform risk-based assessment	Nigerian Standard NIS 554:2015, World Health Organisation guidelines and related policy documents	Chapters 2 and 8

3.3.2. Smart water infrastructure pilots

Over the course of the research, five smart water infrastructures were designed, constructed and operated as pilot projects in different study areas. These pilots generated longitudinal, context-specific IoT and operational data and were used within the iterative research cycle to test and refine the emerging sustainability framework under real service conditions. Figure 3-2 presents images of the completed smart water infrastructures in the study communities, anonymised with all potentially identifying details removed in accordance with ethical requirements**.** In each case, the system functions as a practical intervention that responds to severe water poverty by providing continuous, monitored water services, while simultaneously operating as an embedded research platform through which infrastructure performance, utilisation patterns, behavioural responses and distributional outcomes can be measured and analysed. Their deployment grounds the methodological framework in real world practice and enables evaluation of the impacts of the solution on households and communities within a transdisciplinary enquiry.



Figure 3-2: Smart water infrastructure pilots.

3.4. Analytical approaches

3.4.1. Statistical, spatial, and qualitative analytical techniques

The analytical strategy used in this thesis is structured to support the transdisciplinary and iterative research design. It combines statistical, spatial and qualitative techniques to describe infrastructure conditions, test statistical relationships between key variables, and support interpretation across scales. Descriptive statistics are used to summarise the key characteristics of the data, providing an overview of the findings before more detailed inferential statistical modelling, including regression-based and other multivariate analyses, is undertaken.

Bivariate techniques, including correlation coefficients and related measures of association, are then used to examine relationships between determinants and outcomes, while regression and other multivariate models are applied where joint effects and

multivariable explanation are required. Spatial and Geographic Information Systems (GIS) analyses map the distribution of infrastructure, characterise service environments and support proximity-effect modelling, and time-series analysis of Internet of Things (IoT) data is used to evaluate reliability, utilisation and non-revenue water over 1,095 days of smart water kiosk operation. In the water-quality component, analyses of interrelationships among contaminants and simulation of proxy-based monitoring strategies assess the feasibility of simplified testing in resource-constrained settings. Qualitative material and practitioner insights are integrated to interpret quantitative findings, and methodological triangulation is used to compare and combine results from different methods and data sources.

3.4.2. Modelling and equation based analytical approaches

Modelling and equation-based analytical approaches are used to transform multidimensional, often qualitative sustainability constructs into quantitative and comparable metrics. The Predictive Iterative Sustainability Model (PISM) in Chapter 5, for example, converts Likert-scale survey responses and weighted factors into a Viability Rating (VR), which is then combined with predicted income and expenses to generate a Sustainability Rating (SR). Chapter 6 extends this approach by deriving Self-Sustainability Rating (SSR), Reliability Rating and related smart water infrastructure performance metrics from IoT-based time series of revenue water, non-revenue water, water credit and operating expenses. Chapter 7 applies logistic regression to quantify how spatial and behavioural variables influence household adoption, and Chapter 8 specifies rule-based proxy equations and correlation structures that translate detailed groundwater-quality results into simplified screening tools suitable for low-resource contexts. Details of these analytical approaches, including full equations, variable definitions, assumptions and diagnostic tests, are provided in the methodology sections of the empirical chapters where each model and technique is implemented, evaluated and reported.

3.5. Ethical considerations

Ethical oversight for the research was provided by the University of Technology Sydney Human Research Ethics Committee, with approval number UTS HREC REF NO. ETH23-7980**.** This approval covers all empirical components reported throughout the thesis. Informed consent, protection of privacy and secure data handling were maintained for all household, community, clinic and IoT data, and particular care was taken when working with water poor and vulnerable communities to ensure that participation did not compromise access to services.

The empirical work involved direct engagement with communities in southwestern Nigeria and the operation of smart water infrastructure in those settings. Study specific details of ethical procedures and community engagement relevant to data collection, analysis and interpretation are provided in the methodology sections of Chapters 4 to 8.

3.6. Methodological scope, limitations and contribution

The methodological choices outlined in this chapter reflect the need to balance conceptual rigour with empirical feasibility in water-poor, data-scarce settings. The empirical work is concentrated in communities in south-western Nigeria identified through large-scale diagnostics as suitable sites for implementing and monitoring smart water infrastructure. This focus is consistent with the central aim of the research, which is to develop and empirically validate a transdisciplinary framework for sustainable water infrastructure solutions in Nigeria. The framework is therefore most directly applicable to Nigerian settings and to contexts with similar socio economic and institutional conditions; use in other settings requires careful adaptation and local validation rather than direct transfer. At the same time, the methodological design is not confined to the specific study locations. It is organised around transferable components, including community diagnostics, viability assessment, pilot-based learning, longitudinal monitoring, and iterative refinement, that can be applied in other Nigerian regions provided they are recalibrated to local hydrogeological, socio-economic, institutional, and behavioural conditions. The south-western case studies thus serve as the empirical foundation for wider methodological adaptation.

Within this scope, some methodological constraints should be acknowledged. Sample sizes differ across the empirical components, and in situations where secondary data are required, comparable data are not always available with the same level of detail for all locations and variables. Financial and logistical constraints, including the high cost of collecting primary data, implementing and operating smart water infrastructure pilots, and undertaking certified laboratory analysis of water quality, limited the number of pilot sites and samples that could be included. These constraints are reported in the empirical chapters and are taken into account when assessing the strength and reach of the findings.

At the same time, the methodological approach represents a substantive contribution. It combines a coherent transdisciplinary approach, grounded in an integrated set of theoretical frameworks, with a novel iterative research cycle and a linked set of empirical studies across multiple scales and methods. Together, these elements create an integrated methodological configuration that, based on the available literature, has not previously been applied in the Nigerian water context. This configuration enables sustainability to be assessed using consistent quantitative metrics and qualitative evidence across different stages of the infrastructure life cycle, providing a robust, context specific basis for planning, implementing and monitoring sustainable water infrastructure solutions in Nigeria, and a structured foundation for adaptation in other settings. It also establishes the methodological architecture that links the empirical chapters that follow, bringing field diagnostics, predictive modelling, longitudinal monitoring, behavioural analysis, and water quality assessment within a single iterative research design.

Chapter 4: Field Diagnostics for Water Infrastructure Sustainability in Nigeria

This Chapter is based on the following Publication:

Adeoti, O. S., Kandasamy, J., & Vigneswaran, S. (2024b). Water infrastructure sustainability challenge in Nigeria: A detailed examination of infrastructure failures and potential solutions. *Water Supply*, *24*(6), 2066-2076.
https://doi.org/10.2166/ws.2024.127

Overview

This chapter extends the systematic review in Chapter 2 through a large-scale, context-specific field investigation of why and how systems fail in practice. Considering the widely reported non-functionality and financing and governance gaps, it operationalises the multi-domain drivers identified in the literature into empirical instruments that characterise local conditions, examine failure pathways, and generate evidence for planning and management.

Field diagnostics were conducted across 1,696 communities in three Nigerian states: Oyo, Osun and Ekiti. The investigation combines technical assessment of borehole condition, a classification of functionality status, records of service events, and targeted community engagement to document reasons for failure, maintenance practices and local constraints. Together, these data quantify cross-factor interactions and assemble a comparable record of infrastructure-failure patterns, their determinants and the structural conditions that undermine sustainability.

Drawing on this evidence, the chapter examines failure trajectories and uses the functionality status classification to reflect on-the-ground conditions. It assesses the alignment between the state-level multidimensional poverty index (MPI) and observed access, and considers technical and ownership factors associated with asset longevity.

The chapter contributes to the overarching research question and to the sub-research questions introduced in Chapter 1. It applies the functionality status taxonomy, documents asset histories and operations and maintenance (O&M) effectiveness, and classifies ownership and O&M responsibilities alongside community-reported challenges to examine how the factors that shape sustainability interact across the infrastructure life cycle. It deploys large-scale field diagnostics and focused community engagement to generate planning inputs for a sustainability framework, such as siting criteria, maintenance trigger points and ownership risk flags. It also establishes the empirical baseline, variable definitions and data structures that enable subsequent chapters to develop and validate sustainability metrics and adaptive management tools through pilot implementations.

4.1. 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 and 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 (WHO & UNICEF, 2019). Nigeria is emblematic of these challenges, with almost half of its water infrastructure non-functional (Andres et al., 2018a), 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., 2018a), with broad implications for community health and economic development (UNICEF & WHO, 2019).

This study extends the systematic review by Adeoti et al. (2023), which synthesised research on the sustainability of water infrastructure in Nigeria. In their review, Adeniran et al. (2021) addressed the aging challenges of boreholes, while Oyekale and 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 life cycle 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 analysing 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, this 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.

4.2. Methodology

4.2.1. Study Area

This study was conducted in the states of Oyo, Osun, and Ekiti, strategically chosen within Nigeria's South west. 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 prioritised 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 generalisability of its findings, a principle supported by Vasileiou et al. (2018).

Figure 4-1, 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.

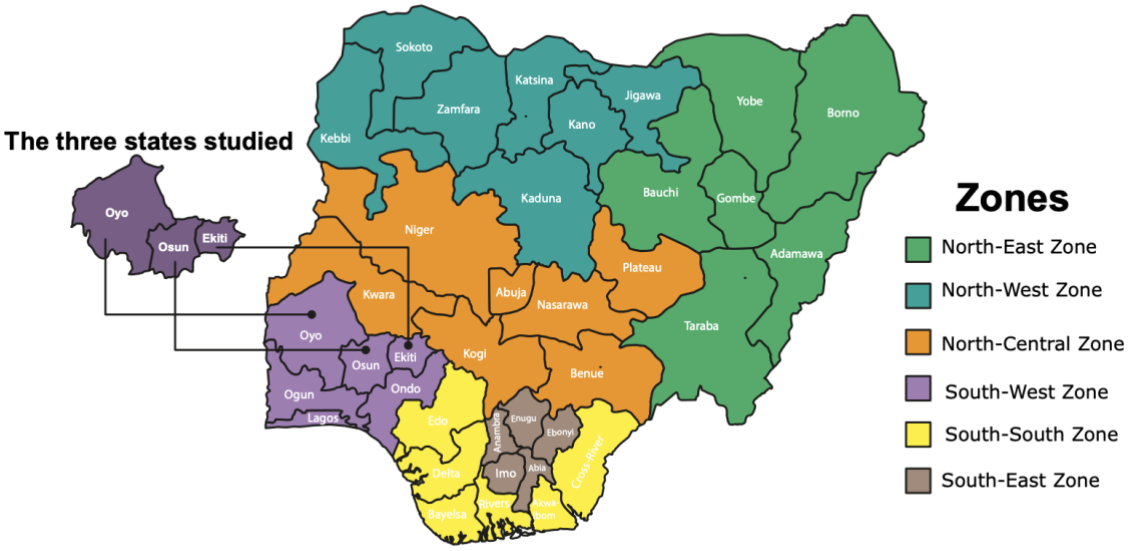


Figure 4-1: Map of Nigeria highlighting the three surveyed states.

4.2.2. 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.

4.2.2.1. 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 analysing water infrastructure challenges.

4.2.2.2. Data Analysis Approach

Borehole Functionality Trajectory Analysis: The evaluation of the failure trajectory utilised a sequential model to analyse the status progression of boreholes from fully

operational to completely abandoned. The analysis involved categorising 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 visualising 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 visualise and analyse 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 nonparametric 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 the Spearman's rank correlation coefficient formula:

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

where,

ρ = Spearman's rank correlation coefficient.

$\mathbf{d_i}$ = difference between two ranks of each observation.

n = no. of observations.

This calculation was integral to validating the observed spatial patterns and contributed to a statistically examination of the hypothesised 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 visualisation with Spearman's rho analysis and quantitative and qualitative technical assessments, provides, for the first time in Nigeria, 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.

4.3. Results and Discussion

4.3.1. Borehole Status and Functionality Assessment

Survey across 1,696 communities revealed that 844 (49.8%) lacked any improved water sources. Of the 852 public boreholes evaluated, 434 were functioning, while 418 were non-functional, with the functioning and failed categories summing to the full set of boreholes assessed. Boreholes were categorised 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 Figure 4-3, offering a comparative perspective of borehole functionality.

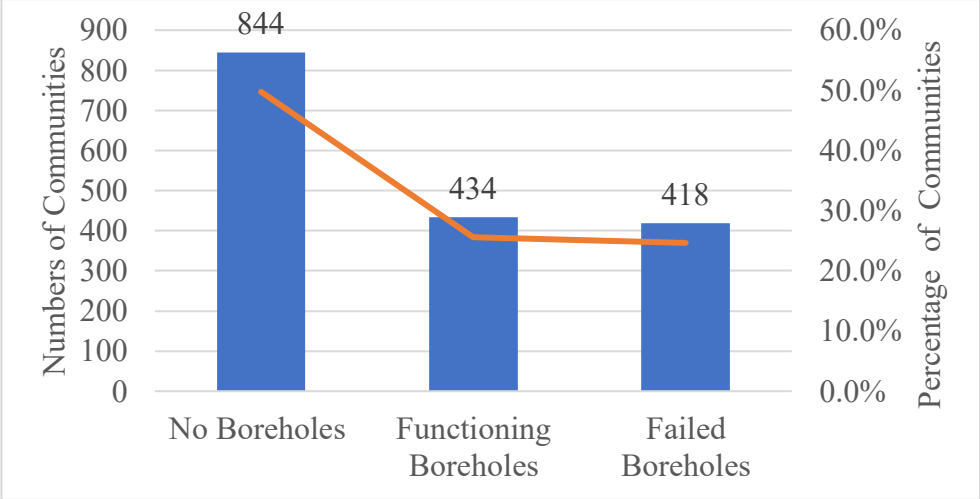


Figure 4-2: Status of Boreholes in the Surveyed Communities

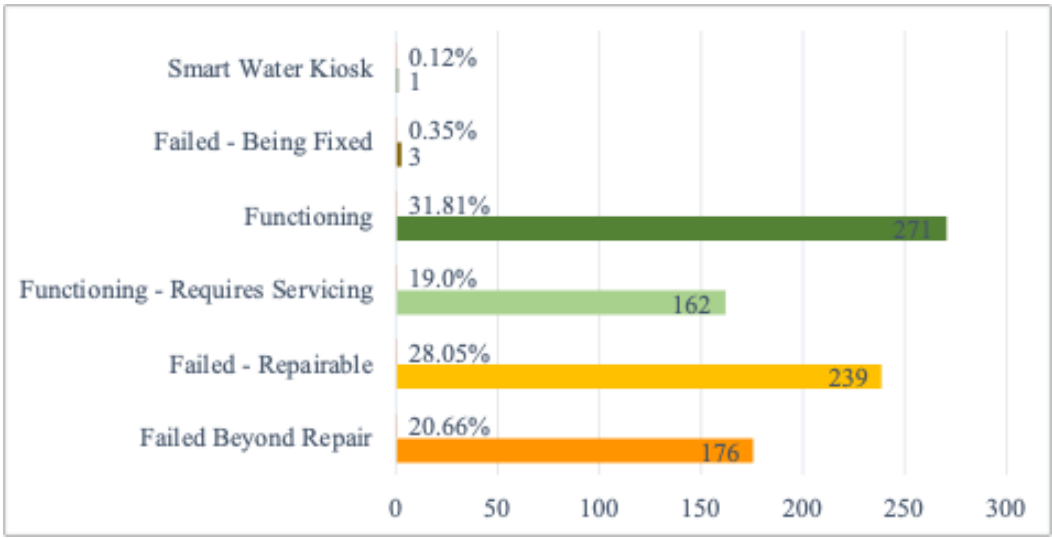


Figure 4-3: Borehole Statuses Report Across 1,696 Surveyed Communities.

4.3.2. Trajectory of Borehole Functionality

The research found a pattern in the borehole life cycle 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. The collected data reflect this alarming trend. Figure 4-4 presents the sequential failure trajectory, showing that boreholes in a repairable state that are not repaired, with only 3 (0.35%) actively under repair, often deteriorate to failure beyond repair due to prolonged delays in repair.

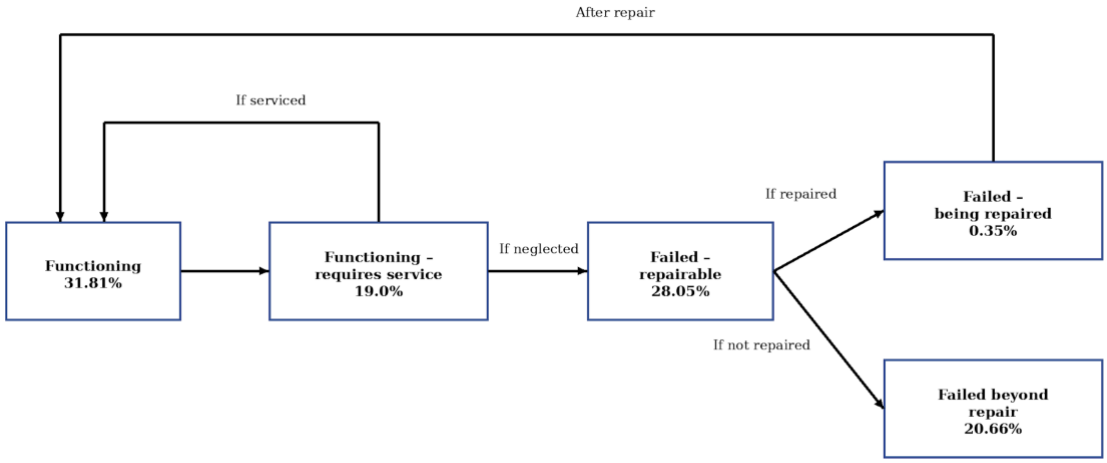


Figure 4-4: Trajectory of borehole functionality from full operation to total abandonment, showing possible deterioration and recovery states. Each box shows the observed proportion of assessed boreholes in that condition.

To avert this prevalent cycle of borehole failure illustrated in Figure 4-4, some strategic adaptations are recommended:

1. An institutional framework that prioritises sustainable water management and maintenance to facilitate repair and improve infrastructure longevity (Hassenforder & Barone, 2018).
2. A centralised data system with IoT integration for real-time monitoring and predictive maintenance, enhancing project efficacy and infrastructure durability (Ahmed et al., 2021; Barton et al., 2019).

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.

4.3.3. Assessment of Multidimensional Poverty Rates and Water Infrastructure Correlation

This section examines the relationship between state-level multidimensional poverty rates and the condition of water infrastructure and access within communities across the three surveyed states. Using GIS mapping and Spearman's rho, the analysis tests whether higher poverty rates correspond to more significant challenges in water infrastructure, as is often assumed.

4.3.3.1. GIS Analysis of Water Infrastructure Disparities Across the Surveyed States

Analysis of water infrastructure across Oyo, Osun, and Ekiti indicates that a lower Multidimensional Poverty Index (MPI) does not necessarily predict better water infrastructure conditions. As highlighted in Table 4-1, 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 the current study's scope, which concentrates on these three states to directly assess their correlation. The absence of comparable localised studies on infrastructure failure trajectories in other Nigerian states precludes direct comparisons, highlighting the unique contribution of this investigation. The findings are corroborated by a Spearman's rho test reported in Section 4.3.3.2, which evaluates the correlation strength between MPI and water access. This test helps evaluate the significance of the observations in this section.

Table 4-1: 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 (%)	Multi-dimensional 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

Figures 4-5, 4-6, and 4-7 provide colour-coded GIS representations of water-infrastructure status in Oyo, Osun, and Ekiti States, respectively, highlighting the spatial distribution of functional and non-functional boreholes. These visualisations illustrate infrastructural disparities and support understanding of the relationship between water access and poverty levels.

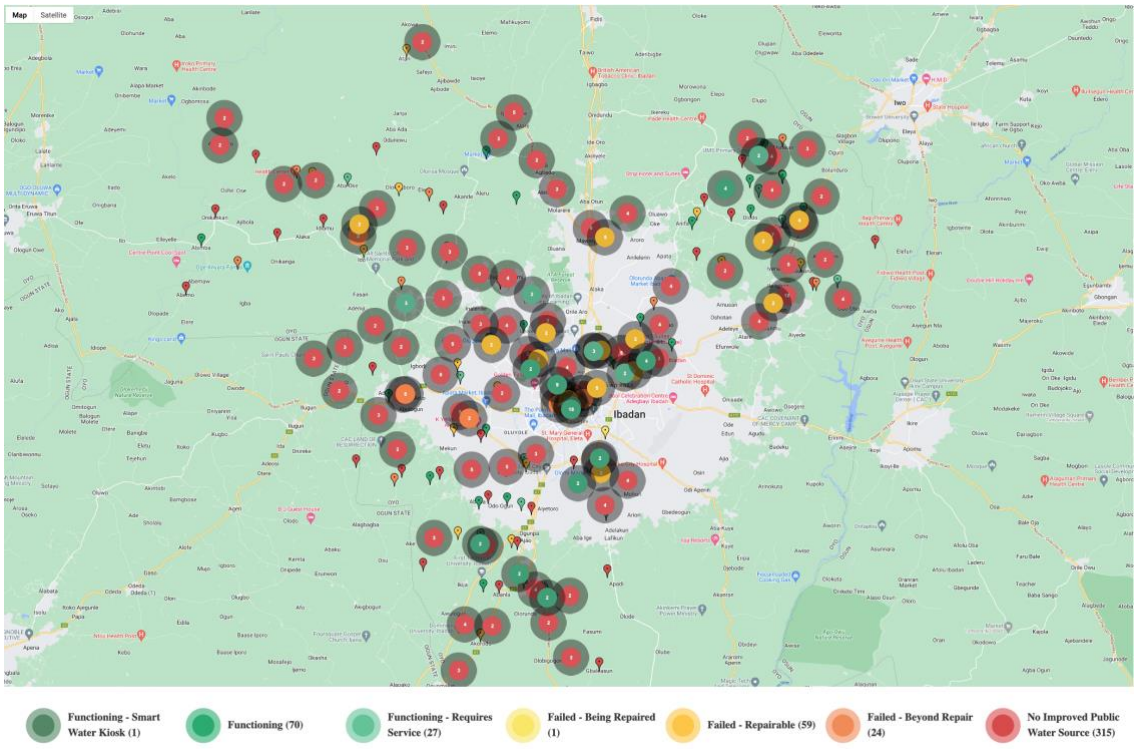


Figure 4-5: GIS Representation of Water Infrastructure Status in Oyo State

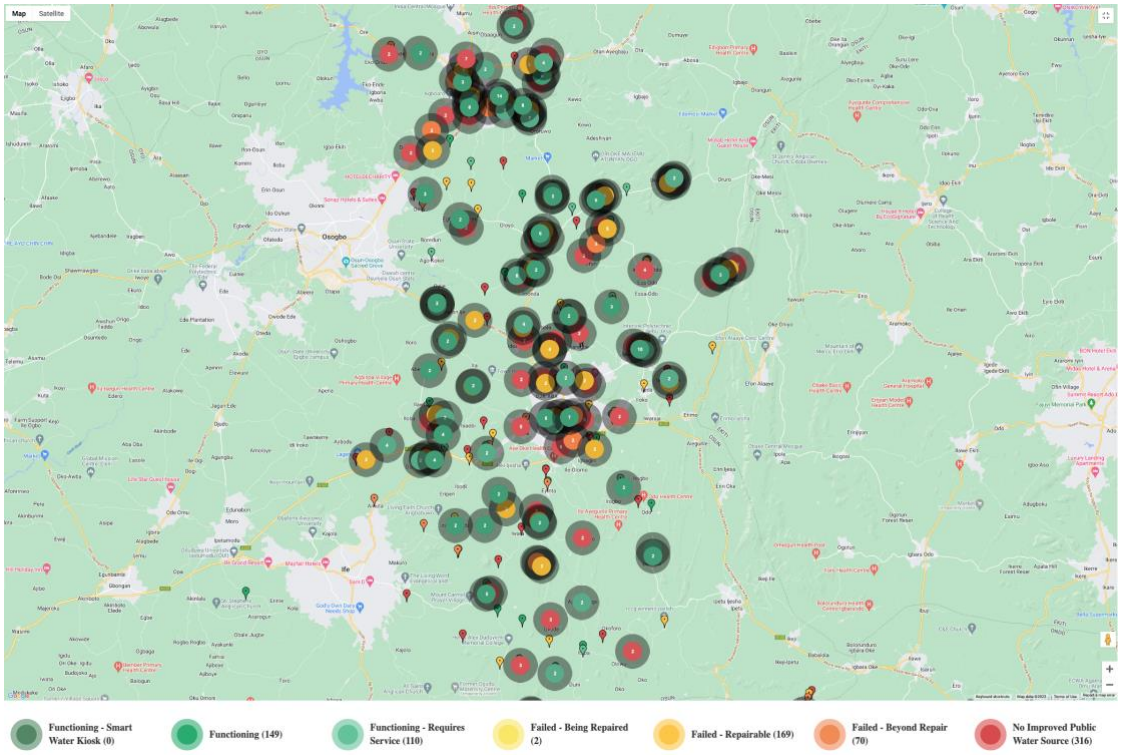


Figure 4-6: GIS Representation of Water Infrastructure Status in Osun state

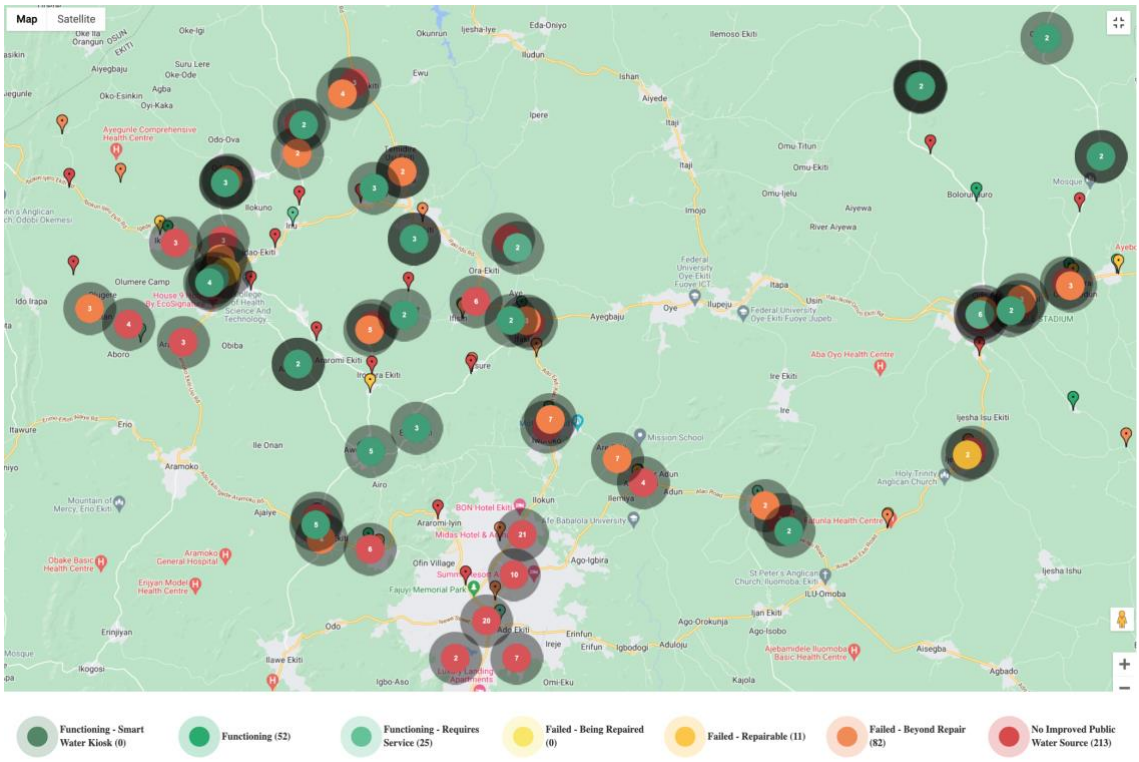


Figure 4-7: GIS Representation of Water Infrastructure Status in Ekiti state

4.3.3.2. Spearman's Rank Correlation Analysis

Following the data presented in Table 4-1, Table 4-2 aligns the ordinal rankings of water infrastructure functionality with the multidimensional poverty indices (MPI) 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.

The 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.

The 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.

Table 4-2: 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

Rank 1 represents the best scenario, while Rank 3 denotes the worst scenario.

Taken together, this assessment suggests that state-level poverty metrics are an incomplete guide to community water-infrastructure and deprivation conditions. Aggregation at state scale can mask substantial within-state heterogeneity and context-specific risks. Localised assessments, including community-level GIS mapping of functionality status (Figures 4-5, 4-6, and 4-7), provide a more fine-grained view of access conditions and failure patterns. Incorporating such local diagnostics alongside broader indicators may help align interventions and resource allocations with observed needs and constraints, and, in turn, support more effective and sustainable water-infrastructure planning.

4.3.4. Technical Reason for Borehole Failures and Material Implications

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

4.3.4.1. Technical Causes of Borehole Failure

Upon analysing 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 4-8, indicate specific areas that require targeted interventions to improve borehole functionality.

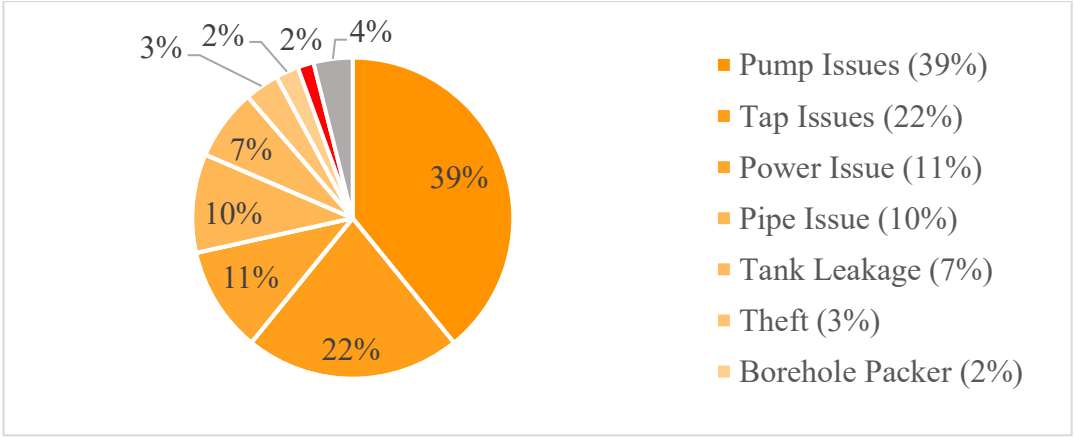


Figure 4-8: Technical Issues Causing Borehole Failures

4.3.4.2. 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 prioritising cost over quality has proven to be counterproductive, as evidenced by the high rate of component failures. Prioritising the procurement of higher-quality materials could significantly enhance the longevity and reliability of boreholes, ultimately contributing to sustainable water infrastructure development.

4.3.5. 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 (totalling seven) were functional, yielding 0% failure rate. However, the limited sample size of these categories necessitates caution in deriving broad conclusions. Table 4-3 presents functionality status by ownership category.

Table 4-3: Ownership and Borehole Functionality

Borehole Owners	Number of Boreholes	Functioning Boreholes	Failed Boreholes	Failure Rate
State Governments	281 (41.6%)	177 (63%)	104 (37%)	37%
Federal Government	161 (23.8%)	94 (58.4%)	67 (41.6%)	41.6%
Politicians	74 (10.9%)	49 (66.2%)	25 (33.8%)	33.8%

Community Groups, Local Society, and Associations	62 (9.2%)	49 (79%)	13 (21%)	21%
Local Government	27 (4%)	14 (51.9%)	13 (48.1%)	48.1%
NGOs and Foundations	26 (3.8%)	16 (61.5%)	10 (38.5%)	38.5%
Private Sponsors	25 (3.7%)	16 (64%)	9 (36%)	36%
Schools and Health Centres	3 (0.4%)	3 (100%)	0 (0%)	0%
Church/Mosque	4 (0.6%)	4 (100%)	0 (0%)	0%
Owner Unknown	13 (2%)	12(93%)	1(8%)	8%

4.3.5.1. 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 underutilisation 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.

As shown in Figures 4-5 to 4-7, the GIS mapping of water-infrastructure status reinforces the need for government agencies and NGOs to ground installation and management decisions in local conditions, including water demand and community engagement. Adopting a community-centred approach to project conception and delivery may enhance borehole functionality and longevity and, in turn, support more reliable water access and security.

This requires more than consultation at the point of installation. Sustainability is more likely where community engagement is structured across the project life cycle and linked to local operational capacity. In practical terms, this includes involving users in site selection and service design, assigning clear local responsibilities for routine monitoring

and maintenance, training community members and local technicians to undertake basic repairs and fault reporting, and strengthening awareness of source protection, hygienic water handling, and the service implications of delayed maintenance. Such measures can reduce the interval between emerging defects and corrective action, while also improving the alignment between infrastructure design, local demand, and day-to-day management (Adeoti, 2008; Emmanuel & Bamidele, 2013; Khan et al., 2018; Oyekale & Ogunsanya, 2012).

4.4. Summary and Synthesis

This chapter completes the diagnostic component (Cycle 1) of the iterative research cycle outlined in Chapter 3. Building on the 265 challenges identified in Chapter 2, standardised field diagnostics were conducted across 1,696 communities in Oyo, Osun and Ekiti. The technical assessment showed that 49.8% of communities lacked an improved water source and that, among public boreholes, 28.05% had failed but were still repairable, while 20.66% had failed beyond repair.

A trajectory-based failure model demonstrated that progression from “failed but repairable” (28.05%) to “failed beyond repair” (20.66%), with only 0.35% of boreholes under repair, is driven by a lack of timely maintenance. The diagnostic pattern also shows that deterioration is not purely linear: where servicing or repair occurs, movement back towards functionality remains possible, but where intervention is delayed, repairable failure is more likely to progress into failure beyond repair and eventual abandonment. Ownership analysis indicated that community-owned projects were less likely to fail, with a 21% failure rate compared with 41.6%, 37%, 48.1% and 38.5% for federal, state, local government and NGO projects respectively. These patterns reflect the fact that community-owned schemes are more often installed in response to locally recognised needs, supporting utilisation and local responsibility, whereas schemes allocated primarily on the basis of state-level indicators, rather than community-level needs assessments, are more prone to underutilisation and neglect.

GIS mapping and Spearman’s rho analysis showed that the state-level multidimensional poverty index did not have a significant relationship with local community water poverty,

indicating that state-level poverty metrics are an incomplete guide to community-level water infrastructure deprivation.

In synthesising these findings, the chapter shows that sustainability outcomes are shaped by demand, affordability, governance, institutional arrangements, ownership and technical quality. Infrastructure failure emerges not as a single technical event, but as the cumulative outcome of weaknesses in planning, maintenance, institutional responsibility, and local fit. This evidence supports the concept of location viability, in which pre-construction assessment of community demand, willingness to pay, institutional responsibility and technical risk is central to predicting long-term functionality. The practical implication is that site selection, ownership structure, maintenance planning, and local operational capacity should be treated as core design variables from the outset of project development, rather than as secondary concerns to be addressed after construction**.** It also emphasises that sustainability should be treated as a life-cycle property shaped by decisions before, during and after construction.

However, the contribution here remains primarily diagnostic: it identifies where and why schemes fail and highlights key predictors of sustainability, but it does not yet translate these findings into a quantitative decision model with clearly defined indicators and thresholds for assessing location viability. The evidence generated in this chapter therefore provides the empirical bridge from descriptive failure analysis to the predictive planning model developed in Chapter 5. Chapter 5 addresses this gap by translating the 265 challenges identified in Chapter 2, along with the field diagnostic results from this chapter, into quantitative Viability Rating and Sustainability Rating measures within the Predictive Iterative Sustainability Model (PISM). Through this model, the thesis moves from descriptive diagnostics to a metric-based pre-construction framework designed to guide project location decisions and support iterative refinement of planning processes.

Chapter 5: Predictive Modelling for Water Infrastructure Sustainability Planning

This chapter is based on the following Publication:

Adeoti, O. S., Kandasamy, J., & Vigneswaran, S. (2024a). Sustainability framework for water infrastructure development in Nigeria: A modeling approach. *Water Supply*, *24*(8), 2933–2945. https://doi.org/10.2166/ws.2024.193

Overview:

This chapter develops the Predictive Iterative Sustainability Model (PISM) as a pre-construction decision tool that predicts and refines the sustainability performance of proposed water-infrastructure projects. It builds directly on Chapter 2, which identified 265 interrelated sustainability challenges, and on the Chapter 4 field diagnostics, which quantified failure trajectories across 1,696 communities. Together, these insights are translated into a quantitative modelling framework that supports evidence-based site selection, design optimisation, and maintenance planning within a transdisciplinary, life cycle sustainability framework.

PISM integrates theoretical and empirical elements from ecological systems theory, the theory of planned behaviour, and complex adaptive systems theory, linking community-level data with engineering and financial variables. It comprises two interdependent components joined by a predictive feedback loop. The Viability Rating (VR) provides pre-construction screening using measurable indicators of expected use, maintainability, and financial feasibility. The Sustainability Rating (SR) evaluates operational viability against recurrent costs, support mechanisms, and contextual risks. As performance data accumulate, the model recalibrates VR weights and decision thresholds, progressively enhancing predictive accuracy.

Through this modelling process, PISM transforms the descriptive diagnostics of earlier chapters into a replicable, data-driven framework capable of forecasting sustainability outcomes before construction and updating them through post-construction feedback. It

therefore represents the methodological bridge between empirical diagnostics and implementation, forming the analytical foundation for sustainability assurance across the infrastructure life cycle. By establishing predictive and adaptive mechanisms at the pre-construction stage, PISM ensures that construction decisions are grounded in measurable indicators of viability and long-term performance.

5.1. Introduction

The pursuit of safe and sustainable water supplies is a critical global challenge, affecting billions of people. Over 2.1 billion people worldwide lack access to safely managed drinking water, and 785 million lack basic water services, primarily in rural areas (Bain et al., 2014b; UNICEF & WHO, 2019). This highlights the urgency of achieving Sustainable Development Goal (SDG) 6.1, which calls for universal and equitable access to safe and affordable drinking water. Globally, the sustainability of water resources remains a pervasive challenge, with innovative methodologies emerging across various regions to enhance the predictability and sustainability of water infrastructure.

For instance, in Taiyuan, China, a region facing severe water shortages, researchers have developed a model using principal component analysis and a backpropagation neural network to predict water demand, outperforming traditional models (Wu et al., 2021). Similarly, in another study, a multifaceted approach to assess water supply sustainability was proposed, employing a multivariate water supply index to combine various sources of supply (Khoshoei et al., 2023). This method provides a new basis for evaluating water sustainability in regions dependent on multiple water sources.

Further refining prediction methodologies, another study from China used an optimised grey and Markov model to improve the accuracy of domestic water consumption predictions, addressing issues like overfitting which plague traditional grey prediction methods (Wang et al., 2021). Meanwhile, Song et al. (2024) introduced a risk analysis for water resource carrying capacity in the central plains region of China, utilising an improved entropy weighting method combined with gray correlation analysis. This comprehensive approach considers economic, social, and ecological environments, offering a methodological guide for sustainable water resource management.

In Africa, particularly Nigeria, the challenge of achieving sustainable water infrastructure is notably critical. Approximately 46% of water infrastructure is non-functional, significantly impeding progress towards Sustainable Development Goal 6.1 (Adeniran et al., 2021; Andres et al., 2018b). Failures in water infrastructure arise from a complex interplay of factors, including technical limitations, social dynamics, financial constraints, institutional weaknesses, environmental pressures, and political realities (Adeoti et al., 2023). These challenges vary greatly depending on the location; developed countries typically experience minimal failure rates, whereas developing nations like Nigeria face widespread issues (UN Water, 2022). Within Nigeria itself, stark disparities exist between urban and rural settings, exemplified by the Isale-Oja community in Ibadan, one of this study's focus locations (Adeoti et al., 2024b). This underscores the critical need to assess local conditions influencing water infrastructure sustainability comprehensively.

This research responds to this need by pioneering an innovative methodology to predict infrastructure sustainability in the planning phase of project implementation, utilising the concept of a Location Viability Rating (LVR), a metric designed to capture the unique community circumstances that influence whether water infrastructure projects remain functional and sustainable over time.

Predicting the sustainability of water projects requires a precise definition of sustainability. The concept of sustainability, particularly in the context of development, often faces challenges due to its broad and varied interpretations (Barbosa et al., 2014; Dovers & Handmer, 1992). This study specifically focuses on "infrastructure sustainability," defined as the ability of infrastructure to support and contribute to long-term economic and environmental well-being (Olanipekun et al., 2014; Song & Wu, 2021).

Sustainable infrastructure is conceptualised as durable, resilient to environmental change, and capable of enhancing community well-being. It should remain functional throughout its designated lifespan and be resilient to issues such as community security and safety risks, vandalism, wear and tear, and the impacts of climate change. The integration of

innovative technologies for efficiency, alongside strong governance and institutional support, is crucial. Consistent funding is vital to maintain operational infrastructure, providing the necessary financial resources and human capital (Adeoti et al., 2023; Khan et al., 2018; Oyegoke et al., 2012).

A holistic approach is essential for addressing water infrastructure sustainability. While Adeoti et al. (2023) propose a Water Infrastructure Sustainability Framework encompassing all project stages, a notable gap exists in Nigeria, as evidenced by a systematic literature review by Koppa et al. (2023). Their analysis found only six frameworks related to sustainable infrastructure in Africa, with none specifically targeting water infrastructure, highlighting a significant shortfall in tailored frameworks for regions like Nigeria (Oraegbune & Ugwu, 2020).

Rigorous pre-implementation assessments are a hallmark of infrastructure projects in developed nations, with stringent standards exemplified in Europe (Niekerk & Voogd, 1999) However, Diaz-Sarachaga et al. (2016) highlight a critical shortcoming when applying these frameworks to developing countries like Nigeria. Addressing this disparity, this study introduces an innovative framework designed for the real-world conditions of developing countries. This framework, built on a foundation of global insights, local data, and integration of multiple theoretical frameworks, developed the Viability Rating (VR) determined through a Likert scale survey assessing community readiness for sustainable water projects, based on 265 sustainability issues identified by Adeoti et al. (2023). The Sustainability Rating (SR) is another pivotal component, which assesses project sustainability by incorporating financial factors and leveraging VR to enhance prediction accuracy. This methodology enables iterative refinement of SR predictions through a conceptually integrated model that evolves with real-life project data.

In essence, this study develops a practical, metric-driven framework and tool for planning and evaluating water projects. Although developed and tested in remote Nigerian communities, the framework can be adapted to similar socio-economic contexts in other regions.

5.2. Methodology

5.2.1. Theoretical Framework: A Transdisciplinary Approach

Introduction to the Framework: The framework integrates insights from ecology, behavioural science, socio-technical studies, and complex systems to address the multifaceted challenges of water infrastructure in Nigeria. As advocated by Robinson (2008) and Wickson et al. (2006), this transdisciplinary approach is inherently problem-focused and collaborative, making it well-suited to tackling the social, cultural, environmental, institutional, and economic aspects of water infrastructure sustainability (Boyer et al., 2015). The study employs iterative and participatory methods, integrating insights from multiple disciplines, stakeholder feedback, and local observations. This approach ensures a balance of academic rigor and practical application, exemplifying how a transdisciplinary method can bridge theoretical knowledge with real-world relevance.

Community selection and Ecological Systems Theory: Bronfenbrenner's Ecological Systems Theory (1979), as applied to environmental contexts by Crawford (2020), forms the foundation for the community selection process used in this study. This theory recognises that community well-being is shaped by complex interactions within environmental systems. A standardised tool was employed to identify communities facing severe water scarcity, considering the interplay of ecological, social, and economic factors in these locations. This approach ensures that the chosen communities are not only grappling with immediate water challenges but also serve as exemplars of how ecological systems influence the long-term success of water infrastructure projects.

Questionnaire Design: The questionnaire design is based on the Theory of Planned Behaviour (TPB) (Ajzen, 1991; Ajzen & Schmidt, 2020), informed by Adeoti et al. (2023)'s systematic review which identified 265 sustainability challenges. Adapting TPB principles, a Likert-scale format is used to assess community attitudes toward sustainable water infrastructure.

Location Viability Rating and Sustainability Rating: Complex Adaptive Systems Theory (CAS) (Chan, 2001; Holden, 2005) informs the development of the Viability

Rating (VR) and Sustainability Rating (SR). This perspective acknowledges the dynamic interplay of sustainability factors within communities. VR and SR act as indicators for predicting the likely success of sustainable water infrastructure projects. They are informed by both theoretical foundations and real-world data from water projects. Together, these features ensure that the model remains responsive to the unique circumstances of each community, enabling a comprehensive evaluation of water infrastructure sustainability across diverse contexts.

5.2.2. Study Area

This study investigates five communities within Oyo State, Nigeria, selected from the 1,696 communities assessed by Adeoti et al. (2024b). Data from Adeoti et al. (2024b) were thoroughly reviewed to identify areas with the most pressing water challenges.
These communities, identified through precise GPS coordinates and enhanced by local insights, were chosen to represent severe water scarcity conditions in rural and peri-urban settings. While conceptually, three communities would have sufficed to test the predictive capacity of our model, five were ultimately selected to broaden the scope of data collection and enhance the robustness of our sustainability assessments.

- Aponmode Community (Lat: 7.5276, Long: 3.9142) in Moniya, Ibadan, faces suburban water scarcity with residents relying on an unprotected well as their primary water source, reflecting issues with aging infrastructure and inadequate water supply systems.

- Isale Oja in Ijaye Orile (Lat: 7.6301, Long: 3.8462) is a stark example of rural water poverty, where the community depends on an unhygienic and unprotected well, highlighting the absence of reliable water sources.

- Omilabu Village (Lat: 7.5465, Long: 3.9456) deals with extreme remote area water challenges, with the main water source being an unhygienic stream, indicative of the acute difficulties in accessing safe drinking water.

- Alabata Village (Lat: 7.5874, Long: 3.8688), located along Iseyin Road in Ibadan, primarily relies on rainwater and unprotected wells, illustrating the peripheral urban area's struggle with inconsistent water supply.

- Ajila/Irepodun in Idi Ayunre (Lat: 7.1611, Long: 3.9214) represents rural area with no improved water sources, depending on rainwater and an unhygienic stream.

5.2.3. Sample Space

Cochran's Formula was employed and factors such as population, household size and house counts were considered. It is important to note that interviews were conducted at the household level, where a household represents a family unit residing in a single dwelling. Even though a single house might contain multiple households, interviewing one household provides valuable insights for that entire house.

While the calculated sample size for Aponmode Community was 61 households, a larger number of residents was surveyed to strengthen the generalisability of the findings (Vasileiou et al., 2018). In Alabata Community, the required sample from 500 households was at least 87. Omilabu Community, with 122 households, necessitated a sample of 37 households. For Isale Oja Ijaye, with 422 households, 80 were needed in the sample, and Ajila/Irepodun Idi Ayunre, with 367 households, required a sample of 56. In total, 321 households were required across all five communities.

The formula used for determining the sample space in each community is as follows:

Total Number of Households (H) in Community:

$$H = \frac{P}{A} \quad (1)$$

Where:

- P = Total population
- A = Average people per household

Sample Size Using Cochran's Formula:

$$n = \frac{z^2 \times p \times (1-p)}{E^2} / \left[1 + \left(\frac{z^2 \times p \times (1-p)}{E^2} - 1\right) / H\right] \quad (2)$$

Where:

- Z = Z-score for 95% confidence level
- p = Estimated proportion of the attribute in the population (0.5 assumed)
- E = Margin of error (5%)

Adjusting for Design Effect:

To account for the survey design, particularly the clustering effect in sampling, the design effect (DE) was computed using the formula:

$$DE = 1+(b-1) \times ICC \quad (3)$$

Here:

- b = Average number of households per house
- ICC = Intra-cluster correlation coefficient (0.1 assumed)

Final Number of Houses to Survey (n_final)

$$n_{final} = n_{\frac{adjusted}{b}}$$

(4)

Where:

- $n_{adjusted}$= Adjusted sample size after accounting for design effect
- n_{final} = Number of houses to survey

The detailed sample size calculation for Aponmode Community is provided in Appendix 2, Section 1**.** The same methodological framework was applied uniformly to the remaining four communities.

5.2.4. The Predictive Iterative Sustainability Model (PISM): Structure, Formulation and Calibration

The Predictive Iterative Sustainability Model: The PISM is a dynamic framework and practical tool designed to predict the viability and sustainability of water infrastructure within communities. PISM employs a two-step rating process. First, the Viability Rating (VR) is calculated using a conceptual formula applied to weighted survey responses. This

formula generates a nuanced index reflecting each location's potential for sustainable water infrastructure projects. The model then progresses to the Sustainability Rating (SR), which further refines the viability assessment by incorporating financial considerations such as predicted income, operational, and maintenance costs. This ensures the sustainability score aligns with a project's long-term financial feasibility.

PISM is designed to be progressively enhanced through iterative refinements using real-world project data. While the specifics of these enhancements are beyond the scope of this study, the conceptual formula guiding the iteration is shown in Figure 5-1, with further details in Appendix 2, Section 3. This iterative process is essential for improving the model's predictive capability, progressively increasing accuracy until convergence is achieved.

Obtaining VR through Likert Scale Questionnaire: The study utilised a survey using a Likert scale to gather data on community sustainability factors. Respondents rated their answers on a scale of 1 (least desirable) to 5 (most desirable). Details about the questionnaire are provided in Appendix 2, Section 2, Table A2.1. Responses were tallied under respective factors; each assigned a weight reflecting its sustainability impact. The weighting structure was developed through a two-stage process. First, the systematic review identified the major sustainability factors affecting water infrastructure in Nigeria and established their relevance to long-term project performance. Second, field experts were consulted and asked to score these factors in order of importance to project sustainability. These expert scores were then used to assign the factor weights reported in Table 5.1, with higher weights given to factors judged to exert stronger influence on long-term viability and sustainability. These weighted responses were aggregated to calculate the Location Viability Rating (VR) for each community, providing a quantitative assessment of their sustainability potential.

Conceptual Development, Mathematical Formulation for VR, SR, Adjusted Factor, and Convergence of the Model: Figure 5-1 presents the Predictive Iterative Sustainability Model's (PISM) approach to predicting water infrastructure sustainability. It begins by establishing the Viability Rating (VR) for each community, followed by a predicted Sustainability Rating (SR). This prediction provides water agencies with crucial

empirical data for pre-construction sustainability assessments. Upon project completion, the actual SR of the water infrastructure is obtained. The deviation between the predicted SR and the actual outcome informs the adjustment factor needed to refine future SR predictions.

This iterative refinement process is core to model improvement. Recognising the data requirements for VR assessment, PISM incorporates a method to substitute VR with the average of actual SRs (aSRs). This average becomes the new predictive coefficient, improving SR prediction practicality and accuracy by leveraging real-world project data. Figure 5-1 illustrates this transition, while the detailed conditions and mathematical proofs are elaborated in Appendix 2, Section 3, which provides a comprehensive breakdown of the PISM methodology, including the underlying calculations and logical flow.

The iterative process aims for convergence, where the gap between predicted and actual SRs falls within an acceptable error margin, given sufficient real-world project data. This process, from initial prediction to convergence, establishes a foundation for predicting sustainable water infrastructure.

Even in its current form, before achieving full convergence, PISM demonstrates usefulness as a predictive tool for sustainability. The SR predictions for the five communities studied were informed by extensive survey data and reflect observed conditions with reasonable accuracy. Therefore, in its current state, PISM represents a substantial framework with the potential to enhance water infrastructure planning and sustainability assessment.

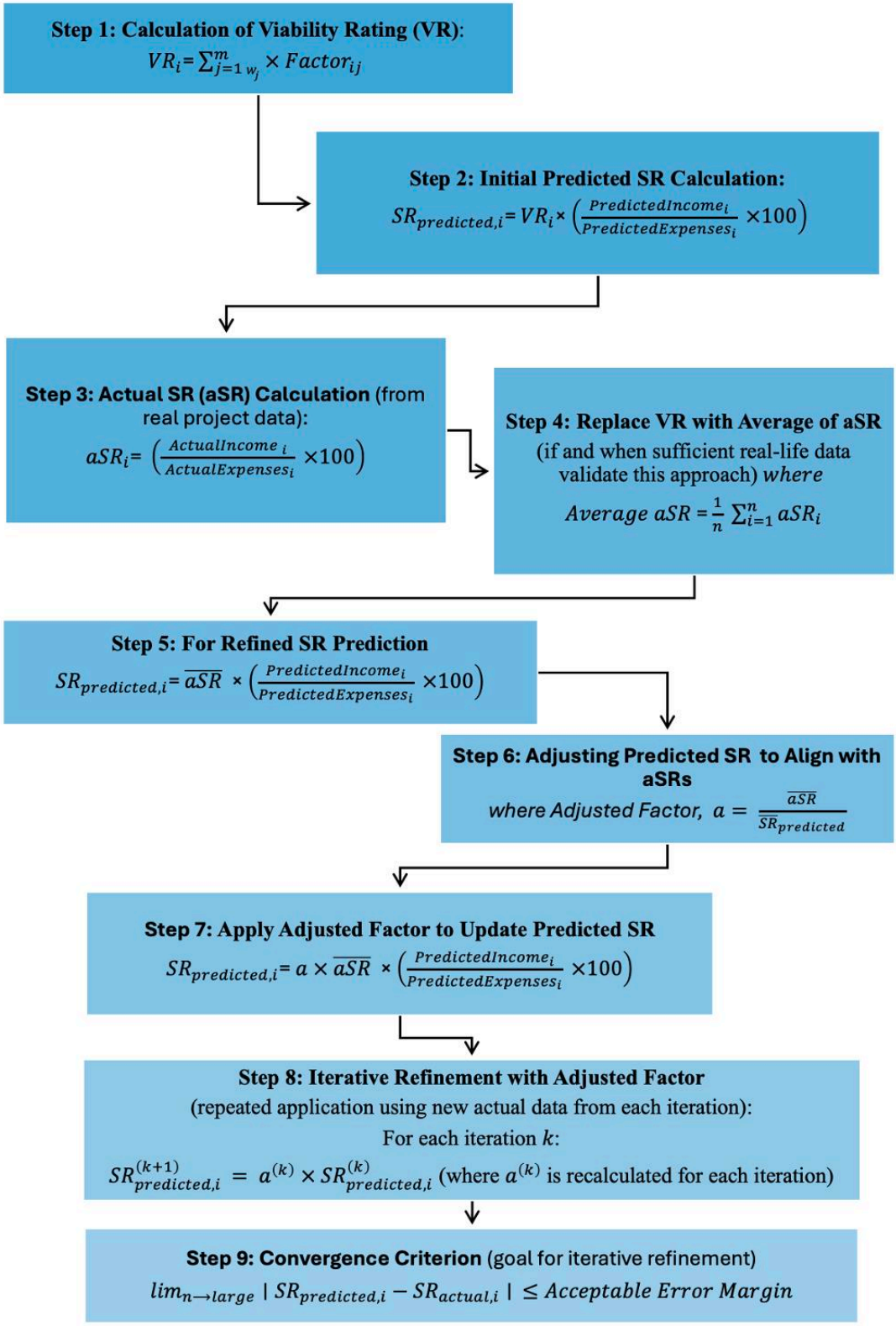


Figure 5-1: Flowchart of the Predictive Iterative Sustainability Model (PISM) Methodology

5.2.5. Methodological Rigor and Data Integrity

Addressing Methodological Subjectivity: The study's methodology, leveraging a transdisciplinary approach, integrated insights from industry experts and academic researchers to ensure the validity of the survey instruments and data-collection protocols. Data collection was standardised across all study locations to minimise biases, using Likert-scale questionnaires to transform subjective qualitative perceptions into consistent, quantitative data across surveyed households.

Managing Anomalous and Erroneous Data: To handle anomalous or erroneous data, a verification process was implemented during data entry and subsequent analysis phases. Prior to data collection, all data collectors underwent comprehensive training to ensure uniformity in methods, procedures, questions, and techniques across all sites. This standardisation was crucial in minimising data variability and potential biases. Using Likert heatmaps, each questionnaire response was reviewed to identify potential anomalies, enabling corrections or the exclusion of erroneous data to uphold the integrity and accuracy of the findings.

5.3. Results and Discussion

5.3.1. Viability Ratings of Surveyed Communities - Likert Scale Assessment

The VRs obtained from the Likert-scale questionnaire reflect comprehensive assessments across the five studied communities. The questionnaire, summarised in Appendix 2, Section 2, Table A2.1, includes a sample of 10 questions specifically assessing community water poverty, one of the 12 sustainability factors covered by the full set of 70 questions. To enhance data robustness and mitigate non-response bias, responses were collected from 380 households (88 in Aponmode, 96 in Alabata, 45 in Omilabu, 86 in Isale-Oja, and 65 in Ajila), exceeding the required sample size of 321.

Heatmaps were created to visualise the VR data for each community. Figure 5-2 presents the Aponmode community heatmap of the Likert responses, while Figures A2.1–A2.4 in Appendix 2 present the Likert heatmaps for the remaining four communities. These heatmaps show the distribution of responses across all 70 questionnaire questions,

highlighting variations in sustainability challenges and opportunities. For example, Figure 5-2 depicts the response patterns for Aponmode. Question 1 (Q1) on access to safe drinking water reveals a range of experiences: 27 households (30%) consistently have access, 18 (20%) mostly have access, another 18 (20%) sometimes have access, 12 (13.6%) rarely have access, and 13 (14%) never have access. This detailed depiction underscores the urgent need for targeted sustainable infrastructure interventions, given that 14% of households experience severe water poverty. It also exemplifies how the Viability Rating (VR) assesses crucial factors through a comprehensive analysis of all 70 questions.

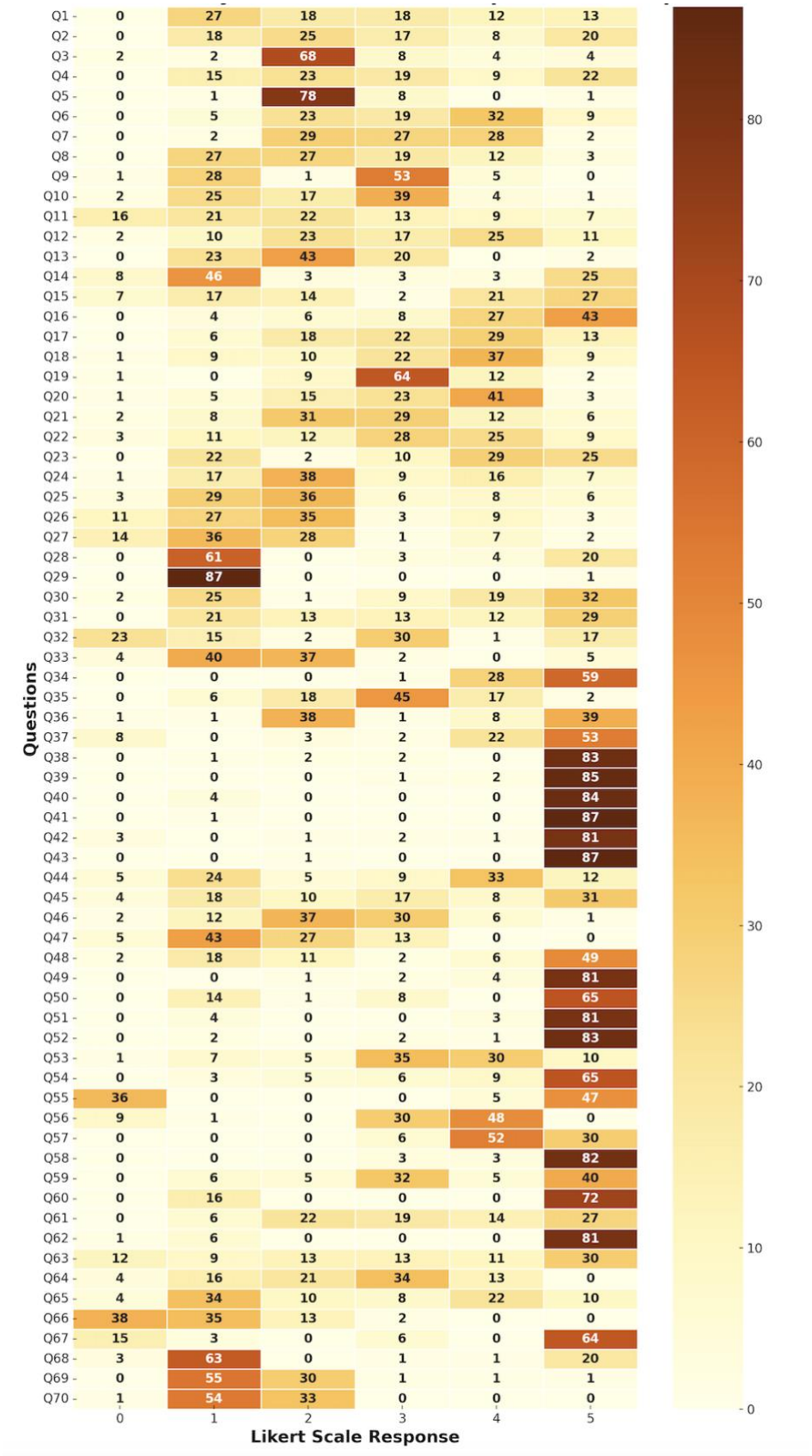


Figure 5-2: Aponmode Community Assessment: Heatmap of Likert Responses

5.3.2. Viability Ratings Scores of Surveyed Communities

Utilising the VR formula outlined in the Methodology section, the aggregated Community Viability Rating (VR) was computed following Likert survey analysis. This process transitioned qualitative community perspectives into a quantifiable VR, encompassing various sustainability factors.

Table 5-1: Community VR score

			Aponmode		Alabata		Omilabu		Isale-Oja		Ajila	
Factors	Weight Assigned (W)	HP Scores	Means	Factor Score	Means	Factor Score	Means	Factor Score	Means	Factor Score	Means	Factor Score
Water Poverty Rate	20	85	45.65	10.74	44.06	10.37	38.84	9.14	50.10	11.79	46.34	10.90
Financial Factor	10	60	29.48	4.91	28.95	4.83	29.84	4.97	29.57	4.93	27.71	4.62
Social Factor	10	35	21.35	6.10	19.76	5.65	20.40	5.83	21.13	6.04	20.75	5.93
Environmental Factor	10	35	33.5	9.57	33.06	9.45	33.64	9.61	32.99	9.43	30.42	8.69
Economic Factor	5	25	13.44	2.69	13.48	2.70	14.49	2.90	14.51	2.90	12.71	2.54
Security Factor	5	25	22.05	4.41	23.43	4.69	24.00	4.80	21.80	4.36	21.24	4.25
Engineering Capabilities	5	15	10.56	3.52	10.46	3.49	11.84	3.95	8.40	2.80	10.25	3.42
Technology Consideration	2	10	9.14	1.83	8.44	1.69	5.24	1.05	8.28	1.66	8.49	1.70
Modernity	5	5	3.83	3.83	3.64	3.64	4.02	4.02	3.79	3.79	3.22	3.22
Political Consideration	5	5	4.27	4.27	4.71	4.71	3.93	3.93	4.41	4.41	3.97	3.97
Population Consideration	5	10	8.06	4.03	7.75	3.88	8.04	4.02	7.92	3.96	7.65	3.83
Project Specific Question	18	30	17.19	10.31	16.67	10.00	17.30	10.38	19.75	11.85	18.14	10.88
Total Scores (VR)			66.22%		65.06%		64.59%		67.91%		63.95%	

Weights are expressed as percentages, while HP represents the highest possible score that can be obtained for each factor. The weighting structure used in this table is described in Section 5.2.4.

The VRs in Table 5-1 range from 63.95% to 67.91%, indicating a relatively narrow band of baseline viability for water projects across these communities. This narrow range underscores that VR alone cannot predict sustainability outcomes. Instead, the VR functions as an initial input to the predictive component of PISM, which estimates the Sustainability Rating (SR). Within this framework, the community with the highest VR is expected to have the highest predicted SR, implying a greater probability that the infrastructure will achieve long-term sustainability.

By pinpointing communities with the highest VRs, investments can be prioritised in locations where water projects are most likely to be viable and sustainable in the long term. Viability Ratings (VRs) thus inform investment decisions by highlighting communities with conditions that are favourable for successful and sustainable water projects.

5.3.3. Predicted Sustainability Rating (SR) and Sensitivity Analysis

The SR for the studied communities is derived using a formula that balances predicted income with predicted expenses, modulated by the Viability Rating (VR). The computation process is as follows:

SR Prediction Formula

$$SR_{Predicted,i} = VR_i \times \left(\frac{PredictedIncome_i}{PredictedExpenses_i} \times 100\right)$$

Predicted Income Calculation

Predicted income is estimated through a combination of average water demand per household (AWDH) and the estimated amount households are willing to pay per litre of water (EAHWP), factoring in the volume of water supply capacity (VWSC) relative to AWDH and the proportion of households willing to pay (PHWP)

Predicted Expenses Composition:

These are the total expected costs of operation ($COST_{op}$), maintenance ($COST_{ma}$), and repair ($COST_r$) combined.

Adjustment for Exceeding Supply:

In instances where the water supply capacity per household (VWSC/AWDH) exceeds the estimated total number of households in the community (EHC), the formula adjusts to use EHC in place of VWSC/AWDH.

Hence, the comprehensive formula used to obtain the SR becomes:

$$SR_{predicted,i} = VR_I \times \left(\frac{AWDH \times EAHWP \times \left(\frac{VWSC}{AWDH} \times PHWPW\right)}{COST_{op}+COST_{ma}+COST_r} \times 100 \right) \text{ for TWPSCH} \leq EHC \text{ or}$$

$$SR_{predicted,i} = VR_I \times \left(\frac{AWDH \times EAHWP \times (EHC \times PHWPW)}{COST_{op}+COST_{ma}+COST_r} \times 100 \right) \text{ for TWPSCH} > EHC$$

The formula considers the total water project supply capacity per household in relation to the community's population to account for variations in water demand, income generation, and financial sustainability. This ensures that the predicted SR reflects the specific dynamics of each community.

The explanations for each variable, and the detailed development of the SR prediction formula, are provided in the Appendix 2, Section 3. Table 5-2 presents the determined SR for each of the 5 studied communities.

Table 5-2: Predicted Water Infrastructure SR in the Surveyed Communities

Community	VR	AWDH (Litres)	EAHWP	VWSC (Litres)	PHWPW	TWPSCH	EHC	PE	PI	Predicted SR
Aponmode	66.22%	150.6	₦ 0.55	20,000	78.4%	133	433	₦2,000	₦ 8,668	287%
Alabata	65.06%	122.7	₦ 0.51	20,000	71.9%	163	500	₦2,000	₦ 7,301	238%
Omilabu	64.6%	108.2	₦ 0.54	20,000	77.8%	185	122	₦2,000	₦ 5,557	179%
Isale-Oja	67.91%	175.5	₦ 0.69	20,000	90.7%	114	422	₦2,000	₦12,478	424%
Ajila	63.95%	142.2	₦ 0.46	20,000	72.3%	141	367	₦2,000	₦ 6,612	211%

A one-way sensitivity analysis was conducted on the lower-bound predicted Sustainability Rating (SR) values reported in Table 5.2 by varying key assumed inputs in the model by ±10% while holding the remaining terms constant. The detailed results are presented in Table 5.3. The analysis showed that predicted SR was most sensitive to the estimated amount households are willing to pay (EAHWP), the proportion of households willing to pay (PHWPW), and total predicted expenses. Across all five communities, a 10% increase or decrease in EAHWP or PHWPW produced a corresponding 10% increase or decrease in predicted SR, while a 10% decrease in predicted expenses increased SR by 11.1% and a 10% increase reduced SR by 9.1%. Changes in average water demand per household (AWDH) had no effect on four of the five communities because, under those conditions, the household-capacity term offset demand in the

revenue calculation. Omilabu was the exception, where the estimated number of households constrained projected uptake and a ±10% change in AWDH produced a corresponding ±10% change in predicted SR. These results indicate that willingness to pay, expected uptake, and recurrent cost assumptions exert the strongest influence on model outputs.

Table 5-3: One-way sensitivity analysis of lower-bound predicted SR values under ±10% variation in selected assumed inputs

Community	Baseline SR (%)	AWDH -10%	AWDH +10%	EAHWP -10%	EAHWP +10%	PHWPW -10%	PHWPW +10%	Expenses -10%	Expenses +10%
Aponmode	286.97	286.97	286.97	258.28	315.67	258.28	315.67	318.86	260.88
Alabata	237.53	237.53	237.53	213.78	261.28	213.78	261.28	263.92	215.94
Omilabu	179.47	161.52	197.41	161.52	197.41	161.52	197.41	199.41	163.15
Isale-Oja	423.69	423.69	423.69	381.32	466.06	381.32	466.06	470.77	385.17
Ajila	211.41	211.41	211.41	190.27	232.55	190.27	232.55	234.9	192.19

Note: Each value in the table is a recalculated lower-bound predicted Sustainability Rating (SR), expressed as a percentage, after varying one assumed input by ±10% while holding all other inputs constant. The values do not represent percentage changes in SR. For example, a value of 258.28 for Aponmode under "SR if EAHWP decreases by 10%" means that the predicted lower-bound SR becomes 258.28% when EAHWP is reduced by 10%.

5.3.4. Delineating Project Viability Through Predicted Sustainability Ratings

The analysis of Predicted SRs in Table 5-2 reveals a standout case: Isale-Oja with an SR of 424%. This translates to a predicted financial ratio of income being 4.24 times greater than expenses, indicating a strong potential for Isale-Oja to sustain water infrastructure through healthy income generation relative to projected expenses.

An interesting contrast emerges when comparing VRs and SRs. Despite a lower VR of 63.95% for Ajila community compared to Omilabu 64.6%, Ajila exhibits a higher SR of 211%. This seemingly counterintuitive finding can be explained by water project supply capacity in relation to population density. Omilabu's higher TWPSCH compared to its EHC suggests a lower population density. This translates to lower water demand and potentially lower income from water sales compared to Ajila, despite a slightly higher

VR. Therefore, while VR suggests Ajila has a slightly lower baseline suitability for the project, the SR suggests its potential for financial sustainability is stronger due to a more favourable population-to-water supply ratio. Ajila's higher SR highlights the crucial role of population density and water demand in financial sustainability. This case underscores the need to consider community-specific factors beyond just baseline viability for accurate forecasting of water project success.

Isale-Oja's exceptional SR of 424% (predicted income-to-expense ratio of 4.24:1) reinforces the link between economic surplus and sustainable water infrastructure. The variation in SRs across communities with similar VRs further emphasises this point. This highlights the significant influence of economic realities beyond baseline viability on the long-term financial sustainability of water projects.

The PISM enhances the accuracy of Sustainability Rating (SR) predictions by leveraging the Viability Rating (VR) as a starting point to account for various sustainability factors within the model. This strategic use of predicted SRs in the pre-construction phase empowers decision-makers to identify communities that not only require but are also economically prepared for sustainable water infrastructure investments. This methodology is crucial in addressing the persistent challenges in Nigeria's water sector, where substantial public and donor investment has been lost to failed projects, hindering water access for millions of Nigerians (Adeniran et al., 2021; Andres et al., 2018b; Otun et al., 2011). The strength of the PISM lies in its iterative design, incorporating real-world data to refine projections and enhance decision-making. This process not only supports the targeted allocation of resources but also aligns with global sustainability goals, ensuring the long-term success and effectiveness of water infrastructure developments.

5.3.5. Model Iteration and the Path to Convergence for Accurate Prediction

The iterative refinement of the PISM is designed to ensure that the predicted Sustainability Rating (SR) converges with the actual SR within an acceptable margin of error, represented by $\lim_{n\to\text{large}} | SR_{\text{Predicted,i}} - SR_{\text{actual,i}} | \leq$ Acceptable Error Margin. This convergence criterion, a quantitative measure, is crucial for model validation using real-life water project data for calibration. Achieving

convergence suggests the model's predictive capability is reliable enough to forecast the success of water infrastructure projects before construction begins.

The model's core design hinges on integrating empirical data into its prediction mechanism. Through iterative recalibration driven by the ratio of actual to predicted SRs: $a = \frac{\overline{aSR}}{\overline{SR}_{predicted}}$, the model is continuously refined. This adjustment process ensures the model remains aligned with real-world outcomes, thereby enhancing the precision of its forecasts.

In this study, five communities utilised VR to comprehensively assess critical factors for sustainable water infrastructure projects. VR effectively facilitates the prediction of a project's Sustainability Rating (SR) during the planning and pre-construction phase, aiding in the selection of viable locations. However, VR assessments can be resource-intensive, prompting the need for a more efficient approach. In subsequent applications, VR can be replaced by the average SR of completed projects, providing a more economically viable and operationally efficient way to parameterise the model. This substitution leverages real-world data, potentially improving model accuracy while simplifying its application in water infrastructure planning.

The methodology section details an alternative approach, iteratively refined for convergence, to enhance PISM's usability for water agencies. In this approach, VR is replaced by the average SR of completed projects. Because VR functions as a multiplier in SR prediction, this substitution uses observed performance to adjust future predictions and improve the model's practical value for strategic water infrastructure decisions. Convergence between predicted and actual SRs strengthens PISM's predictive capability and demonstrates its potential utility in planning and executing water infrastructure projects. Ongoing refinement and integration of real-world data will further enhance its forecasting performance and support its application in sustainable water infrastructure development.

5.4. Limitations

Refining the accuracy of PISM in Nigeria and comparable contexts requires real-world implementation. This, in turn, necessitates post-construction data collection to assess infrastructure performance, a process that demands substantial financial backing. Securing this funding hinges on collaboration with government agencies, philanthropies and international organisations**.** In practical terms, this requires a shared planning mechanism through which these actors can assess proposed projects against common evidence and agreed sustainability criteria before implementation. PISM can support such coordination by providing a common basis for project screening, helping stakeholders align decisions on site selection, financing, expected demand, tariff assumptions, operational responsibilities, and post-construction monitoring requirements. Used in this way, the model can reduce fragmented or duplicative interventions and strengthen the connection between funding decisions, implementation arrangements, and long-term sustainability objectives. The primary challenge lies in overcoming financial constraints and obtaining long-term commitment from these key partners.

5.5. Summary and Synthesis

This chapter developed the Predictive Iterative Sustainability Model (PISM) as a pre-construction tool to evaluate the viability of a location for water project readiness and to predict the sustainability of the intended water solution. Using 70 Likert-scale indicators grouped under 12 distinct sustainability factors and adjusted via weights to reflect their relative importance, PISM aggregates community characteristics into a Viability Rating (VR). VR then serves as a multiplying coefficient with the income–expense ratio to generate a predicted Sustainability Rating (SR). Descriptive statistics and income–expense modelling were used to compute VR and SR for each community.

Applied to five water-poor communities, the model generated VR values between 64% and 68%, indicating a relatively narrow band of baseline viability for water projects across these locations. This narrow range underscores that VR alone cannot predict sustainability outcomes, but it does provide a minimum baseline that a location must meet to be considered ready for a sustainable water project. The predicted SR ranged from

179% to 424%, indicating substantial variation in predicted financial sustainability once demand, willingness to pay, supply capacity and cost structures are incorporated. The SR results also reveal a standout case where a higher VR does not translate into a higher SR. This counterintuitive pattern is explained by the relationship between water supply capacity and population density, highlighting the importance of economies of scale in cost recovery.

PISM also introduced a conceptual convergence pathway, which requires iterative refinement to ensure that the predicted SR converges towards the actual SR within an acceptable error margin. The convergence criterion can be expressed as:

by $\lim_{n\to\text{large}} \mid SR_{\text{Predicted,i}} - SR_{\text{actual,i}} \mid \leq \text{Acceptable Error Margin}$

This criterion provides a quantitative basis for model validation using real projects and supports progressive adjustment of indicator weights and model parameters as empirical data accumulate.

However, validating the model requires post-construction longitudinal data. This chapter does not yet test PISM against long-term operational data or incorporate post-construction outcomes that can constrain revenue and affect actual SR. Smart Water Infrastructure (SWI) equipped with IoT telemetry provides a practical means to collect such evidence and to understand the underlying drivers of performance. The next chapter (Chapter 6) evaluates the effectiveness of SWI in addressing the sustainability challenges identified in the preceding chapters and provides empirical evidence from real-world deployments to support PISM validation.

Chapter 6: Smart Water Infrastructure for Resilience and Sustainability

This Chapter is based on the following Publication

Adeoti, O. S., Haremi, R., Kandasamy, J., & Vigneswaran, S. (2025c). Evaluating the effectiveness of smart water management systems in enhancing the resilience and sustainability of water infrastructure in Nigeria. *AQUA-Water Infrastructure, Ecosystems and Society*. https://doi.org/10.2166/aqua.2025.291

Overview

This chapter evaluates Smart Water Infrastructure (SWI) as a practical delivery model and measurement platform for resilient, sustainable water services in Nigeria. Using an IoT-instrumented smart kiosk, it provides the longitudinal operational evidence needed for adaptive management and for refining the life cycle sustainability framework developed in this thesis. It also provides the real-world operational data required to validate and progressively improve the Predictive Iterative Sustainability Model (PISM) developed in Chapter 5. The analysis quantifies reliability, cost recovery, revenue water (water sales), non-revenue water (NRW), utilisation, water credit, operations and maintenance (O&M) needs, and the sustainability rating (SR), and identifies constraints specific to water-poor communities in Nigeria that materially affect sustainability, including overlapping aid and infrastructure underutilisation. Together, these results show where SWI sustains performance, where targeted operational controls are required, and how post-construction data can be used to strengthen planning and monitoring rules within the framework.

6.1. Introduction

Ensuring access to safe and affordable drinking water is fundamental for sustaining life and supporting the global development framework (Bain et al., 2014b). Central to this framework is the United Nations Sustainable Development Goal 6.1 (SDG 6.1), which aims to achieve universal and equitable water access for all by 2030 (United Nations, 2015). This goal is integral to the global sustainability agenda, intersecting with other SDGs focused on education, economic growth, and environmental sustainability (Aly et al., 2022; Satterthwaite et al., 2020; UN-Water, 2016). However, escalating challenges from climate-induced droughts, floods, pollution, alongside rapid population growth and urbanisation, intensify pressures on water infrastructure assets (Gupta et al., 2020; Misra, 2014; Sachidananda et al., 2016). These challenges highlight the urgent need for innovative technologies and adaptable solutions that can effectively respond to changing environmental conditions and demographic demands, ensuring sustainable water access for all (Ramos et al., 2019).

In response to these escalating challenges, many countries are increasingly adopting smart water management systems (Gupta et al., 2020). These systems leverage advancements in the Internet of Things (IoT) to revolutionise water management and distribution (Ramos et al., 2019; Singh & Ahmed, 2021). Recent studies, including those by Fatehi-Nobarian et al. (2023) Fatehi-Nobarian and Fard Moradinia (2024), highlight the effectiveness of advanced modelling techniques, such as wavelet-ANN hybrid models and harmony search algorithms. These models optimise hydraulic operations and predict seepage in earthen dams, offering more precise, cost-effective solutions that enhance the forecasting and management of water-related challenges. Smart systems improve the efficiency of water management, promotes sustainable water use, and enable detection and management of potential issues like leaks or contamination (Adeoti et al., 2024b; Olatunde et al., 2024; Ramos et al., 2019). The shift toward smart water management systems represents a critical evolution in the approach to water sustainability, embodying a tech-forward solution to some of the most pressing environmental and water resources management challenges of our time.

However, developing countries face challenges more complex than those in developed nations, grappling not only with global climate change threats but also with infrastructural

deficiencies that cannot meet the escalating water demands of rapidly growing populations (Adeniran et al., 2021; Adeoti et al., 2023, 2024b; Olatunde et al., 2024). These challenges are further exacerbated by a high failure rate of existing water infrastructure, frequently causing service disruptions and inefficiencies that stall progress, despite increased efforts and investments (Adeoti et al., 2023). This infrastructural inadequacy undermines water security and hampers economic development and health outcomes, perpetuating a cycle of adversity (Hope et al., 2020). Therefore, adopting smart water management strategies in these regions must be tailored to address both universal environmental challenges and unique local infrastructural deficits.

Smart water management in developing countries requires strategic implementation to tackle the unique complexities affecting water infrastructure sustainability. Highlighting these complexities, Olatunde et al. (2024) compare smart water management systems in Africa with those in developed regions such as the United States, elucidating the distinct challenges that developing nations face. Nigeria, Africa's most populous country and one severely impacted by water management challenges, serves as a pivotal case study. This context positions Nigeria as an ideal setting to assess the effectiveness of smart water management systems and to generate insights for overcoming sustainability challenges in comparable developing regions, underscoring the significance of this study.

Recognising the multifaceted challenges to infrastructure sustainability, this study adopted a transdisciplinary approach integrating technical, environmental, social, and economic perspectives (Brandt et al., 2013; Lawrence & Després, 2004). Ecological Systems Theory guided community selection and Complex Adaptive Systems Theory informed dynamic infrastructure design, enabling a comprehensive framework that addresses socio-ecological interactions. Engagement with local experts ensured that solutions were innovative and culturally appropriate. This integrative approach resulted in a technologically sophisticated smart water kiosk, attuned to the cultural and economic realities of Nigerian public boreholes.

In Nigeria, boreholes are essential for tapping into extensive groundwater reserves, to supply domestic and communal water needs. However, these systems often face technical failures and socio-political challenges that impair their efficiency (Adeniran et al., 2021; Adeoti et al., 2024b; Andres et al., 2018a). This research examines a smart water kiosk

as a strategic solution to enhance the use of borehole water. The primary objective is to assess the effectiveness of smart water management systems in improving resilience, reducing failure rates, and ensuring sustainability in an underserved Nigerian community.

Key metrics detailed in the methodology section were analysed to address the research objectives. Utilising a transdisciplinary framework, this study addresses both technical and socio-economic aspects of smart water solutions, ensuring contextually relevant and sustainable approaches. This systematic analysis, the first of its kind in applied research, offers actionable insights for addressing infrastructure deficits and failures in Nigeria and similar socio-economic regions.

The findings of this study are poised to significantly advance access to safe and affordable drinking water in Nigeria and have implications for similar regions globally, contributing to the discourse on sustainable water management and infrastructure resilience. This research aligns with national and international development goals, including the UN's SDG 6.1, and demonstrates the scalability of smart water management systems to address widespread infrastructure challenges.

6.2. Methodology

Figure 6-1 is a flowchart of the study's methodology, procedure and approach. This visual representation illustrates the progression of the research process.

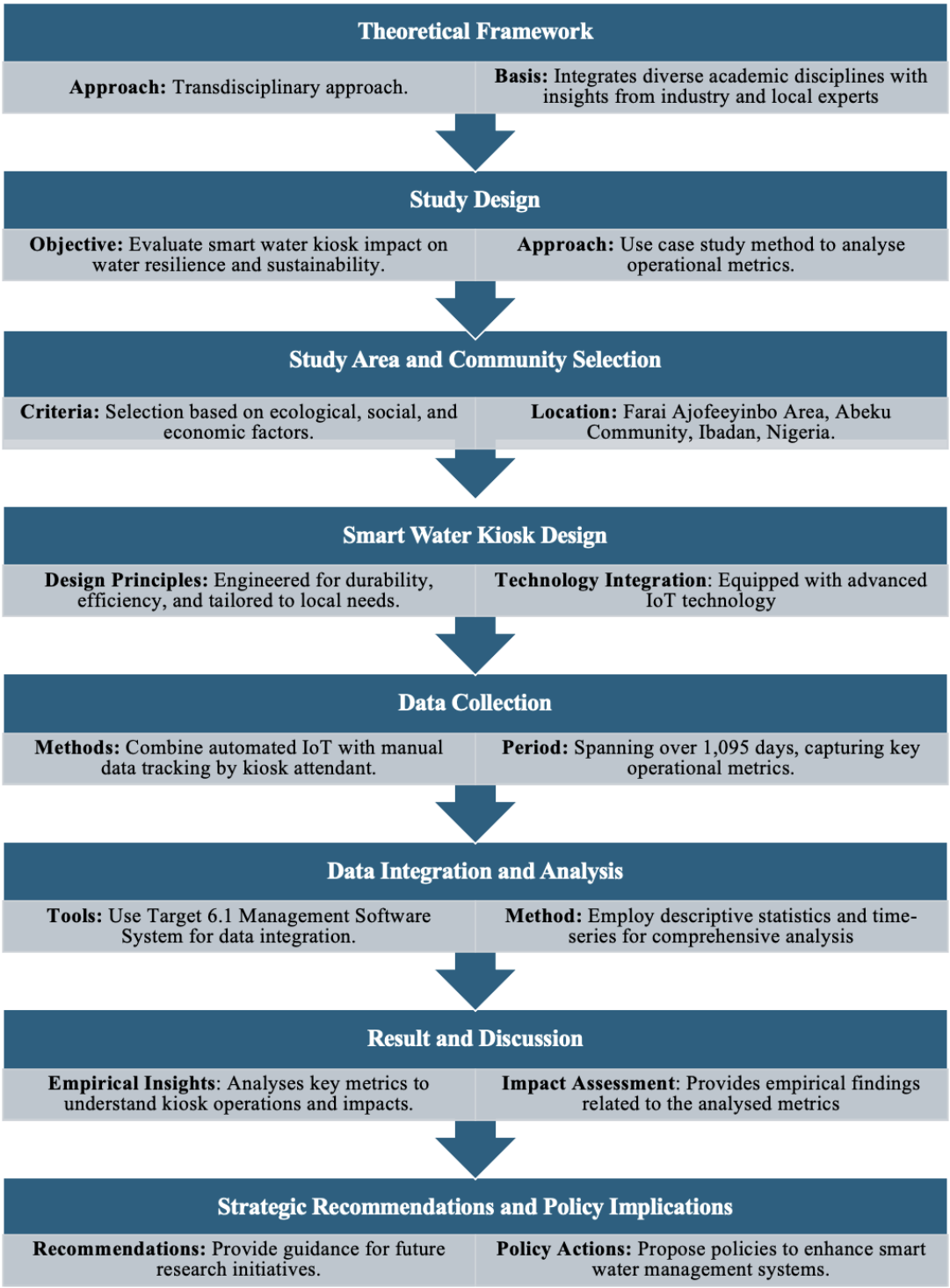


Figure 6-1: Flowchart of the Study's Process

6.2.1. Theoretical Framework

This research employs a transdisciplinary theoretical framework, integrating academic theories with practical insights from industry experts and local community experiences

(Robinson, 2008). This approach ensures that the smart water management systems developed are scientifically robust and tailored to meet the specific needs and conditions of the study community. By addressing complex water management challenges, the aim is to create solutions that are effective, sustainable, and contextually relevant.

6.2.2. Research Design

Employing a case study design, this study explores the effectiveness of a smart water kiosk in an underserved Nigerian community. The case study method allows for detailed analysis of operational metrics and their impact on the community's water infrastructure, resilience, and sustainability. The definition of 'sustainability' within this research encompasses the durability of the infrastructure, its resilience to environmental changes, and its capacity to enhance community well-being by providing safe drinking water. Crucially, it includes the infrastructure's ability to remain functional throughout its designated lifespan, generating enough funds to cover operational, maintenance, and repair costs (Adeoti et al., 2024a).

6.2.3. Metrics Evaluated

The selection of key operational metrics, specifically the Self-Sustainability Rating (SSR), Sustainability Rating (SR), and Reliability Rating, reflects a strategic approach to quantifying the performance of the smart water kiosk. These primary performance metrics, complemented by additional metrics such as Revenue Water, Non-Revenue Water, Water Credit, Overall Water Dispensed, and Overall Kiosk Usage, were chosen to provide detailed insights into the operational dynamics of the kiosk. Collectively, these metrics enable a comprehensive evaluation of its performance. This detailed assessment not only underscores the kiosk's financial viability and operational reliability but also highlights its social impact, offering critical insights into operational challenges and presenting data-driven solutions.

6.2.3.1. Key Performance Metrics:

- **Self-Sustainability Rating (SSR):** This metric quantifies the infrastructure's ability to cover all operational and maintenance costs through revenue from water sales, without reliance on external funding.

$$SSR = \left(\frac{\sum_N \text{Revenue Water)}}{\sum_N \text{Expenses}}\right) \times 100$$

- **Sustainability Rating (SR):** Measures the ability of the infrastructure to cover operational and maintenance costs through combined revenue streams, including water sales and external support such as donations and government funding

  $$SR = \left(\frac{\sum_N \text{Revenue Water} + \sum_N \text{Support}}{\sum_N \text{Expenses}}\right) \times 100$$

  Where:

  $\sum_N$ denotes the summation of values over N periods.

  N: the total number of days in the analysis period

- **Revenue Water:** Income from water sales over the analysis period (N days)

- **Expenses:** Total cost of operation, maintenance and repair over the analysis period (N days)

- **Support:** Income from donations and other contributions, excluding revenue from water sales

- **Reliability Rating:** Evaluates the functionality of the kiosk over time, reflecting its dependability and capacity to provide uninterrupted service.

  $$\text{Reliability Rating} = \left(\frac{\text{Total Operational Days} - \text{Days with Interruptions}}{\text{Total Operational Days}}\right)$$

  Where:

  Total Operational Days: total number of days in the analysis period

  Days with Interruptions**:** number of days with service disruption or failure during the analysis period.

6.2.3.2. Additional Metrics for Comprehensive Analysis

- **Overall Water Dispensed:**

  $\sum_{n=1}^{N}$(Daily Water Dispensed)

- **Water Credit:**

  $\sum_{n=1}^{N}$(Volume of Free Water)

- **Non-Revenue Water (NRW):**
  $\sum_{n=1}^{N}(\text{Total Water Dispensed} - \text{Revenue Water} - \text{Water Credit})$

6.2.4. Study Area and Community Selection

Utilising Ecological Systems Theory adapted by Crawford (2020), the Abeku Community in Ibadan, Oyo State, Nigeria, was selected from 1,696 communities assessed by Adeoti et al. (2024b). Abeku, with significant water-related challenges and prevalent poverty, exemplified by reliance on unhygienic water sources, provided a pertinent setting for testing the water kiosk's impact and scalability. Community engagement was essential, beginning with pre-construction consultations that incorporated local inputs into the kiosk's design and continuing with their active participation in operational feedback. This involvement ensured the kiosk adapted to local needs and facilitated dynamic system refinement. A community-nominated kiosk attendant, employed full-time, played a pivotal role in bridging communication between the research team and the community, providing crucial feedback and community insights to adjust kiosk operational strategies.

6.2.5. Smart Water Kiosk Design

Designed for adaptability and resilience, the smart water kiosk incorporates Complex Adaptive Systems Theory (CAS) and established civil engineering and environmental science practices (Chan, 2001; Holden, 2005). Referenced in Figure 6-2, its architectural and engineering features are based on Adeoti et al. (2024b)'s analysis of technical failures in Nigerian water infrastructure, providing crucial insights for constructing durable structures.

The kiosk utilises advanced IoT technology and algorithmic software to remotely monitor and analyse key operational metrics, adapting to environmental and social changes to meet community needs. This setup ensures the kiosk is effectively tailored to achieve the research objectives.

The system's scientific and practical robustness is underpinned by a framework built on prior research, including operational metrics defined in Adeoti et al. (2024a). That study employed a Likert-scale questionnaire to analyse 265 sustainability factors, forming a

solid foundation for applying the Self-Sustainability Rating (SSR) and Sustainability Rating (SR) to assess infrastructure sustainability (see Chapter 5). The integration of rigorous, evidence-based frameworks with modern technologies, together with active collaboration with local experts and users, validates the kiosk's scientific and practical relevance and exemplifies the transdisciplinary approach adopted in this study.

Strategically placed within a 10–15-minute walk for 1,000 of the estimated 2,200 community members, the kiosk's location maximises accessibility and operational efficacy, operating 12 hours daily throughout the week.

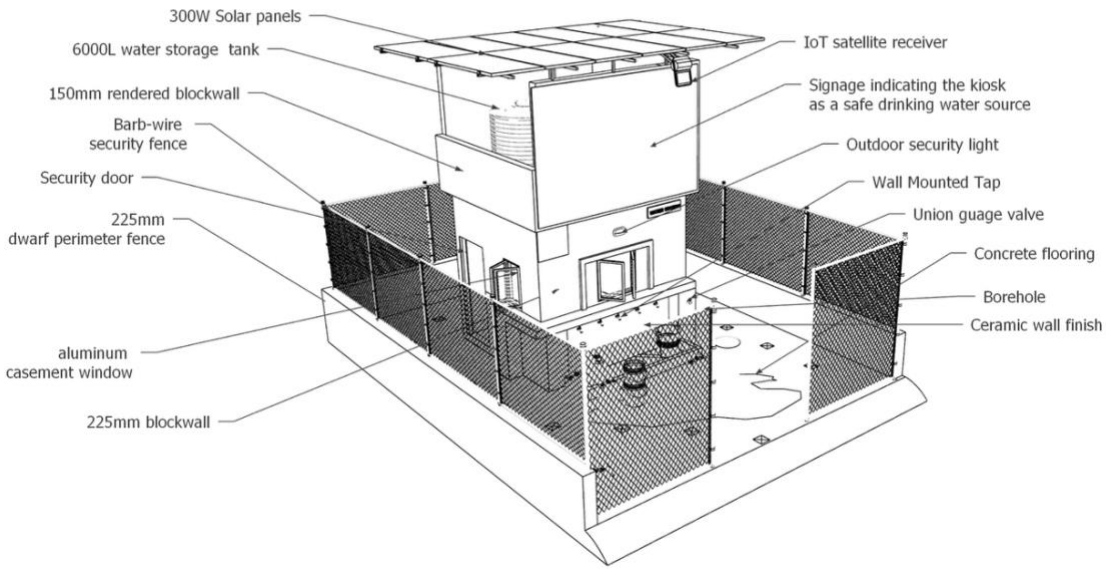


Figure 6-2: This figure illustrates the smart water kiosk's architectural design, highlighting key components.

6.2.6. Data Collection

6.2.6.1. Data Collection Period

Data was systematically collected from the smart water kiosk over 1,095 days (three years), from May 21, 2021, to May 19, 2024. This period was chosen to encompass a full range of operational scenarios, which is critical in settings like Nigeria where infrastructure often fails within such a timeframe (Khan et al., 2018). Monitoring the kiosk over these years was vital for capturing detailed data on wear and tear and other

technical issues, providing an in-depth evaluation of the effectiveness of smart water management strategies in enhancing infrastructure resilience.

6.2.6.2. Data Collection Methods

Data collection over the 1,095-day period at the smart water kiosk was conducted through a combination of automated and manual methods, ensuring continuous and comprehensive data acquisition. Automated data were gathered via IoT devices, while manual entries were recorded daily by the kiosk attendant. The detailed methodologies for both data collection and subsequent analysis, utilising the Target 6.1 software with various statistical techniques for real-time analysis, are provided below.

Automated Data Collection: The smart water kiosk utilises IoT technology provided by Farmbot, an Australian IoT company, to monitor and record key operational data such as the volume of water dispensed, tank water levels, and overall system functionality. This data is transmitted to the Farmbot system. The Application Programming Interface (API) of the Farmbot system is integrated with the Target 6.1 Software, an algorithmic platform developed by an Australia-based research and development company, which facilitates real-time analysis and comparison of both automated and manually entered data.

Manual Data Collection: Concurrently, with IoT measurements, the Kiosk Attendant manually collects daily data on essential user metrics such as water credit and revenue water, which is entered into the Target 6.1 software. This software validates the manually reported data by cross-referencing it with the overall water dispensed as recorded by IoT technology.

Anomaly Detection and Data Integrity: When IoT data is unavailable, the Target 6.1 software employs the predictive formula outlined below to estimate water dispensed in real-time, ensuring data continuity. This approach also helps detect erroneous inputs, as predicted values typically align closely with actual IoT data. Significant deviations from predicted and IoT values would prompt a thorough investigation to identify and rectify the cause. Discrepancies are meticulously analysed, and any detected anomalies were corrected or removed from the dataset to ensure accuracy. This method effectively manages and rectifies data anomalies, ensuring the integrity of our research findings.

Predictive Formula for Water Dispensed (WD)

$$WD = (RW + WC) \times X \quad (1)$$

$$WD = NRW + (RW + WC) \quad (2)$$

$$NRW = \text{Avg}\ (NRW\%)\ \text{of}\ WD \quad (3)$$

$$WD = \frac{(RW+WC)}{(1-\text{Avg}(NRW\%))} \quad (4)$$

$$X = \left(\frac{1}{1-\text{Avg}\ (NRW\%)}\right) \quad (5)$$

$$\text{Avg}\ (NRW\%) = \frac{\sum \text{NRW\% of each period}}{\text{Number of Periods}} \quad (6)$$

Where

WD is overall water dispensed

RW is the revenue water

WC is the water credit

NRW is the Non-Revenue Water

X is the adjustment factor needed to scale (RW +WC) up to the overall water dispensed

6.2.6.3. Validation and Uncertainty Assessment of Formula-Based Predictions:

- **Formula Validation:** The predictive formula is validated against actual IoT data from periods when IoT was operational, ensuring its accuracy and reliability under real-world conditions.
- **Utility During IoT Downtimes:** The formula continues to monitor and estimate water usage when IoT is offline, maintaining essential data continuity for system management.
- **Combined Use with IoT:** By merging formula-based predictions with IoT data, the approach enhances data integrity, enabling the identification and investigation of anomalies and outliers.
- **Methodological Uncertainties:** The formula's primary limitation is its inability to immediately detect sudden outliers caused by external factors such as community gatherings or holidays, which can significantly alter usage patterns.
- **Mitigation of Uncertainties:** To mitigate this, the strategy involves minimising IoT downtimes and relying on the synergy between formula-based predictions and IoT data, which collectively improve data accuracy and reliability.

6.2.7. Method of Data Analysis

This study utilises the Target 6.1 software system, designed for comprehensive real-time analysis of various water management metrics such as revenue water, non-revenue water, water credit, and total water dispensed. Employing analytical techniques like descriptive statistics and time-series scatter plots, the system is crucial for performing comparative and trend analysis and for assessing the impact of these metrics. It facilitates effective visualisation and contextual evaluation of data trends and temporal variations.

Furthermore, the Target 6.1 software allows the kiosk attendant to manually input data, such as revenue water, which is automatically synchronised with data from the Farmbot IoT for robust real-time analysis. This real-time analysis is essential for the immediate verification of manual entries, enhancing data accuracy and reliability by swiftly enabling identification and correction of any discrepancies. This feature is vital in dynamically responding to community interactions with the kiosk, which significantly influence metric evaluations. For instance, an increase in kiosk usage due to a community event was quickly detected and analysed to understand the surge's causes, enriching the dataset for ongoing analysis and offering insights into external factors impacting the kiosk's operation.

6.2.7.1. Optimising Kiosk Performance through Real-Time Data Analysis

Real-time analysis of evaluated metrics enhances the management of the smart water kiosk, facilitating prompt identification and correction of operational inefficiencies. This targeted analysis is crucial for progressing towards key performance indicators, specifically aiming to achieve a Self-Sustainability Rating (SSR) of 100% and a high reliability rating. These metrics are fundamental in measuring the success and long-term viability of the kiosk.

6.3. Result and Discussion

6.3.1. The Smart Water Kiosk Utilisation Rate is 7.63% of its Capacity

Figure 6-3 presents a time-series scatter plot of water dispensed at the kiosk over three years, detailing both revenue water (paid) and water credit (free) periods. The peak daily

usage was recorded at 7,267 litres. Over the 1,095-day study period, the kiosk dispensed a total of 1,671,497 litres, averaging 1,526 litres per day, which is only 7.63% of the kiosk's designed capacity of 20,000 litres per day. This capacity was established through aquifer testing to assess potential groundwater output.

Despite the theoretical capacity to serve up to 1,000 people daily from a community of 2,200, based on the UN's recommendation of 20 litres per person per day (Howard et al., 2020), actual usage was significantly low, averaging about 7.63% of the total capacity. This notable underutilisation underscores the discrepancy between potential and actual water use, reflecting a complex interplay of factors that influence consumption rates.

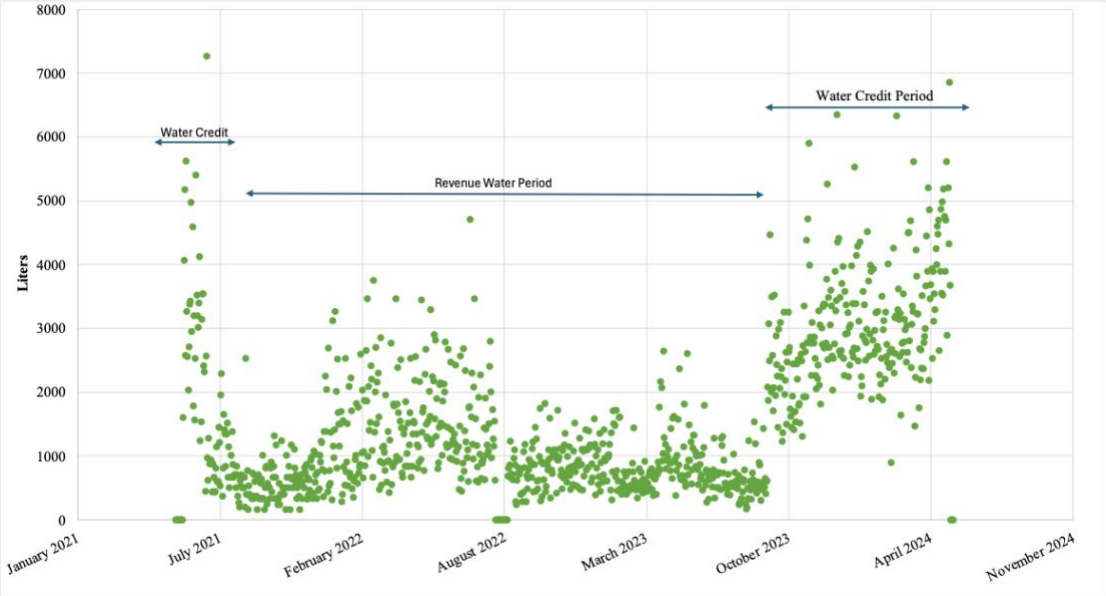


Figure 6-3: Daily Water Usage Trends at the Smart Water Kiosk

6.3.1.1. Factors Contributing to Kiosk Underutilisation

The investigation into the underutilisation of the smart water kiosk uncovered key challenges that hinder its full potential:

- **Proximity**: Although the kiosk is suitably located within 10 to 15-minute walking distance for approximately 1,000 of the estimated 2,200 people in the community, many households within this radius still find the distance inconvenient.

- **Persistent Underutilisation Across Payment Periods**: Figures 6-4 (free-water) and 6-5 (paid) show consistently low daily volumes across all phases. In the initial free-water period (01/06/2021–04/07/2021; 34 days), Figure 6-4 shows all daily values below 5,000 L and clustered near 2,000 L, resulting in an average of 1,898 L/day (9.49% of the 20,000 L/day capacity). In the subsequent free-water period (01/09/2023–15/05/2024; 258 days), the pattern is similar to the initial free-water period, with most days near 2,000 L and an average of 1,821 L/day (9.11%). Between these free-water windows, the paid revenue-water period (05/07/2021–31/08/2023; 788 days) shown in Figure 6-5 exhibits the lowest usage, with most days below 1,000 L and an average of 578 L/day (2.89%). Overall, average daily usage remained below 9.5% of the kiosk's designed capacity across all periods.

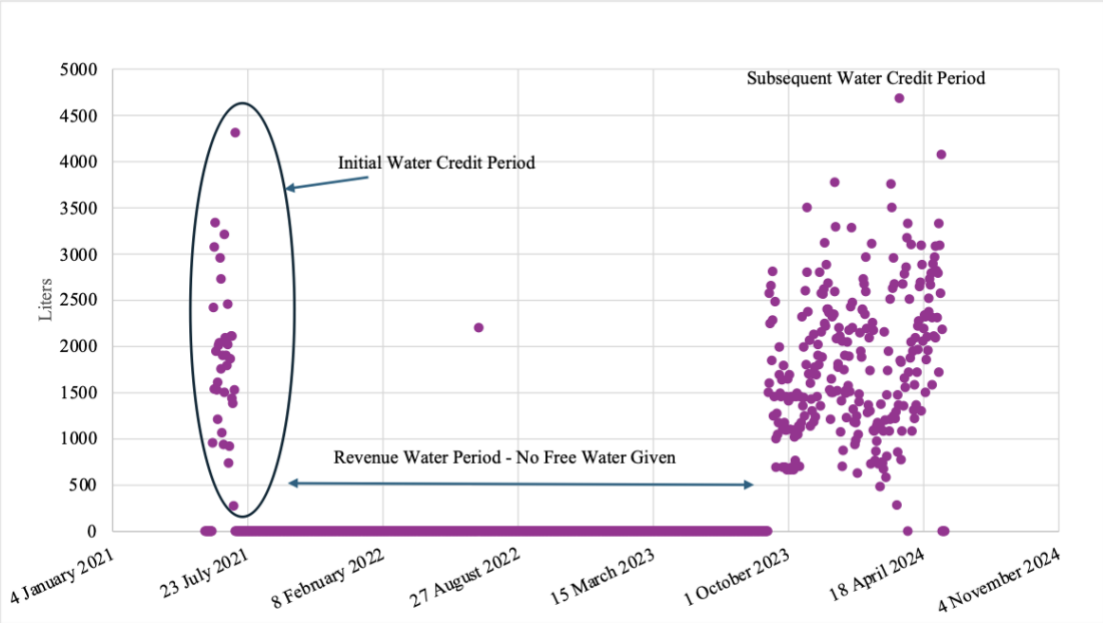


Figure 6-4: Distribution of Free Water Across the Study Period.

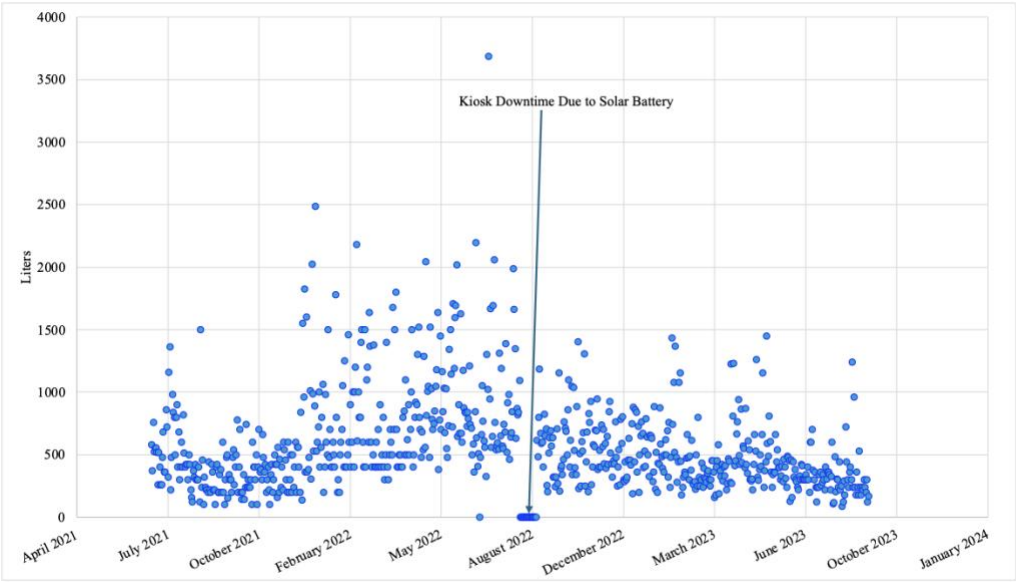


Figure 6-5: Time-Series Scatter Plot of Revenue Water Usage

- **Dry and Rainy Seasons**: Figure 6-6 presents seasonal trends in kiosk usage. Average daily usage was higher in the dry season (December–February) at 1,747 litres/day (8.74% of the 20,000-litre/day capacity) and lower in the rainy season (March–November) at 1,454 litres/day (7.27%). On a monthly basis, average usage was 157,826 litres/month in the dry season and 133,113 litres/month in the rainy season, both well below the kiosk's monthly capacity of 600,000 litres. Despite the modest increase in daily and monthly averages during the dry months, utilisation remained far below capacity in both seasons.

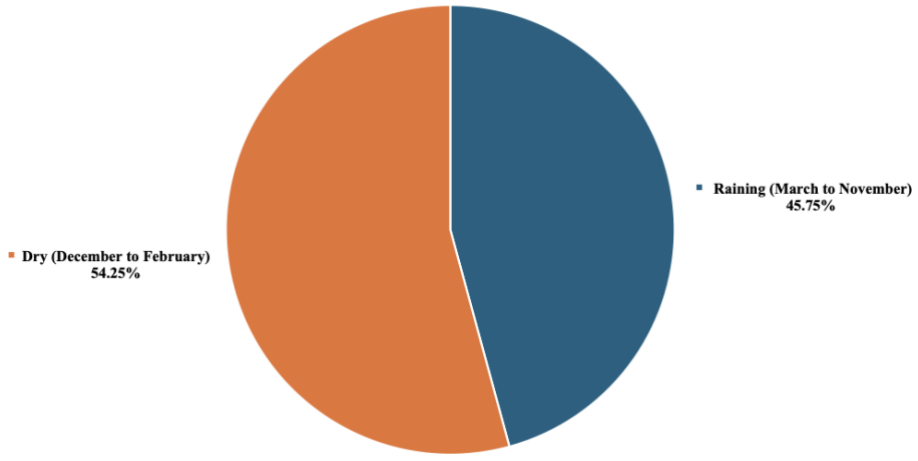


Figure 6-6: Seasonal Trends in Water Usage at the Smart Water Kiosk

- **Preference for Unsafe Alternative Water Sources:** Residents predominantly use unprotected wells, considered unsafe and unhygienic by national and UN standards for drinking water. These sources are favoured due to their proximity and convenience, illustrating a community preference for accessibility over quality. Despite the visibly unsafe conditions of these water sources, residents report no negative health effects from their long-term use. The absence of adverse health effects, despite using wells deemed unsafe, contradicts formal definitions of water poverty that label these communities as water-poor. This disparity highlights the need to revise how water poverty is assessed, ensuring evaluations reflect the actual conditions and perceptions of the communities.

6.3.2. Water Usage Decreased by 68.4% When Charged Compared to When Free

Drawing on the free-water and paid-period results reported above (see Figures 6-4 and 6-5), the combined free-water average was 1,831 L/day, whereas the paid revenue-water average was 578 L/day — an approximately 68.4% decrease when charges applied. This marked reduction indicates affordability constraints, with many residents unable or unwilling to pay the nominal fee of ₦25 per 25-L jerrycan. This finding underscores the need for strategies to enhance community willingness to pay and supports the implementation of policies that provide federal and state subsidies for those who cannot afford water costs.

The scale of this reduction indicates that affordability and water pricing are central determinants of underutilisation in this setting. Although the free-water periods did not produce high utilisation relative to the kiosk's design capacity, the sharp decline once charges were introduced shows that price materially shapes the conversion of potential demand into revenue water. In practical terms, this means that operational sustainability cannot rest on tariff setting alone or on the assumption that technical reliability will automatically generate willingness to pay. Pricing strategies need to be calibrated to

household liquidity, perceived value relative to existing sources, and the wider local water economy, including the availability of free or low-cost alternatives.

6.3.3. 22% Self-Sustainability Rating Observed During Revenue Water Period

As shown in Figure 6-7, the kiosk's Self-Sustainability Rating (SSR) during the paid revenue-water phase was 22%. Over this period (788 days), income from water sales totalled ₦445,725, while operation, maintenance and repair expenses totalled ₦2,000,934, giving SSR = (₦445,725 ÷ ₦2,000,934) × 100 = 22%. Although this is below the desired 100% SSR, it is notable, particularly since some developed countries, such as Italy, report recovery rates below 44% (Reynaud, 2016). Traditionally, service costs in these contexts are subsidised by donor agencies and government budgets (Erm, 2003). This 22% cost recovery reflects a partial willingness within the community to pay for water services. Strategies to enhance SSR could include increased community education on the benefits of sustainable infrastructure. However, on current figures, closing the gap between SSR and full self-sustainability would require either an increase in water-sales revenue from ₦445,725 to approximately ₦2.0 million, equivalent to a rise of about 349%, or a reduction in recurrent expenses of about 77.7% if revenue remained unchanged. These magnitudes suggest that the gap cannot be bridged through community education alone. More plausible improvement would depend on a combined strategy that raises paid utilisation through affordability-sensitive tariff design and stronger demand alignment, protects revenue from displacement by overlapping free-water interventions, and uses structured external support for cost components that are unlikely to be fully recovered through tariffs alone, such as major repairs or social water-credit provision.

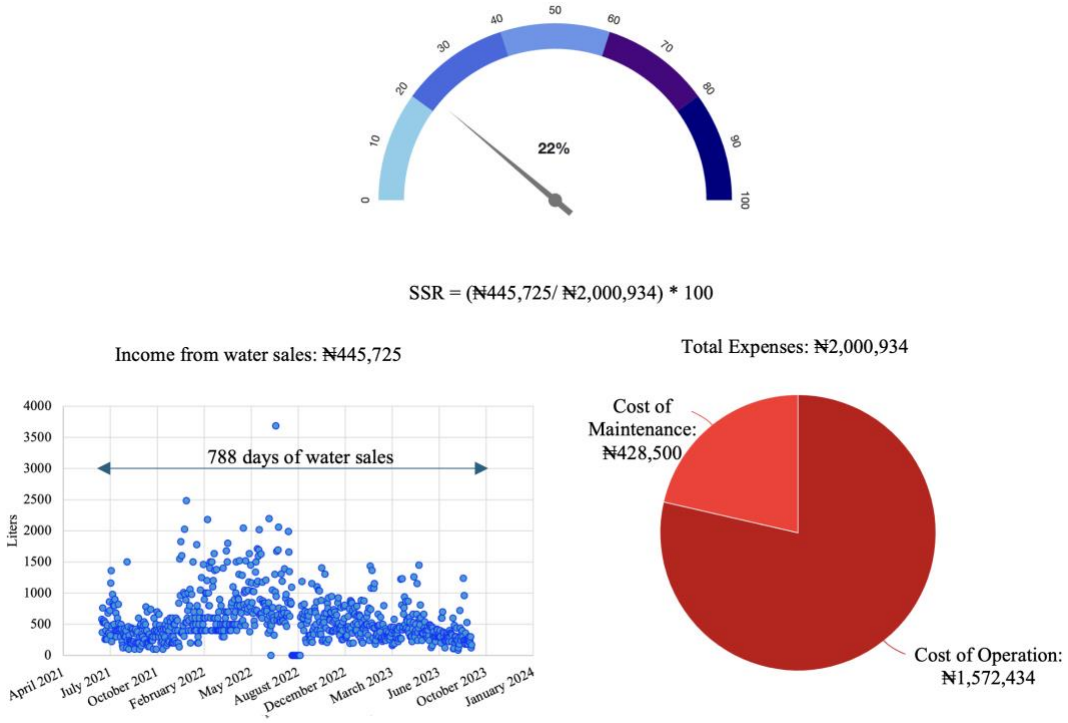


Figure 6-7: Self-Sustainability Rating of Kiosk During Revenue Water Period (July 5, 2021, to August 31, 2023)

6.3.4. Overlap of Aid Impact Reduced Self-Sustainability Rating from 22% to 0%

Overlap of aid occurs when multiple aid initiatives target the same community without coordinated efforts, often leading to infrastructure redundancy or conflicts in resource utilisation. During the 1,095-day study, significant shifts in water distribution occurred on the 833rd day, as depicted in Figure 6-8. The installation of a free-use well by another NGO within the community abruptly eliminated the willingness to pay for kiosk water services, causing revenue water (blue dots) to drop to zero while water credits (purple dots) increased.

This transition caused a complete loss of revenue water, critically impacting the kiosk's ability to cover operational, maintenance, and repair costs, as the community was no longer willing to pay for kiosk water due to the alternative free-use well. To prevent the

abandonment of the kiosk, water was subsequently offered for free as credit, causing the self-sustainability rating (SSR) to plummet from 22% to zero.

This scenario also highlights the missed opportunity to educate the community on the importance of paying for water, critical for securing funds needed to sustain water infrastructure assets. Moreover, the free-use well, lacking a structured revenue model for maintenance, risks disrepair and abandonment, compounding sustainability challenges across the community (Adeoti et al., 2024b). These dynamics underscore the need for coordinated strategies among aid organisations to ensure the long-term sustainability of infrastructure projects. A practical implication is that organisations working in the same community should coordinate proposed installations, service models, and subsidy arrangements before deployment, using shared community diagnostics to reduce the risk that one intervention unintentionally undermines the financial viability of another.

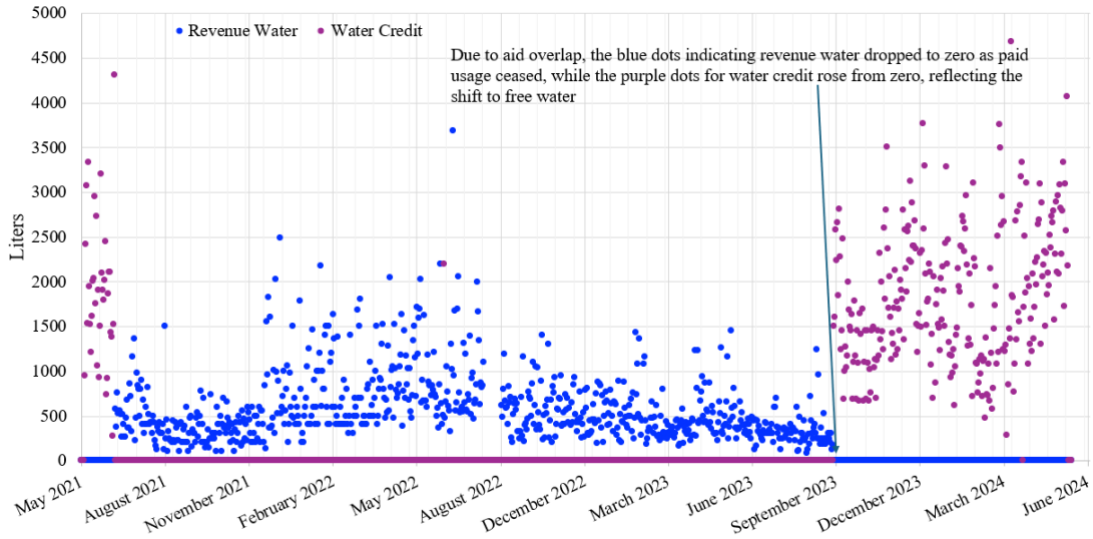


Figure 6-8: Scatter Plot Illustrating the Shift from Revenue Water to Water Credit Due to Aid Overlap

6.3.5. Non-Revenue Water Constituted 41.24% of Total Water Dispensed

Figure 6-9 presents a time-series scatter plot displaying the total volume of water dispensed (in green) and its associated non-revenue water (NRW, in red) over the study

period of 1095 days. NRW accounted for 41.24% of the total volume, highlighting significant challenges in managing water losses. While the current underutilisation of the kiosk moderates the immediate financial impact of this high NRW, such losses would become unsustainable should the infrastructure operate at its maximum utilisation capacity. At full capacity, NRW would significantly compete with potential revenue, undermining the kiosk's ability to recover costs and maintain financial sustainability. This critical situation underscores the urgent need for targeted strategies to reduce NRW and enhance water distribution efficiency, crucial for improving the project's sustainability. In Nigeria, monitoring and reporting of NRW are not widespread, despite significant water losses being a major issue for water utilities in developing countries like Nigeria (Ali, 2024). Furthermore, the combined sectors of water supply, sewerage, waste management, and remediation accounted for only 0.33% of Nigeria's nominal GDP in the third quarter of 2023 (National Bureau of Statistics, 2023). The pathway to effectively increasing revenue from water hinges on implementing smart water management systems, such as the smart water kiosk used in this study, which are crucial for accurately accounting for water usage and developing effective strategies to manage and reduce NRW.

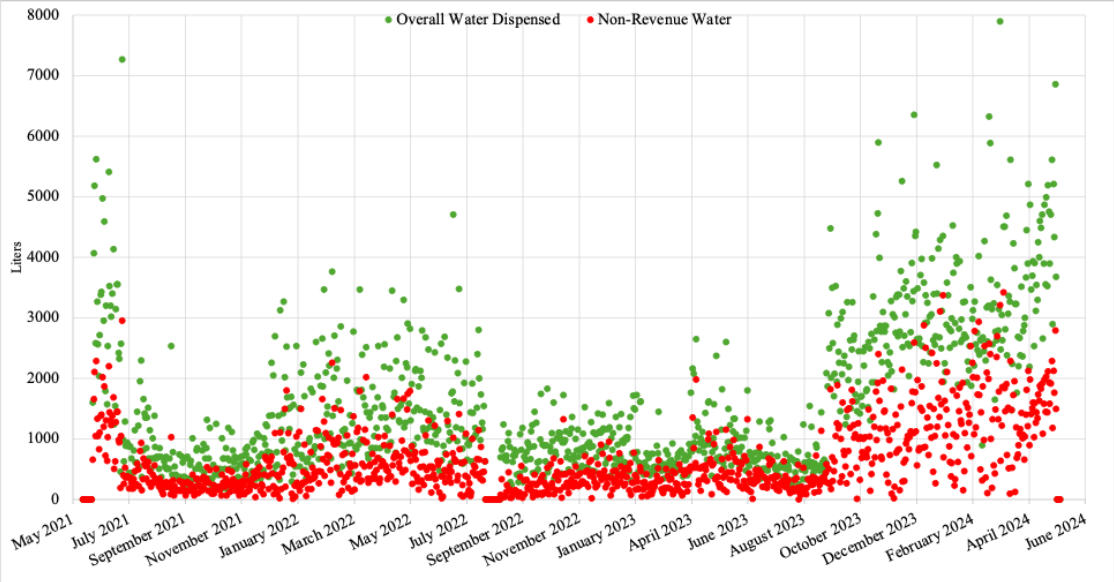


Figure 6-9: Time-Series Scatter Plot of Overall Water Dispensed and Associated Non-Revenue Water

6.3.6. Non-Revenue Water Consistency Across Pricing Models

As shown in Figure 6-10 (free-water periods) and Figure 6-11 (paid revenue-water period), non-revenue water (NRW) remained high and broadly similar across pricing regimes: 40.75% during the free-water windows (905,446 L dispensed; 368,955 L NRW; 293 days) and 41.8% during the paid period (766,051 L dispensed; 320,326 L NRW; 788 days).

This consistency contradicts the assumption, argued by Liemberger and Farley (2005), that charging for water could significantly reduce water wastage. The data suggest that NRW rates are consistent regardless of the pricing strategy, supporting Van den Berg (2014) assertion that effective metering, not just pricing strategies, is crucial for managing NRW. Implementing technologies such as automatic shut-off devices for accurate metering could offer a more effective strategy. Future pilots should explore the efficacy of such technologies in reducing NRW.

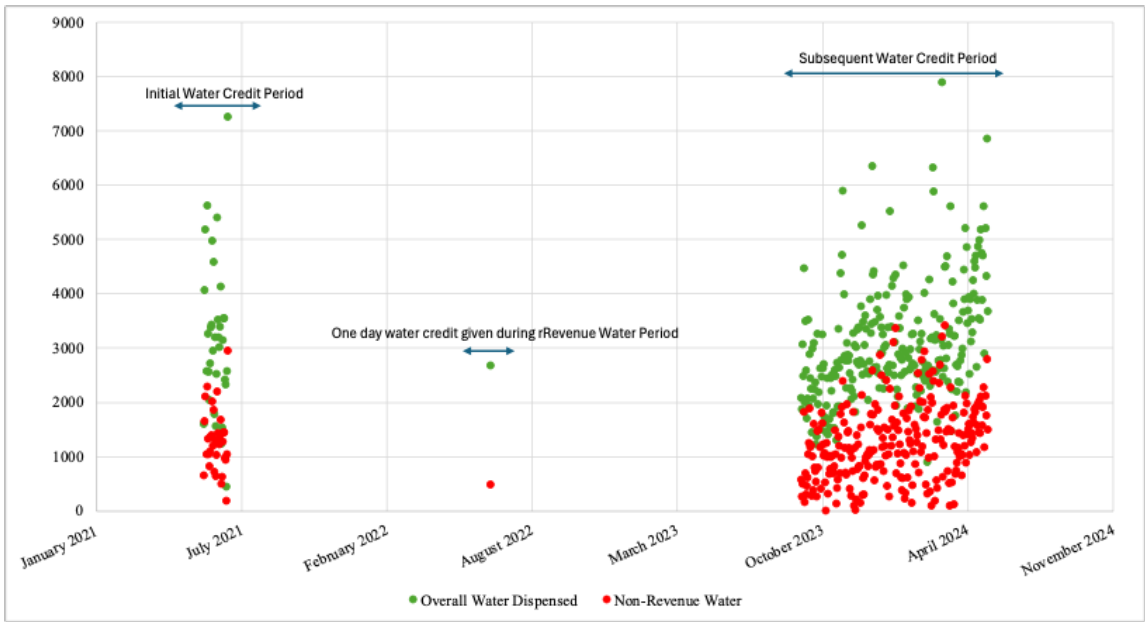


Figure 6-10: Time-Series Scatterplot of Water Dispensed and Non-Revenue Water During Free Water Period

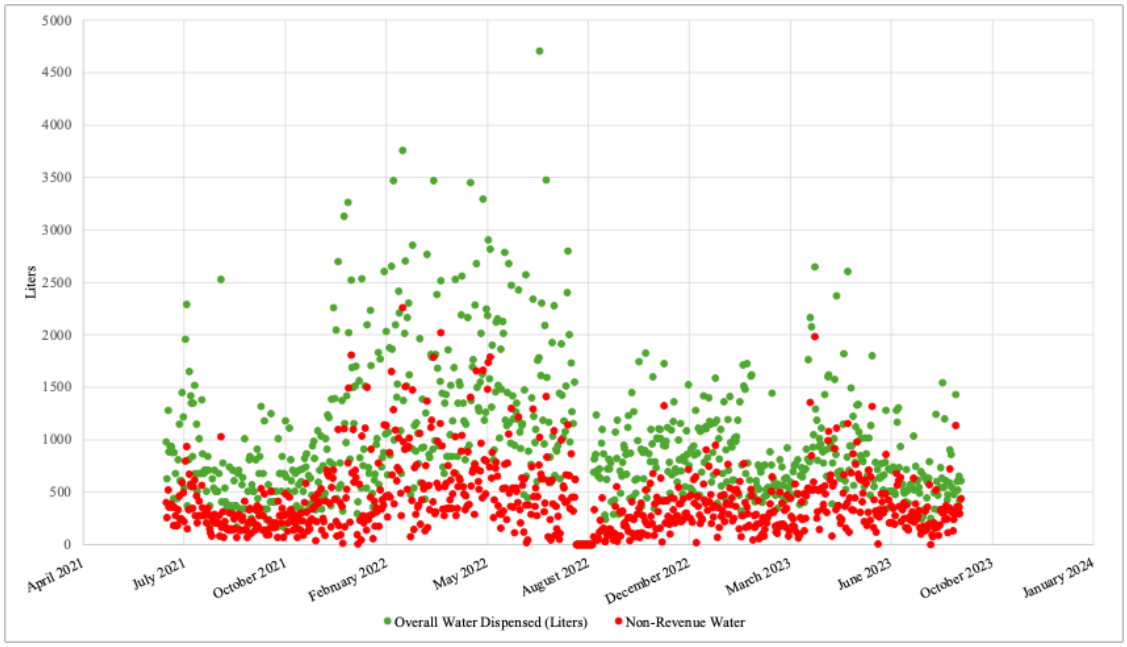


Figure 6-11: Time-Series Scatterplot of Water Dispensed and Non-Revenue Water During Paid Period

6.3.7. Kiosk Usage Is Lowest on Monday at 12.77% of the Week, Making It Optimal for Routine Maintenance

Analysis of weekly water consumption at the smart water kiosk shows the lowest usage on Mondays at 12.77% and the highest on Sundays at 18.1%, as illustrated in Figure 6-12. This trend suggests Monday as the optimal day for maintenance activities like borehole flushing and tank washing, to minimise user disruption. Implementing smart water management systems nationally could facilitate strategic maintenance scheduling, boost operational efficiency, and ensure uninterrupted service. This approach highlights the value of real-time data in enhancing water infrastructure management and user satisfaction.

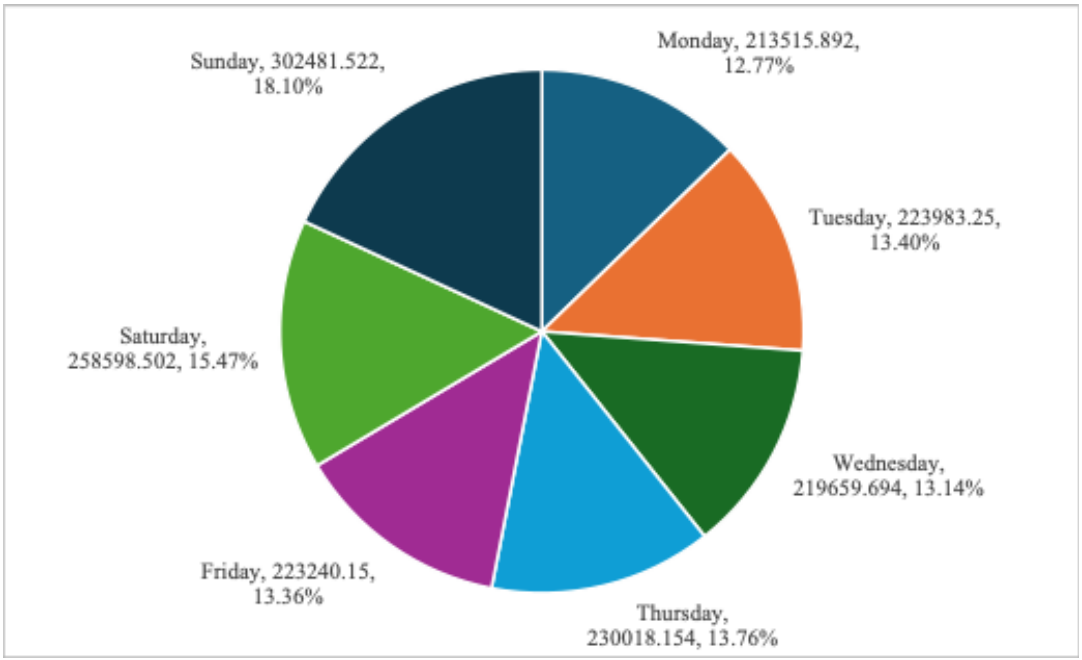


Figure 6-12: Weekly Distribution of Water Consumption at the Smart Water Kiosk

6.3.8. Smart Water Kiosk Achieves 97.1% Reliability and 100% Sustainability Rating

The smart water kiosk demonstrated significant operational success, maintaining a 97.1% reliability rate by functioning effectively for 1,063 out of 1,095 days. This high level of reliability was achieved through continuous monitoring and maintenance facilitated by IoT-based technologies. These systems were instrumental in detecting and addressing operational issues promptly, such as underground leakages, and optimising the timing for routine maintenance without service disruption, thereby ensuring minimal impact on system reliability.

Moreover, despite an initial drop to a 0% Self-Sustainability Rating (SSR) due to aid overlap, meaning the kiosk cannot self-sustain without external support, the kiosk achieved a 100% Sustainability Rating (SR) supported entirely by external funding, covering all operational costs as detailed in Figure 6-13

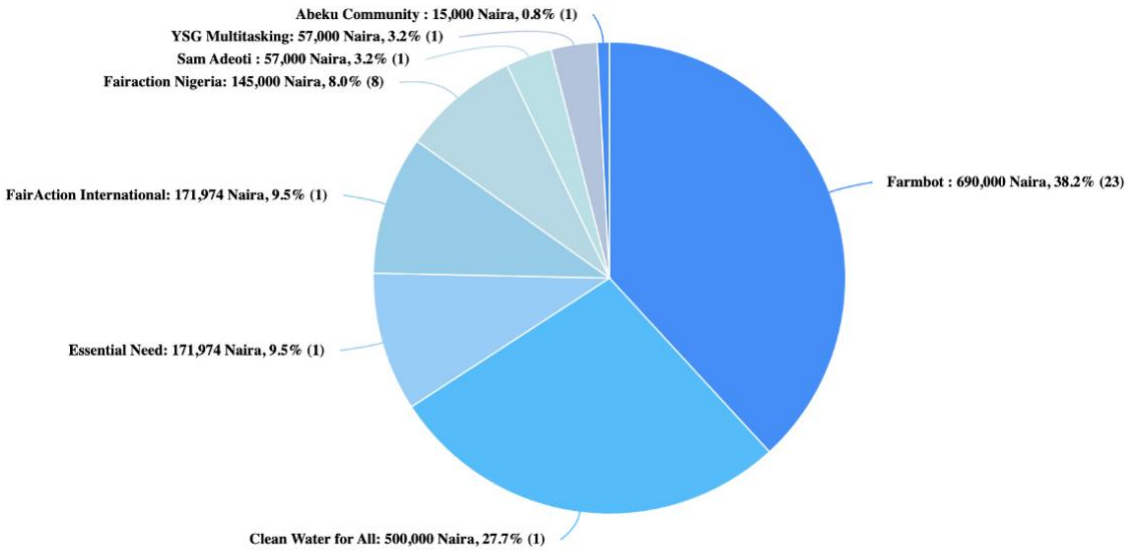


Figure 6-13: Support Contributions for Smart Water Kiosk Operation, Maintenance and Repair

6.3.9. Validation of Smart Water Management Models

The operational efficacy of IoT observed here aligns with the theoretical frameworks proposed by Lee et al. (2015), who advocate integrating ICT with smart water grids to enhance urban water management systems. Consistent with these results, Lee et al. (2015) suggest that ICT integration can streamline operational processes and improve efficiency in managing water resources within smart cities.

Moreover, the empirical results provide a practical benchmark for assessing theoretical models of smart water management. For example, models developed by Fatehi-Nobarian et al. (2023) demonstrate effectiveness in optimising hydraulic operations and predicting seepage in earth dams using advanced meta-heuristic and wavelet-ANN hybrid approaches. Such models could leverage the methodology applied here, which offers a practical framework for evaluating theoretical models in real-world settings.

Overall, the evidence demonstrates the effectiveness of smart water management systems in enhancing the resilience and sustainability of water infrastructure by identifying challenges such as infrastructure underutilisation and aid overlap—phenomena previously undocumented in the literature—and by providing empirical data for data-driven solutions. By leveraging these technologies, this work advances the discourse on integrating innovative solutions to improve water-infrastructure resilience and sustainability in Nigeria and comparable socio-economic regions, offering strategic insights for policy development and technological enhancement.

6.4. Summary and Synthesis

This chapter contributes directly to the development and empirical validation of the life cycle sustainability framework by designing and implementing a real-world Smart Water Infrastructure (SWI) project and demonstrating how SWI can function both as a service model and as a measurement platform. Using 1,095 days of IoT telemetry, the analysis quantifies reliability, cost recovery, revenue water, non-revenue water (NRW), utilisation, water credit, operations and maintenance (O&M) needs, and the Sustainability Rating (SR). The findings show that telemetry-guided maintenance can sustain high reliability while also revealing partial cost recovery (Self-Sustainability Rating, SSR, of 22%) and persistently high NRW of approximately 41%. The marked gap between SR and SSR shows that externally supported sustainability does not equate to financial self-sustainability and that reliable service can coexist with continued dependence on support.

The chapter also identifies two systemic constraints on sustainability. First, overlapping aid emerges as a distinct risk: uncoordinated free alternatives suppress paid uptake, undermine cost recovery, and dilute the impact of installed infrastructure. This reinforces the need for donor coordination, shared data and siting decisions informed by tools such as the Predictive Iterative Sustainability Model (PISM) and verified demand diagnostics. Second, underutilisation is shown to be a persistent constraint under both free and paid service models and is highly price-sensitive, with usage falling by 68.4% when charges are introduced. These patterns highlight the need for stronger pre-construction demand assessment, clearer siting rules and more deliberate community engagement strategies.

Taken together, the findings establish SWI as both a practical pathway for resilient service delivery and a source of longitudinal data needed for adaptive management, refinement of planning and monitoring rules within the framework, and progressive improvement of PISM. They also reinforce a core principle of the research design: each deployment should be treated as a pilot with built-in feedback loops that inform subsequent decisions on siting, service configuration, pricing, O&M scheduling and community engagement.

Despite these contributions, the analysis presented in this chapter has important limitations. It demonstrates that usage remains low even when services are reliable and at times free, but it does not quantify or explain the behavioural or spatial mechanisms that constrain adoption, nor does it derive planning rules or eligibility criteria that would allow these utilisation risks to be anticipated before construction. Chapter 7 addresses these limitations by examining infrastructure underutilisation in depth, analysing behavioural and proximity-related determinants of uptake, and developing pre-construction planning guidance and eligibility criteria to ensure that future deployments are better targeted and more likely to achieve sustainable use.

Chapter 7: Behavioural Dimensions of Sustainability in Water Infrastructure Utilisation

This Chapter is based on the following Publication

Adeoti, O. S., Adeniran, A., Kandasamy, J., & Vigneswaran, S. (2025b). Diagnosing water infrastructure underutilization: a planning framework for behavioral risk, smart monitoring, and SDG 6.1 alignment. *Water Supply*. https://doi.org/10.2166/ws.2025.088

Overview

This chapter builds on Chapter 6, which found that Smart Water Infrastructure performed reliably yet was used at low levels. Recognising underutilisation as a critical threat to long-term sustainability, project impact, and progress towards SDG 6.1, this chapter investigates the behavioural and spatial drivers of adoption. It introduces and empirically validates the Water Infrastructure Underutilisation Principle and examines how perceived safety of existing sources, proximity, and the absence of perceived health risks shape household adoption. The study uses a mixed-methods design that integrates IoT flow data, household surveys, GIS-derived walking times, and clinic records. Within the thesis, this chapter advances the life cycle sustainability framework by converting post-construction evidence into predictive planning guidance, complementing Chapter 5's PISM (predictive planning) and extending Chapter 6's operational evaluation. The chapter's objective is to provide a diagnostic and planning framework for anticipating underutilisation risk and improving alignment between infrastructure delivery, community behaviour, and sustainable adoption in Nigeria and similar contexts.

7.1. Introduction

Under the United Nations' stewardship, the international community is committed to achieving Sustainable Development Goal (SDG) 6.1, which targets universal and equitable access to safe, affordable drinking water by 2030 (United Nations, 2015).

Despite progress, substantial challenges remain, particularly in Sub-Saharan Africa, where pronounced disparities in water infrastructure development and sustainability persist (Adeniran et al., 2021; Adeoti et al., 2023; Andres et al., 2018b). In these regions, the absence of rigorous planning and assessment standards, which are commonly employed in developed countries, impedes the effective implementation and long-term sustainability of water infrastructure projects (Adeoti et al., 2024a; Adshead et al., 2019).

Water systems in developed countries exemplify robust infrastructure planning processes, where pre-construction and resilience assessments are used to manage health, safety, economic risks, and interdependencies (Fekete, 2011; Thacker et al., 2017). High-income countries such as Canada, the Netherlands, and Germany have developed infrastructure criticality criteria to optimise outcomes (Fekete, 2011; Robert, 2003; Vrijling et al., 2004). Despite the importance of these assessments, developing countries like Nigeria often lack such evaluations, leading to resource wastage, recurrent project failures, and widespread underutilisation (Adeniran et al., 2021; Adeoti et al., 2025c; Adeoti et al., 2024a, 2024b). A practical implication is that expanding service access alone does not guarantee household uptake; even technically compliant systems can remain underutilised once delivered.

In Nigeria, most water infrastructure projects, including boreholes and standpipes, are delivered by non-governmental organisations, government agencies, and water authorities, with funding derived from public budgets and international aid (Adeniran et al., 2021; Adeoti et al., 2023; Andres et al., 2018a). Over 60% of the rural population relies on boreholes for daily drinking water. (Akpabio & Takara, 2014; UNICEF & WHO, 2021). Household piped connections are rarely feasible in rural and peri-urban areas due to prohibitive capital and maintenance costs, making communal systems such as boreholes and standpipes the predominant service model. While these systems address immediate shortages, they frequently neglect long-term sustainability (Adeniran, 2022b; Adeoti et al., 2023; Bonsor et al., 2015; Whaley & Cleaver, 2017). A critical gap in pre-construction planning and post-construction monitoring has exacerbated the short-term orientation of these projects, limiting their long-term effectiveness (Abbas et al., 2016; Adeoti et al., 2024a; George-Williams et al., 2024). Consequently, assessing the performance of communal infrastructure over time is vital. Accordingly, this study

evaluates a communal smart water kiosk designed for water-poor rural settings as a realistic alternative to household piped connections.

Infrastructure underutilisation is an insufficiently documented issue affecting communal water systems, despite its major implications for sustainability and investment efficiency (Adeoti et al., 2025c). In this study, underutilisation is defined as the suboptimal use or neglect of functional infrastructure, including in communities officially classified as suffering extreme water poverty under international benchmarks such as UNESCO, UN-Water, and the WHO/UNICEF Joint Monitoring Programme (Programme et al., 2023; UN & WHO, 2024). While these benchmarks provide a useful basis for global comparison (e.g., source type, distance, availability), they do not capture the local behavioural dynamics that determine use. Although underutilisation has been recognised in other infrastructure sectors (Qiao et al., 2024; Uzgör & Şengür, 2022), its manifestations in the water sector remain conceptually underdeveloped and empirically under investigated. This study addresses that gap by providing the first detailed analysis of the behavioural, spatial, and planning dimensions of water infrastructure underutilisation in a resource-scarce, high-need setting.

The chronic underutilisation of water infrastructure undermines cost recovery, economies of scale, and project sustainability, slowing progress toward SDG 6.1. In Nigeria and across Sub-Saharan Africa, project justifications frequently rely on generalised data that lack the granularity to capture local behavioural dynamics shaping uptake and long-term use (Adeoti et al., 2024b; Hope et al., 2020). Similar limitations have been recognised globally, where studies emphasise the importance of modelling context-specific drivers to align infrastructure with demand. Carrying-capacity analysis in Xi'an aligns services with projected need (Yang et al., 2019). In Pakistan, GIS-guided siting in Lahore and MODIS monitoring in Gilgit-Baltistan improve system placement and adaptive management (Siddiqui et al., 2023; Zafar et al., 2021). In the Upper Indus Basin, geomorphological assessment shows how physical setting and governance shape feasible pathways (Ahtisham et al., 2024). Cross-domain evidence on parameter sensitivity reinforces the value of predictive approaches that incorporate local conditions (Ahamad et al., 2020). Together, these insights highlight the importance of demand-aware planning

that moves beyond coverage typologies to address behavioural and spatial determinants of uptake.

Understanding why communities facing extreme water poverty underutilise infrastructure requires attention to behavioural, socioeconomic, and operational factors alongside entrenched planning norms. Frameworks such as RANAS (Risk, Attitudes, Norms, Abilities, and Self-Regulation) support post-construction behaviour change (Mosler, 2012) but are not suited to pre-construction, where predictive rather than corrective assessment is needed. These models depend on extensive post-construction data and prolonged engagement, making them impractical for early planning. In the absence of predictive and pre-construction assessment methods, projects often rely on generalised metrics such as JMP classifications (e.g., “improved” and “unimproved”), which overlook user behaviour and may lead to limited uptake. To address this gap, this study examines behavioural thresholds identifiable before deployment, offering perception-informed, spatially sensitive planning heuristics that can refine water-poverty assessments and support progress toward SDG 6.1 in comparable contexts.

7.2. Methodology

Figure 7-1 provides an overview of the methodology process, summarising the key steps that are elaborated in the subsections that follow.

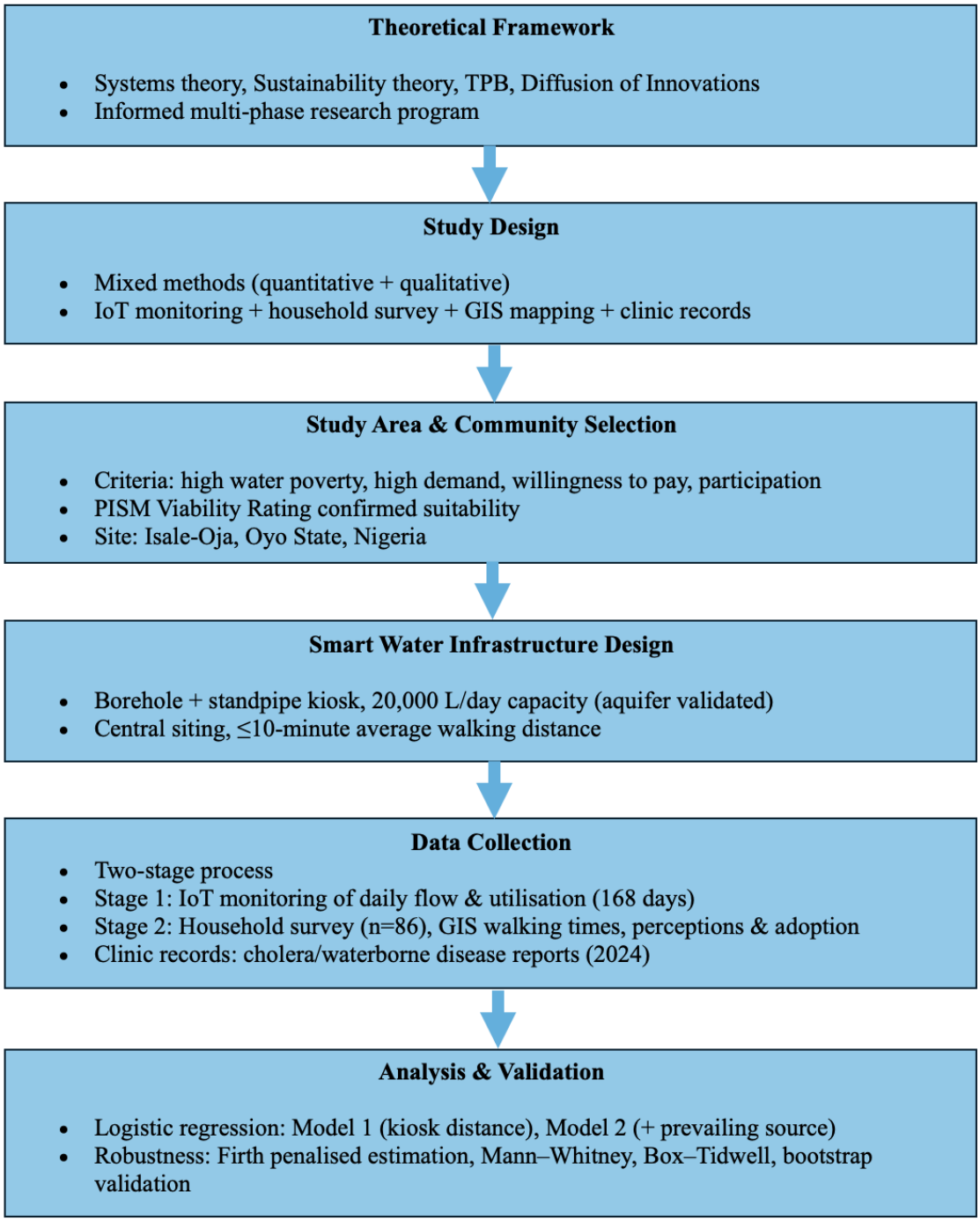


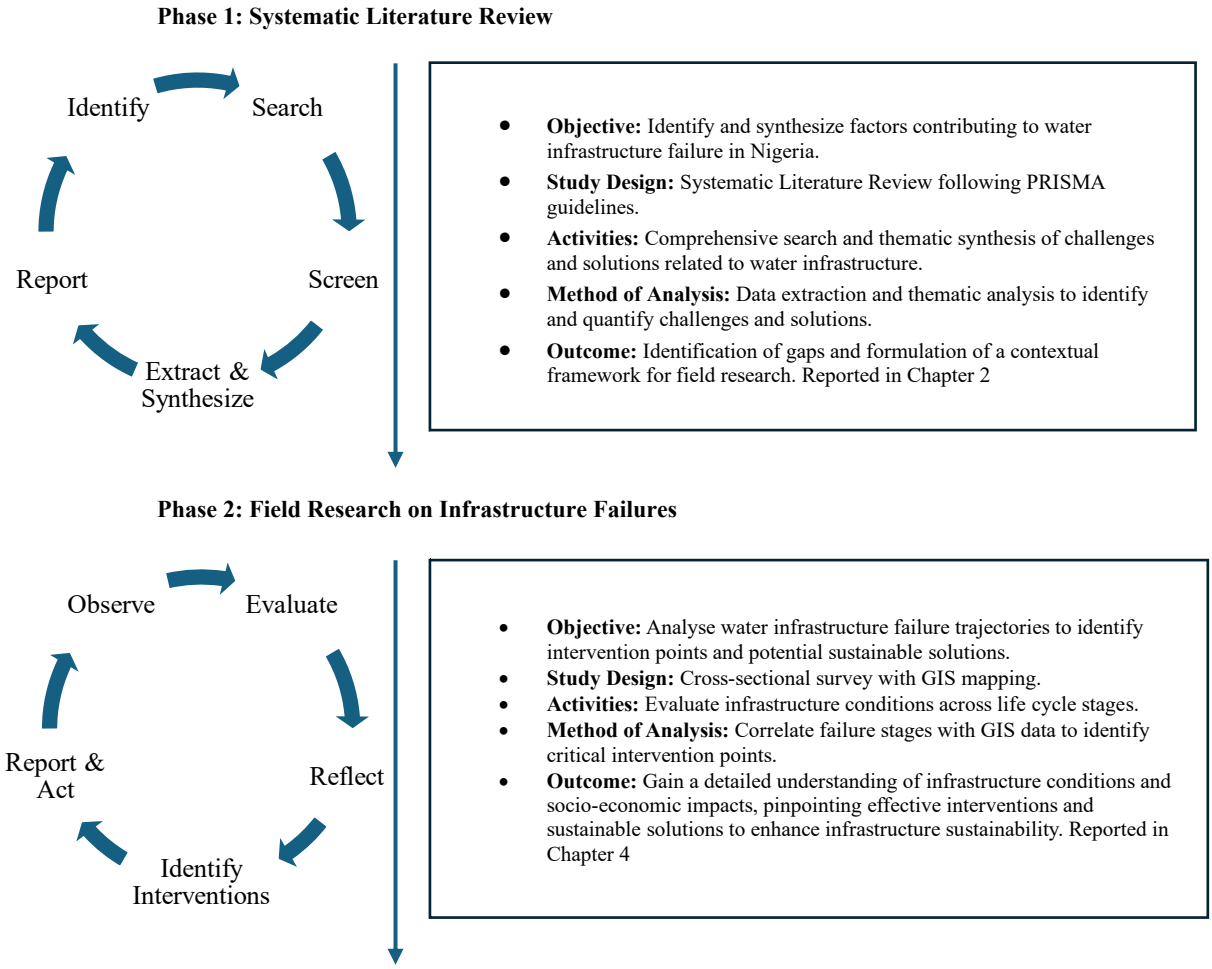
Figure 7-1: Methodology process flowchart

7.2.1. Theoretical Framework

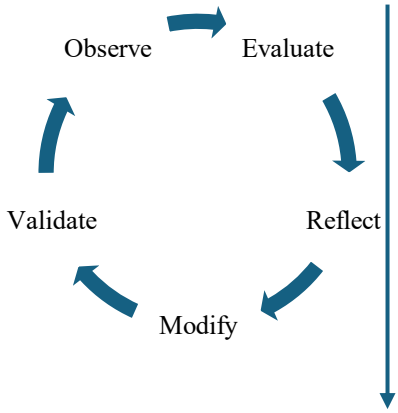
This study integrates four perspectives to examine water-infrastructure sustainability and underutilisation in resource-scarce settings. Systems theory views infrastructure as a

complex adaptive system shaped by technical, institutional, and community dynamics (Meadows, 2008; Ostrom, 2009); sustainability theory emphasises long-term viability and the interdependence of environmental, financial, and governance factors (Harrington, 2016; United Nations Human Settlements, 2006)); the Theory of Planned Behaviour (TPB) links household adoption to attitudes, perceived behavioural control, and subjective norms (Ajzen & Schmidt, 2020); and diffusion of innovations theory explains adoption through perceived advantage and contextual fit (Kaminski, 2011; Sahin, 2006).

These lenses are applied within the iterative research and learning cycle detailed in Chapter 3. Figure 7-2 situates the preceding studies within this sequence and shows how the present chapter draws on those outputs to examine underutilisation as a behavioural and spatial constraint on sustainability. In this orientation, the chapter advances the feedback step by translating behavioural evidence into planning heuristics that refine predictive assumptions and strengthen the life cycle sustainability approach.

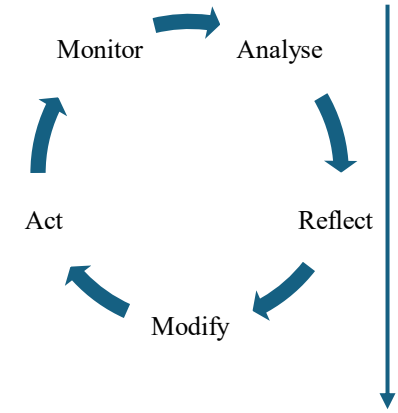


Phase 3: Predictive Iterative Sustainability Model (PISM) Development



- **Objective:** Develop a predictive model using findings from Phase 1 and 2 to assess water project sustainability in Nigeria.
- **Activities:** Apply the PISM using findings from Phase 1 and 2 and make iterative adjustments to the model based on real-world feedback.
- **Study Design:** Predictive Modelling
- **Method of Analysis:**
  - **Data Integration:** Integrate comprehensive data from Phase 1 and 2 to inform the initial modelling.
  - **Iterative Analysis:** Utilize statistical and computational modelling techniques to refine the PISM based on discrepancies between predicted outcomes and actual field data.
- **Outcome:** A validated model predicting project sustainability and effectively informing future interventions. Reported in Chapter 5

Phase 4: Smart Water Infrastructure Solutions and Evaluations



- **Objective**: Evaluate the effectiveness of smart water management systems based on the predictive insights from Phase 3 in enhancing infrastructure resilience and sustainability.
- **Study Design**: Longitudinal monitoring using IoT technology.
- **Activities**: Monitor system performance and gather user feedback via IoT and kiosk attendant reports.
- **Method of Analysis**:
  - **Quantitative**: Analyse IoT data for system performance and usage trends.
  - **Qualitative**: Assess community feedback for acceptance and operational challenges.
- **Outcome**: Insights into operational challenges, community acceptance, and the identification of infrastructure underutilisation as a key sustainability challenge. Reported in chapter 6

Phase 5: Investigating Underutilisation



- **Objective**: Investigate the underutilisation of smart water kiosks in Nigeria, installed based on comprehensive insights and methodologies developed across Phases 1 to 4. This phase aims to explore why infrastructure, meticulously planned and implemented to meet sustainability and operational expectations, remains underutilised.
- **Study Type:** Mixed-Methods Research
- **Design:** Combination of quantitative surveys and qualitative interviews.
- **Data Analysis:** Mixed-methods analysis; quantitative statistical tests and qualitative thematic analysis.
- **Outcome:** A detailed understanding of underutilisation dynamics and strategic recommendations to increase infrastructure use, reported in this chapter, which presents Phase 5 of the multi-phase research within a transdisciplinary enquiry.

Figure 7-2: Flowchart of the Sequential Research Phases.

7.2.2. Study Design

This study investigates the underutilisation of smart water infrastructure (SWI) in a high-need Nigerian community, focusing on the behavioural and spatial dynamics influencing household adoption. Using a mixed-methods design, it combines quantitative monitoring of infrastructure usage with qualitative assessments of community perceptions and access barriers. Usage was tracked through IoT-based monitoring of the SWI, while additional data sources included a household survey on perceptions, behaviour, and socio-demographic factors; GIS-based estimates of walking time to water sources; and clinical records of waterborne illness from a local facility. Together, these sources support a multi-dimensional analysis of household adoption. The SWI evaluated incorporates a borehole and standpipe, reflecting the communal service model predominant in rural and peri-urban Nigeria, where household piped connections are rarely feasible due to capital and maintenance constraints. Framing the analysis around SWI thus captures the practical infrastructure realities of water-poor communities and enables an evaluation directly relevant to their predominant service conditions.

7.2.3. Study Area

The Isale-Oja community in Oyo State, Nigeria (Latitude: 7.6301; Longitude: 3.8462) was selected as the study site due to documented water-access challenges, infrastructure needs, and alignment with national and international benchmarks for water poverty, based on assessment criteria from the WHO/UNICEF Joint Monitoring Programme (JMP) and the Nigeria Bureau of Statistics' Multiple Indicator Cluster Survey (Nigeria Bureau of Statistics & UNICEF, 2022; Programme et al., 2023). Among 1,696 communities mapped through field visits, Isale-Oja was identified as one of the most water-poor (Adeoti et al., 2024b). A location viability rating using the Predictive Iterative Sustainability Model (PISM) confirmed its suitability for Smart Water Infrastructure deployment (Adeoti et al., 2024a). Selection criteria included high water-poverty rates, demand, willingness to pay, and community participation. Reliance on unhygienic and unprotected wells that were visibly discoloured, malodorous, and unsafe further illustrated its status as an exemplar of rural water poverty. Although no laboratory testing was conducted in this

phase, field observations confirmed these wells would not meet drinking water standards. This targeted selection anticipated high utilisation of the installed infrastructure, addressing immediate need, maximising impact, and supporting long-term sustainability.

7.2.4. Infrastructure Design

Figure 7-3 depicts the architectural design of the Smart Water Infrastructure (SWI) installed in Isale-Oja, strategically positioned within a central cluster for accessibility within an average ten-minute walk for intended beneficiaries. Designed with a daily output capacity of 20,000 litres, it targets the community's estimated water demand of 15,090 to 19,345 litres per day, derived from a survey of 86 households and the Predictive Iterative Sustainability Model (PISM) from Phase 3 (See Figure 7-2). The kiosk's capacity was validated through aquifer testing, confirming sufficient groundwater yield to meet Isale-Oja's water needs effectively.

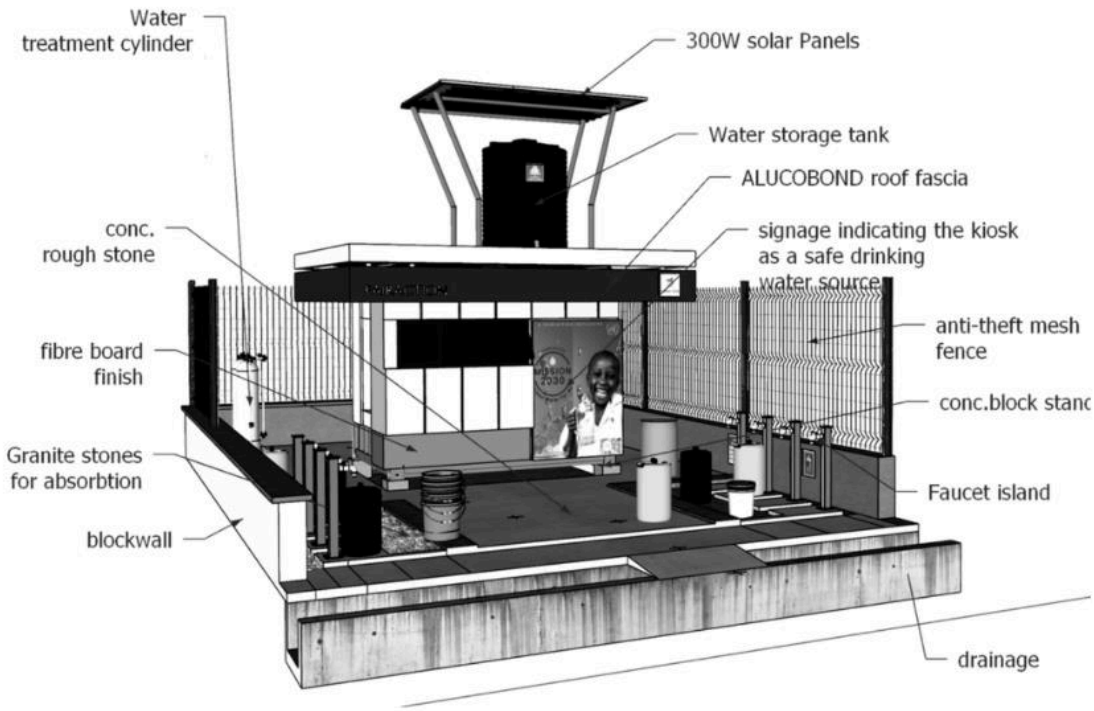


Figure 7-3: Architectural Design of Smart Water Infrastructure (SWI) in Isale-Oja Community, Illustrating Key Components

7.2.5. Data Collection

Data collection was conducted in two stages to thoroughly assess both the quantitative and qualitative aspects of the water infrastructure's utilisation.

7.2.5.1. Stage 1. Infrastructure Utilisation Monitoring

The utilisation rate of the smart water kiosk was continuously monitored using an IoT device that recorded the total water dispensed daily. This IoT setup, as described in Adeoti et al. (2025c), incorporates advanced processes for data anomaly detection, data validation, and data integrity. Over the observation period, total water dispensed was computed as

$$\mathrm{T} = \sum_{n=1}^{N}(\mathrm{WC_n} + \mathrm{RW_n} + \mathrm{NRW_n})$$

Where N is the number of days; WC_n is water credit (free water) on day n; RW_n is revenue water (sold) on day n; and NRW_n is non-revenue water on day n. Equivalently, period totals satisfy $\mathrm{T} = \mathrm{WC} + \mathrm{RW} + \mathrm{NRW}$. The kiosk utilisation rate was then

$$Utilisation\ rate = \frac{T}{N \times Daily\ Capacity}$$

7.2.5.2. Stage 2. Utilisation Investigation

This stage involved a comprehensive household survey to examine utilisation of the Smart Water Infrastructure (SWI) and the reasons for non-utilisation. Survey items covered reasons for non-use, alternative water sources for general and drinking purposes, perceptions of water quality and health outcomes, and household adoption of the SWI. Clinical data from local clinics were integrated to triangulate community perceptions against documented cases of water-related disease. In addition, GIS technology was used to map household locations relative to the kiosk and alternative sources, providing precise measures of physical accessibility.

Sample size determination. The household sample size was calculated using Cochran's formula with a finite-population correction and a design effect to account for clustering. Based on community mapping by Adeoti et al. (2024a), the Isale-Oja population was estimated at 1,900 people, with an average of 4.5 persons per household and 3 households per house. Although the use of averages may reduce household-level variability, it provides a consistent and transparent basis for estimating survey requirements.

Households in the community

The total number of households, H, was estimated from the population $P$and the average number of people per household A:

$$H = \frac{P}{A} = \frac{1900}{4.5} \approx 422 \text{ households}$$

Cochran's formula with finite-population correction

Using $Z = 1.96$(95% confidence), $p = 0.5$(maximum variability), and $E = 0.05$(margin of error), the finite-population adjusted sample size $n$is:

$$n = \frac{z^2 \times p \times (1-p)}{E^2} / \left[1 + \left(\frac{z^2 \times p \times (1-p)}{E^2} - 1\right) / H\right] = \frac{1.96^2 \times 0.5 \times 0.5}{0.05^2} \div \left[1 + \frac{383.16}{422}\right] = \frac{383.16}{1.908} \approx 201 \text{ households}$$

Design effect for clustering

A design effect was applied using $DE = 1 + (b - 1) \times ICC$, where $b$is the average number of households per dwelling and $ICC$is the intra-cluster correlation coefficient. With $b = 3$and $ICC = 0.1$:

$DE = 1+(3-1) \times 0.1 = 1.2$

$n_{adjusted} = 201 \times 1.2 = 241$

Conversion to houses to survey

The final number of houses to survey was obtained by dividing by the average number of households per dwelling:

$n_{final} = \frac{241}{3} \approx 80 \text{ houses}$

Based on these calculations, the adjusted minimum requirement was 80 houses. A total of 86 houses was surveyed to strengthen representativeness and allow for potential non-response.

The household dataset included:

1. **Perceived Quality**: Household perceptions of SWI, boreholes, protected wells, unprotected wells, and sachet water, rated on a four-point Likert scale (Very Good, Good, Poor, Very Poor).
2. **Health Perception**: Self-reported perceptions of water-related health risks, recorded as a binary variable (Yes/No) with qualitative descriptions of perceived safety.
3. **Distance**: Walking time in minutes to SWI and alternatives, measured using Geographic Information System (GIS) mapping.
4. **SWI Usage**: Binary adoption variable (Yes = 1, No = 0).
5. **Clinic Data**: Records from the Oyo State Ministry of Health (Jan–Dec 2024) on cholera and other water-related diseases, used to compare household perceptions with clinical evidence.

7.2.6. Method of Data Analysis

The choice of analytical relationships was guided by the distribution of responses. All survey variables were first tabulated. Perceived water quality (97.7 % "very good") and health-safety perception (100 % "no issues") showed extreme homogeneity. To quantify this lack of variation, the coefficient of unalikeability was computed:

$$U = 1 - \sum_{i=1}^{k} p_i^2.$$

Where p_i is the proportion in the i^{th} response category. Values below 0.10 denote near-zero variance. Quality ($U = 0.05$) and safety ($U = 0.00$) therefore provided no information for inferential analysis and were treated as baseline contextual constants. Table 7-1 provides descriptive statistics for household-level covariates collected in the survey and explains their treatment in the analysis. Variables with near-zero variance (e.g., perceived quality and safety) were treated as contextual constants. Distance to the

current source was tested in a sensitivity model, where it showed a moderate positive effect but was not statistically significant, and distance to the kiosk was retained as the main explanatory variable.

Table 7-1: Descriptive statistics for household-level covariates and rationale for exclusion

Variable	Distribution / Mean (SD)	N	Treatment in analysis
Uses SWI (adoption)	Yes = 16.3%; No = 83.7%	86	Outcome variable; used as dependent variable
Perceived water quality (general)	91.9% Very good; 5.8% Poor; 1.2% Good; 1.2% Very poor	86	Near-zero variance (ceiling effect); treated as contextual constant
Perceived water quality (drinking)	97.7% Very good; 1.2% Poor; 1.2% Good	86	Near-zero variance; treated as contextual constant
Distance to current source	Mean 2.38 mins (SD 0.99; range 0–6)	86	Considered in sensitivity model; showed a moderate positive effect but was not statistically significant
Distance to SWI	Mean 4.21 mins (SD 2.70; range 1–10)	86	Primary explanatory variable; retained in final models

Inferential modelling: Because distance to the kiosk exhibited meaningful spread while quality and safety did not, household adoption (Use = 1 vs 0) was modelled with a parsimonious binary logistic regression using walking time to the SWI (minutes) as the primary predictor, with a sensitivity model that additionally included walking time to the household's prevailing source. The parsimonious primary model included the only variable exhibiting adequate spread, namely walking time to the kiosk (minutes):

$$\text{logit}\,[P(\text{Use} = 1)] = \beta_0 + \beta_1\,\text{Distance}_{\text{SWI.}}$$

A sensitivity model added walking time to the household's current water source to test robustness while respecting the events-per-variable rule (14 adoption events $\rightarrow \leq$ 2

predictors). Models were fitted with maximum likelihood; McFadden's R^2 assessed explanatory power and likelihood-ratio tests compared nested models. Penalised (Firth) logistic estimates were generated to check for small-sample bias; coefficients differed by < 5 %, confirming stability. All analyses were conducted in R Statistical Software (R Core Team, 2023) using the base package stats and the logistf package for Firth's bias-reduced logistic regression (Heinze & Schemper, 2002)

Targeted robustness checks. To confirm that the proximity effect reflected the data structure rather than sample idiosyncrasy, three checks were applied:

1. **Model-free contrast**: Mann–Whitney U with Hodges–Lehmann median difference and Cliff's δ.
2. **Functional-form test**: Box–Tidwell for logit linearity, with a pre-specified 1-df flexible alternative if required.
3. **Bootstrap validation**: 1,000 replicates reporting ROC AUC, Precision–Recall AUC, Brier score, and calibration intercept/slope.

This stepwise approach preserved statistical power despite limited adoption events, adjusted for ceiling effects in perception variables, and yielded interpretable effect-size estimates for the proximity gradient.

7.3. Result and Discussion

7.3.1. Infrastructure Utilisation: Operating at Only 1.52% of Designed Capacity

Household demand for improved water services in Isale-Oja was estimated at 15,090 to 19,345 litres per day, with 103 of 422 households projected to adopt the Smart Water Infrastructure (SWI) system. The kiosk was therefore designed with a 20,000-liter daily capacity, equivalent to expected utilisation rates of 75.5% at the lower estimate and 96.7% at the upper. However, actual usage during the first 168 days post-launch fell far short (Figure 7-4). The kiosk dispensed an average of 304 litres per day, representing 1.52% of its design capacity.

As shown in Figure 7-4, usage was modestly higher in the first month, peaking at 5.05% when water was provided for free. As described in Section 7.2.3 (Study Area), willingness

to pay was assessed during pre-construction and households were engaged and informed that payment would commence after a one-month introductory free period to support ongoing maintenance. Despite this arrangement, usage during the free month remained low and declined further once payment began. This persistent divergence between projected and observed demand establishes the underutilisation problem that subsequent results examine through household source choices, perceived quality and safety, clinic records, and measures of access.

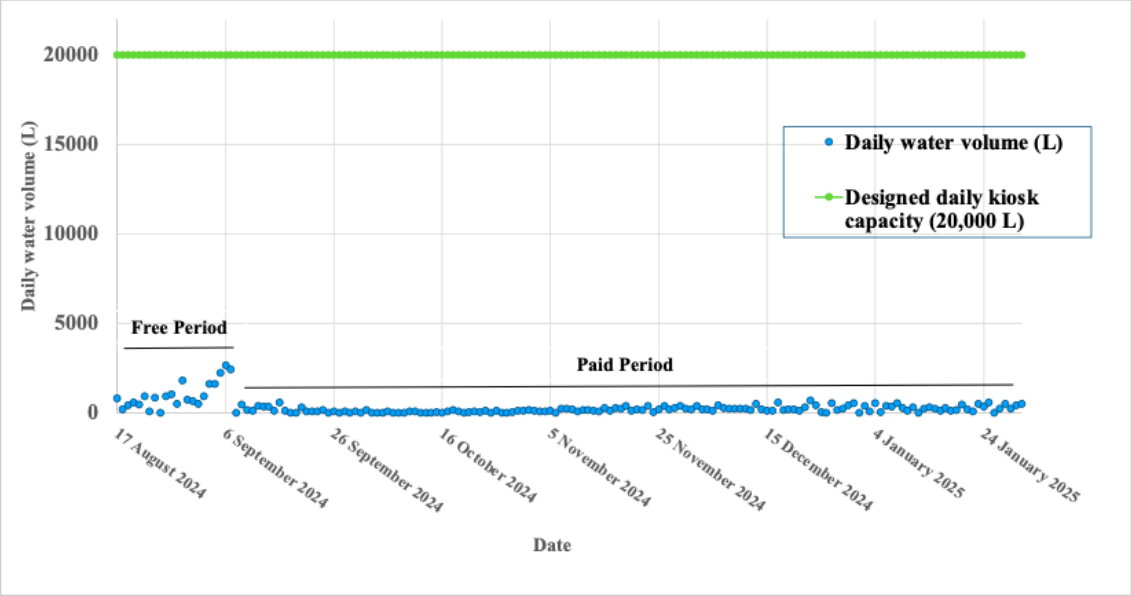


Figure 7-4: Time Series Scatter Plot of Daily Water Kiosk Utilization Compared to Designed Capacity.

7.3.2. Evidence of Persistent Underutilisation from Longitudinal Assessment

Consistent underutilisation, as observed in this study, has important implications for the sustainability of water infrastructure. This finding is reinforced by longitudinal evidence from a 1,095-day evaluation of smart water infrastructure in Nigeria (Adeoti et al., 2025c). Despite continuous monitoring across both rainy and dry seasons and under conditions of free and paid access, utilisation in that study peaked at only 7.63% of design capacity. Underutilisation was therefore evident in both studies, even where technical adequacy and water demand were established. This convergence of evidence

demonstrates that the challenge is recurrent and extends beyond technical sufficiency, highlighting its significance for communities experiencing extreme water poverty.

7.3.3. Alternative Water Sources Utilisation in Isale-Oja

Only 16.3% of 86 surveyed households in Isale-Oja used Smart Water Infrastructure (SWI), indicating a strong preference for alternatives.

7.3.3.1. Non-drinking water sources

- 55% relied on unprotected wells, alone or with other sources.
- 42% used protected wells.
- 19% depended on boreholes.
- 52% supplemented with rainwater.
- 0% used SWI for non-drinking purposes.

Totals exceed 100% because households often used multiple sources (see Figure 7-5).

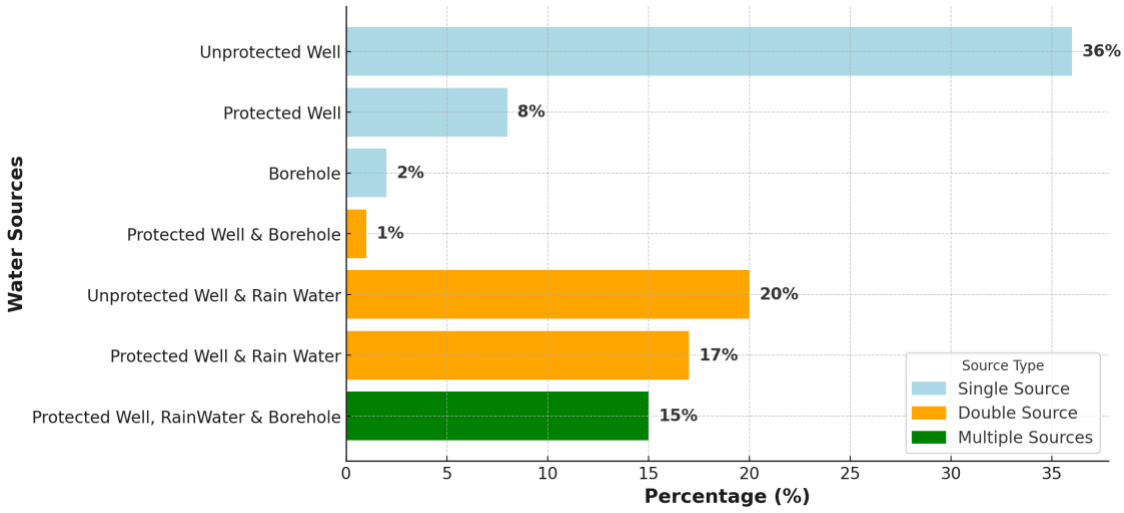


Figure 7-5: Distribution of Water Source Usage for General Purposes

7.3.3.2. Drinking water sources

- 42% used protected wells.
- 37.2% relied on unprotected wells.
- 22.1% depended on boreholes.
- 12.8% used sachet water.
- 16.3% used SWI, alone or in combination.
- 87.2% supplemented with rainwater, reflecting its widespread use for drinking. Availability is seasonal, peaking June–August, declining by September, with dry conditions from November. Although the observation period captured only the late rainy season through the dry season (August–January), SWI utilisation remained consistently low across these months (See Figure 7-4), a pattern also observed in the longitudinal SWI study in Nigeria presented in Chapter 6 (Adeoti et al., 2025c).

As with non-drinking purposes, percentages exceed 100% due to multiple-source use; combinations are detailed in Figure 7-6.

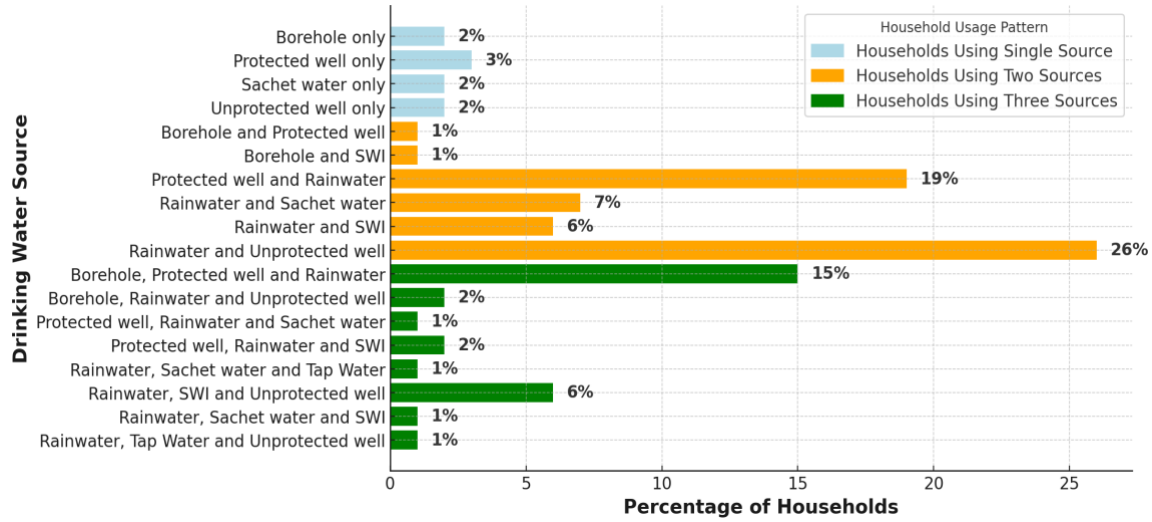


Figure 7-6: Distribution of Water Source Usage for Drinking Purpose.

7.3.4. Drinking Water Quality Perception and Health Safety

7.3.4.1. Self-Reported Perceptions

Survey data from Isale-Oja showed that 100% of respondents reported no water-related health issues, affirming their sources, including unprotected wells (37.2% of households), as safe, despite their classification as unsafe and unimproved by national (Nsdwq, 2015) and international (WHO, 2022b) standards.

7.3.4.2. Quality Perception by Source Type:

- SWI, boreholes, protected wells, and sachet water: 100% of respondents rated these sources as "very good.
- Unprotected wells: 94% rated "very good" and 3% "poor," despite their observed condition as unhygienic and unimproved, highlighting the gap between community perception and technical assessment. This perception of safety, reinforced by the absence of illness, reduces incentives to adopt SWI and underscores the role of perception in underutilisation. Figure 7-7 illustrates this uniformity in perceived quality across sources.

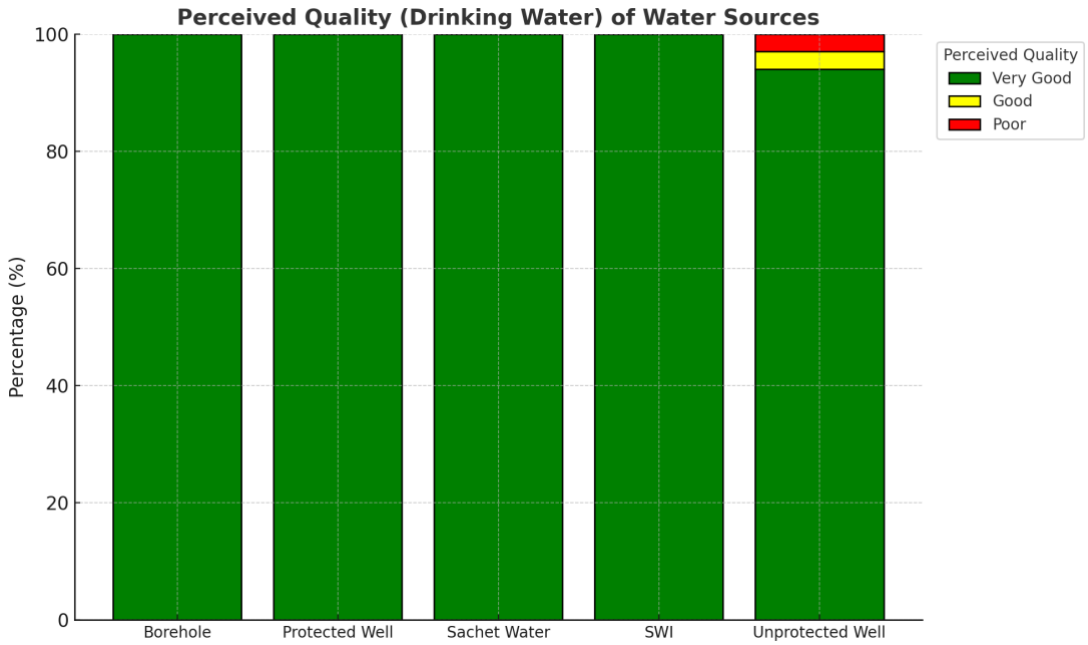


Figure 7-7: Perceived Quality of Drinking Water Sources

7.3.5. Clinic-Validated Outcomes

Clinic records from January–December 2024, covering all 33 local government areas in Oyo State, indicated that only 26 of the state's 3,259 communities reported cholera or other water-related diseases. Isale-Oja was not among them (see Table 7-2). While this absence of documented illness aligns with community perceptions of safety, it does not confirm that water sources are risk-free. Health surveillance systems are prone to underreporting, limited care-seeking, and diagnostic constraints. Nonetheless, the consistency between local perceptions and available clinical data reinforces the behavioural finding that, in the absence of visible or reported illness, communities deem it unnecessary to shift from existing familiar sources. This alignment helps explain why technically improved infrastructure, such as the SWI, may be underutilised even when available and accessible.

Table 7-2: Communities with Water-Related Challenges

Apapa
Kara
Olukolo
Inalende
Olukolo
Inalende
Akintola, Queen Cinema
Kute
Arowolo Dizengoff
Agbokojo Area
Nw5/102 Omitowoju, Ibadan
Aba-Alfa, Ido
No 5, Monilola School Street, Eyin grammar
N0 27 Sowemimo Layout NNPC Apata Ibadan
Yemetu, oja
Oke Are
Academy Olomi
Ile Oju Abere, Isale Afon

Agbonin
Ojude Imam
Olugbon Isale
Bango Alawaye
Ile Aba, Stadium road
Akintola Queen Cinema
Abebi
Nalende

7.3.6. Distance Analysis between Households, Alternative Water Sources, and SWI

GIS mapping showed the following average walking distances in Isale-Oja:

- **Alternative sources:** households were, on average, 2 minutes 23 seconds away, with the farthest up to 6 minutes.
- **SWI:** households were, on average, 4 minutes 13 seconds away, with the farthest up to 10 minutes.

Although the SWI's average distance complied with the United Nations standard for basic water service accessibility, defined as a 30-minute round trip (Cassivi et al., 2018; WHO, 2019), households preferred closer alternatives, typically saving less than 2 minutes irrespective of source safety. Figure 7-8 illustrates the average distances to drinking water sources.

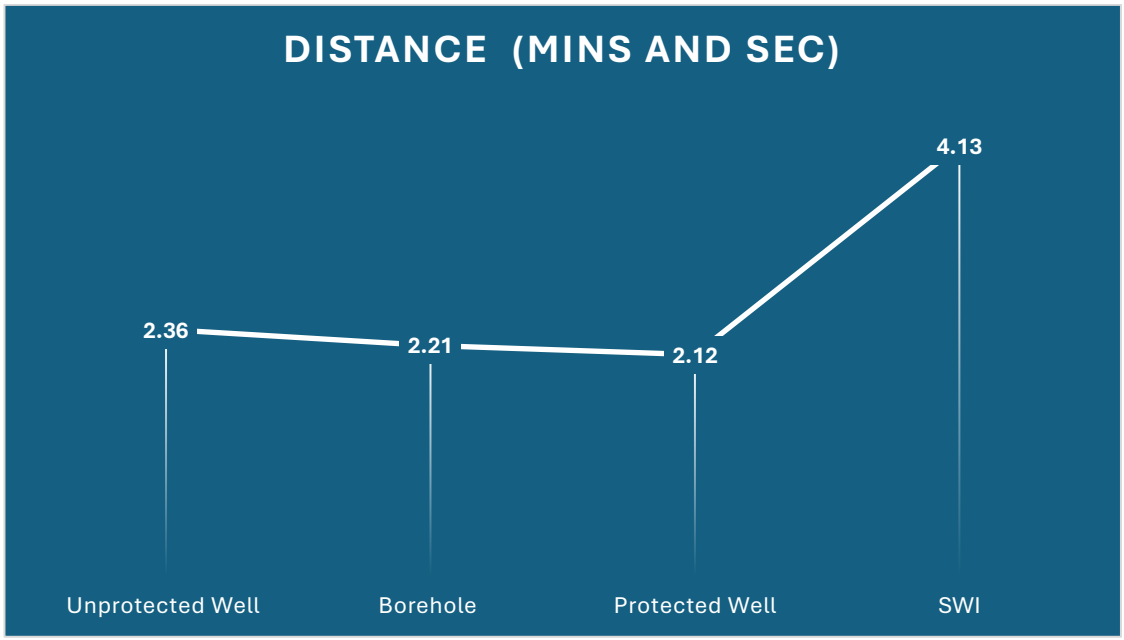


Figure 7-8: Average Distance from households to drinking water sources.

7.3.7. Proximity-effect modelling

Building on the descriptive profile, two logistic-regression models tested whether walking time explains SWI uptake (Table 7-3):

Model 1 (primary): distance to the SWI only. Each additional minute reduced adoption probability by 48% (AOR = 0.52, 95% CI 0.34–0.81, p = 0.003; McFadden R^2 = 0.11).

Model 2 (sensitivity): distance to the SWI plus distance to the prevailing source. The SWI effect remained stable (AOR = 0.55, 95% CI 0.36–0.84), while the added covariate was not significant (AOR = 1.60, p = 0.19; McFadden R^2 = 0.12). Firth-penalised estimates differed by <5%, confirming stability.

Interpretation. The results indicate that where existing sources are perceived as safe and satisfactory, walking time to the SWI appeared to be the key determinant of adoption. Prevailing sources averaged 2.38 minutes away compared to 4.21 minutes for the SWI, and even this modest difference suppressed uptake. This pattern is also consistent with the source-use combinations presented earlier in Figure 7-6. Households were not relying primarily on purchased drinking-water alternatives such as sachet water. Rather, they

continued to use nearby existing sources, especially protected and unprotected wells, often in combination with rainwater. The effect of walking distance should therefore be understood not as a choice between the SWI and distant commercial water sources, but as a choice between the SWI and familiar nearby sources that were already being used and were generally perceived as satisfactory. In this context, even modest differences in walking time were sufficient to suppress uptake. Thus, when familiar sources are closer and perceived as risk-free, new infrastructure, even if treated, reliable, and initially free, is unlikely to displace established behaviour.

The behavioural sequence aligns with the Theory of Planned Behaviour (TPB), which explains adoption through attitudes, subjective norms, perceived behavioural control, and intention. Households displayed favourable attitudes toward familiar sources, a shared norm of perceived safety, and lower perceived behavioural control because longer walking distances constrained access to the SWI. Intention was not directly measured, though a brief rise in usage during the free-water month may indicate temporary willingness to adopt. Behaviour was observed as adoption (use vs non-use). This operationalisation of TPB provides empirical grounding for the Water Infrastructure Underutilisation Principle and suggests that even technically sound infrastructure may remain underutilised when planning does not account for these behavioural drivers.

Table 7-3:Logistic regression of smart-water-kiosk adoption (N = 86)

Predictor	**β (SE)**	**AOR (95 % CI)**	***p***
Primary model			
Walking time to kiosk (min)	−0.65 (0.22)	0.52 (0.34 – 0.81)	0.003
Constant	0.30 (0.58)	1.36 (0.44 – 4.21)	0.598
Sensitivity model			
Walking time to kiosk (min)	−0.60 (0.22)	0.55 (0.36 – 0.84)	0.006
Walking time to current source (min)	0.47 (0.35)	1.60 (0.80 – 3.20)	0.190
Constant	−1.02 (1.14)	0.36 (0.04 – 3.35)	0.370

Note: AOR = adjusted odds ratio; McFadden R^2 = 0.11 (Model 1) and 0.12 (Model 2).

Robustness checks: Robustness checks gave consistent results. Adopters lived closer to the SWI by a median of 3.0 minutes (Mann–Whitney U = 195.0, p = 0.00027), with a

large effect size (Cliff's δ = −0.613) and a Hodges–Lehmann median difference of −3.0 minutes (95% CI −4, −1) (Table 7-4). The proximity effect was linear on the log-odds scale (Box–Tidwell p = 0.930), supporting retention of a linear term. Internal validation for the primary model indicated good discrimination and acceptable calibration: ROC AUC = 0.81 (95% CI 0.69–0.91), Precision–Recall AUC = 0.37 (95% CI 0.20–0.58), and Brier score = 0.112 (95% CI 0.068–0.148), with calibration intercept 0.10 and slope 1.03 (Table 7-5). Maximum-likelihood estimates were checked against Firth's bias-reduced estimates to limit small-sample bias; coefficients differed by less than 5%.

Table 7-4: Model-free contrast of distance to SWI by adoption status

Metric	**Estimate**	**95% CI**	**p-value**	**Notes**
n (adopters / non-adopters)	14 / 72	—	—	—
Median distance to SWI (min): adopters / non-adopters	1.5 / 4.5	—	—	—
Mann–Whitney U	195.0	—	0.00027	two-sided
Hodges–Lehmann median difference (min)	−3.0	[−4, −1]	—	adopters minus non-adopters
Cliff's δ	−0.613	—	—	large effect

Table 7-5: Logistic models and validation

Item	**Estimate**	**95% CI**	**p-value**	**Notes**
Model 1 OR per +1 min (distance to SWI)	0.520	[0.335, 0.806]	0.00346	McFadden's $R^2 \approx 0.11$
Model 2 OR per +1 min (distance to SWI)	0.549	[0.359, 0.841]	0.00585	Includes distance to prevailing source
Model 2 OR per +1 min (distance to prevailing source)	1.598	[0.798, 3.203]	0.186	Not significant
Box–Tidwell nonlinearity p ($x \cdot \ln x$)	—	—	0.930	Linear term retained

ROC AUC (bootstrap-validated)	0.81	[0.69, 0.91]	—	Apparent AUC = 0.807
Precision–Recall AUC	0.37	[0.20, 0.58]	—	Positives = 16.3%
Brier score	0.112	[0.068, 0.148]	—	Null Brier = 0.136
Calibration intercept / slope	0.10 / 1.03	—	—	Logistic recalibration on logit($\hat{p}$)

Context. In Isale-Oja, households perceived existing sources as satisfactory and free of water-related health risks. Under these conditions, walking time to the SWI emerged as the principal determinant of adoption. Convergent evidence from the model-free contrast, the multivariable logistic models, the functional-form check, and bootstrap validation demonstrates that the proximity gradient is statistically robust and behaviourally meaningful at the observed adoption prevalence. This coherent pattern provides the empirical basis for the Water Infrastructure Underutilisation Principle, introduced in the next section.

7.3.8. Introducing the Water Infrastructure Underutilisation Principle

This study introduces the Water Infrastructure Underutilisation Principle, which substantiates established evidence on the influence of distance while contributing new behavioural insight into why technically viable infrastructure remains unused in high-need settings.

The principle holds that in water-poor communities where households perceive their existing water sources as satisfactory and free of health risks, even marginal differences in accessibility can lead to sustained non-use of new infrastructure, regardless of its technical or financial superiority.

7.3.8.1. Empirical Grounding of the Principle

As shown in Section 7.3.6, households in Isale-Oja favoured slightly closer sources that were perceived as safe, even when the SWI offered treated water at no cost. The absence of reported illness, reinforced by clinic records, further illustrates how a lack of perceived harm weakens incentives to switch. These findings empirically substantiate the *Water Infrastructure Underutilisation Principle* and highlight a gap in current water-poverty assessments, underscoring the need for eligibility frameworks that integrate proximity, perception, health outcomes, and affordability.

7.3.8.2. Implications for Water Poverty Assessment

Global monitoring frameworks such as the WHO/UNICEF Joint Monitoring Programme (JMP) provide standardised water access metrics, including availability, accessibility, quality, and safely managed classifications (UNICEF & WHO, 2024). These benchmarks are widely used by funders and agencies to track progress toward SDG 6.1. However, they overlook behavioural dimensions. In Isale-Oja, for instance, unprotected wells deemed unsafe under national (Nsdwq, 2015) and international (WHO, 2022b) standards were nonetheless rated "very good" by households, illustrating how perception can override technical classification.

To address this, water poverty assessments should be expanded to include the following behaviourally predictive variables:

- **Perceived quality and satisfaction:** how households themselves rate or feel about the water they use (e.g., "very good," "safe," "satisfactory"), even when this diverges from national or international safety standards ((Satterthwaite & Mitlin, 2013).
- **Health outcomes** linked to water use, validated against clinic records where possible (Hunter et al., 2010).

- **Proximity of existing sources**: even small distance differences significantly affect adoption (Burt & Ray, 2014; Okumah & Yeboah, 2020).

Integrating these behavioural predictors with assessment metrics or reporting such as JMP can improve diagnostic accuracy, help ensure interventions reflect community realities, and increase the likelihood of sustained adoption. This combined framework may offer greater practical value for planners and funders and provide a more effective pathway for accelerating progress toward SDG 6.1.

7.3.9. Study Limitations

A key limitation was the community-wide perception bias: 97.7% of households rated their sources, including unprotected wells, as "very good," and none reported health concerns. This uniformity limited the use of perceived quality and safety as explanatory variables. To address this, the analysis (i) treated these perceptions as contextual constants, (ii) focused the logistic model on walking distance, which showed sufficient variation, and (iii) triangulated results using Firth-penalised estimation (<5% coefficient drift) and 168 days of IoT flow data, which recorded usage at 1.5% of design capacity.

Another limitation was the absence of laboratory testing of alternative sources such as unprotected wells, which restricts the ability to confirm definitively that sources perceived as safe were in fact unsafe. To address this, it was assumed these sources were unsafe based on their appearance, including discolouration, odour, and unhygienic surroundings. Future research should incorporate laboratory testing to triangulate perceptions of safety with measured contaminants and, where feasible, link results to health outcomes through longitudinal tracking.

A further constraint was the small number of adoption events (14 of 86), which limited model complexity and explanatory power. To mitigate this, robustness checks were applied (non-parametric contrast, functional-form test, and bootstrap validation; see Tables 7-4 and 7-5). While the findings may not be statistically generalisable, the behavioural pattern, methodological approach, and underutilisation principle are

conceptually transferable to other resource-scarce settings facing similar challenges.

7.4. Summary and Synthesis

Water infrastructure in resource-scarce settings often remains underutilised despite being technically sound and publicly funded. This chapter introduces the Water Infrastructure Underutilisation Principle; a behavioural insight developed through an integrated research design. Drawing on household surveys (n = 86), GIS-derived walking times, IoT flow data and clinic records, it investigates adoption behaviour—defined as household uptake of Smart Water Infrastructure (SWI) for drinking—in a Nigerian community classified as water poor. Despite access to treated water from an SWI initially offered for free, only 16.3% of households used the system, while 97.7% rated their existing sources, including unprotected wells, as "very good."

IoT monitoring over 168 days recorded usage at just 1.52% of the system's design capacity. Walking time to the SWI averaged 4 minutes 13 seconds, compared with 2 minutes 23 seconds to alternative sources, and proximity-effect modelling showed that each additional minute of walking reduced the odds of SWI adoption by 48% (AOR ≈ 0.52). These findings reveal a threshold dynamic shaped by perception, proximity and the absence of perceived water-related health risks from existing sources. They support behaviourally informed planning reforms that provide a transferable framework for diagnosing underutilisation risk and advancing SDG 6.1 by aligning infrastructure delivery with community uptake.

However, while this chapter explains why technically sound infrastructure can remain underused, it does not incorporate water quality or treatment feasibility; therefore, the safety dimension of SDG 6.1 remains unaddressed. Chapter 8 addresses this limitation by examining groundwater quality in public boreholes and piloting treatment options in low-resource settings, integrating water-quality risk and practicable treatment pathways into the sustainability framework.

Chapter 8: Water Quality, Treatment Feasibility, and Sustainability Pathways

This Chapter is based on the following Publication

Adeoti, O. S., Kandasamy, J., & Vigneswaran, S. (2025a). *Assessing water safety and treatment feasibility in Nigeria's public boreholes: Toward SDG 6.1 compliance*. Manuscript submitted for publication in Water Policy.

Overview

This chapter addresses the final empirical component of the thesis by integrating water quality and safety into the life cycle sustainability framework. While earlier chapters examined infrastructure functionality, predictive planning, smart operations and behavioural utilisation, this chapter focuses on the safety of delivered water, which is essential to achieving the full intent of SDG 6.1. In the context of Nigeria's widespread reliance on untreated groundwater from public boreholes, it examines how contamination risks can undermine health and sustainability even where infrastructure is present.

A mixed-methods design is applied, combining accredited laboratory analysis of borehole water quality across multiple parameters with correlation and proxy-test modelling and pilot treatment interventions at selected sites. Guided by water safety planning, systems thinking and adaptive governance, the chapter assesses compliance with NIS 554:2015 in resource-constrained settings, tests simplified monitoring strategies and evaluates the technical, socio-technical and financial conditions under which treatment technologies can be integrated into public water systems at scale.

Within the overall research sequence, this chapter extends the sustainability framework from behavioural and operational performance in Chapter 7 to quality assurance, regulation and treatment feasibility, completing the life cycle analysis. It provides the conceptual and empirical basis for incorporating water safety, realistic treatment

pathways and regulatory flexibility into planning and monitoring. Chapter 9 then draws on these results, together with findings from the earlier chapters, to synthesise a comprehensive framework for reliable and safe drinking water access in Nigeria and comparable low-resource settings.

8.1. Introduction

Access to safe drinking water is fundamental to public health and sustainable development, yet global progress remains uneven, particularly in developing regions (UNICEF & WHO, 2021). The United Nations' SDG 6.1 aims to "achieve universal and equitable access to safe and affordable drinking water for all" by 2030 (United Nations, 2015), prompting major investments in groundwater infrastructure, especially public boreholes (Adeoti et al., 2023; Carter, 2015; Rivett et al., 2019). These systems are valued for their perceived reliability, low maintenance requirements, reduced exposure to surface-level contamination, and resilience to climate change, making them a practical solution for underserved communities, particularly in Sub-Saharan Africa (Lapworth et al., 2017; MacDonald et al., 2011). However, this access-driven approach has often overshadowed the need to ensure water safety, which is a critical component of SDG 6.1 (Bain et al., 2014a). Without adequate quality assurance or treatment infrastructure, these boreholes may deliver unsafe water, undermining intended health benefits (Rivett et al., 2019; Verlicchi & Grillini, 2020).

In Nigeria, groundwater is the main drinking water source for over 60% of the population, especially in rural and peri-urban areas, with public boreholes serving as the primary infrastructure to address scarcity (Adeoti et al., 2023; UNICEF & WHO, 2021). Despite this reliance, borehole water is often assumed safe, as reflected in the widespread absence of treatment systems (Egbinola & Amanambu, 2014; Nwinyi et al., 2020). This assumption overlooks the Nigerian Standard for Drinking Water Quality (NIS 554:2015), a legally binding regulation that sets health-based limits for a comprehensive set of parameters, including pH (6.5–8.5), turbidity (<5 NTU), total dissolved solids (<1000 mg/L), arsenic (0.01 mg/L), fluoride (1.5 mg/L), and zero coliforms per 100 mL, among others (Standards Organisation of Nigeria, 2015). Yet compliance with these standards remains limited (Egbinola & Amanambu, 2014). By prioritising access over safety,

current implementation risks undermining both NIS 554:2015 and SDG 6.1, prompting the need to re-evaluate national water provision strategies (Bain et al., 2014a).

Building on the safety challenges outlined, Adeoti et al. (2024b) mapped 1,696 communities across Ekiti, Osun, and Oyo states, identifying 434 functioning public boreholes used for drinking, many of which rely on hand-pumps. These boreholes, funded by diverse stakeholders— namely the Federal Ministry of Water Resources (23.8%), State Governments (41.6%), and other contributors (34.6%) such as Local Governments, NGOs, politicians, and churches—reflect a concerted effort to address water scarcity (Adeoti et al., 2024b). However, none of these boreholes, including those installed by the federal government, have treatment plants, despite NIS 554:2015 mandating stringent safety standards.

This gap highlights a critical disconnect, as Nigeria continues to expand water access through new and existing infrastructure without incorporating treatment, which likely causes many boreholes to fall short of NIS 554:2015 and undermines SDG 6.1's dual focus on access and safety (Bain et al., 2014a). Without assured safety, these efforts risk exposing communities to significant health hazards. As a result, important questions emerge regarding how many of the 434 boreholes require treatment and why federal projects are deployed without it. While technical and financial constraints may contribute, the federal government's failure to meet its own standards signals a deeper systemic issue. Exploring the extent of groundwater contamination and barriers to treatment is therefore critical to ensuring safe water access in Nigeria.

Multiple studies across Nigeria challenge the assumption that groundwater is inherently safe, revealing widespread geogenic and anthropogenic contamination that compromises potability (Omeka et al., 2024). Geogenic risks, such as arsenic and fluoride, arise from natural mineral dissolution. In Ibadan, South-West Nigeria, arsenic exceeds the NIS 554:2015 limit of 0.01 mg/L in 98–100% of groundwater samples across seasons, while fluoride surpasses the 1.5 mg/L threshold in 13–100% of samples, increasing the risks of cancer and fluorosis (Egbinola & Amanambu, 2014). In Gombe State, fluoride levels reach 4.41 mg/L, with widespread dental fluorosis reported (Giwa et al., 2021). Anthropogenic contamination exacerbates these risks, with microbial pollution prevalent

in urban centres (Margat & Van der Gun, 2013). In Benin City, total coliform counts reach 14 MPN/100 mL, exceeding the 0 CFU/100 mL standard (Erah & Akujieze, 2002). In the Niger Delta, 66% of samples fail microbial criteria, and salinity from seawater intrusion raises TDS levels to 1,090 mg/L (Efobo et al., 2020). Given these widespread safety risks, systematic testing and treatment are imperative to safeguard public health and ensure compliance with national standards.

Accordingly, this study builds on the sustainability shortcomings of Nigeria's water infrastructure documented by Adeoti et al. (2023, 2024b), confronting the equally critical, yet largely neglected, dimension of water safety that exacerbates infrastructure failure and undermines progress toward SDG 6.1. The persistent disconnect between national regulatory standards (e.g., NIS 554:2015) and implementation realities underscores the need for a pragmatic, evidence-based approach to water quality within Nigeria's broader sustainability discourse. Consequently, this study pursues two interconnected objectives:

(1) to assess the extent and patterns of borehole contamination by determining the proportion failing to meet NIS 554:2015 standards, identifying commonly failing physicochemical and microbiological parameters, and exploring their interrelationships, thereby providing actionable insights for resource allocation and informing preventive and treatment strategies; and

(2) to pilot basic point-source treatment options (e.g., cartridge filtration, chlorination), evaluating their effectiveness in achieving post-treatment compliance, while critically assessing the suitability of current NIS thresholds for low-resource environments and offering evidence-based recommendations for phased compliance and regulatory reform.

By integrating diagnostic analysis, field-tested interventions, and critical policy evaluation, this study aims to provide a scalable decision-making framework for water quality improvement in Nigeria and similar low-resource settings. The findings are intended to inform sustainable infrastructure design, guide investment in pragmatic treatment solutions, support regulatory evolution and clarify barriers to treatment

scalability as a socio-technical system by considering technical, financial and contextual constraints, thereby advancing both national progress and the global mandate of SDG 6.1.

8.2. Methodology

8.2.1. Theoretical Framework

This study integrates three theoretical frameworks, namely water safety planning, systems thinking, and adaptive governance, to address the complex water safety and sustainability challenges facing Nigeria's public boreholes. The Water Safety Planning (WSP) framework (WHO, 2022a) guides Objective 1 through risk-based assessment of contamination patterns and parameter interactions (e.g., turbidity and microbial contamination), and provides information to Objective 2 by evaluating basic treatments (e.g., filtration, chlorination) for health risk mitigation. Systems thinking (Meadows, 2008) frames treatment scalability as a socio-technical issue where feedbacks among technology, finance, capacity, and regulation determine feasible treatment pathways and sustained compliance. Adaptive governance (Dietz et al., 2003, 2017) supports Objective 2 by advocating phased compliance with NIS 554:2015 to balance public health goals with feasibility in resource-constrained settings. Together, these frameworks underpin an evidence-based strategy for advancing SDG 6.1 in Nigeria.

8.2.2. Research Design

This study employed a mixed-methods design, integrating cross-sectional quantitative analysis with an embedded case study and a field-based pilot treatment facility, complemented by qualitative investigation of scalability barriers. The design provided diagnostic breadth through quantitative water quality assessment, contextual depth via site-level case analysis, and applied relevance through real-world intervention testing.

8.2.3. Study Area

The study covered two distinct site categories: selected public boreholes across four states, and smart water kiosks with treatment in Oyo State.

8.2.3.1. Public Boreholes Across Four States

Seventeen borehole water samples were analysed across four Nigerian states: Lagos (7 samples), Oyo (6 samples), Ogun (3 samples) and Delta (1 sample). Five samples were collected directly through field-based sampling, while twelve were obtained from laboratory archives following outreach to accredited testing facilities. Together, these samples form a purposive dataset reflecting diverse hydrogeological and socio-economic contexts, including urban-industrial zones in Lagos and peri-urban and rural communities in Oyo and Ogun.

8.2.3.2. Smart Water Kiosks in Oyo State

Two smart water kiosks located in Oyo State, Isale-Oja in Ijaye Orile (Lat: 7.6301, Long: 3.8462) and Alabata Village (Lat: 7.5874, Long: 3.8688), were selected based on prior location viability assessments by (Adeoti et al., 2024a) and their infrastructural readiness to accommodate integrated treatment systems (Adeoti et al., 2025c). Pre-intervention water quality testing confirmed non-compliance with NIS 554:2015 at both locations, making them suitable case studies for piloting context-appropriate treatment technologies. Figure 8-1 illustrates the architectural layout of the kiosks, while Figure 8-2 presents the treatment process configuration implemented at each site.

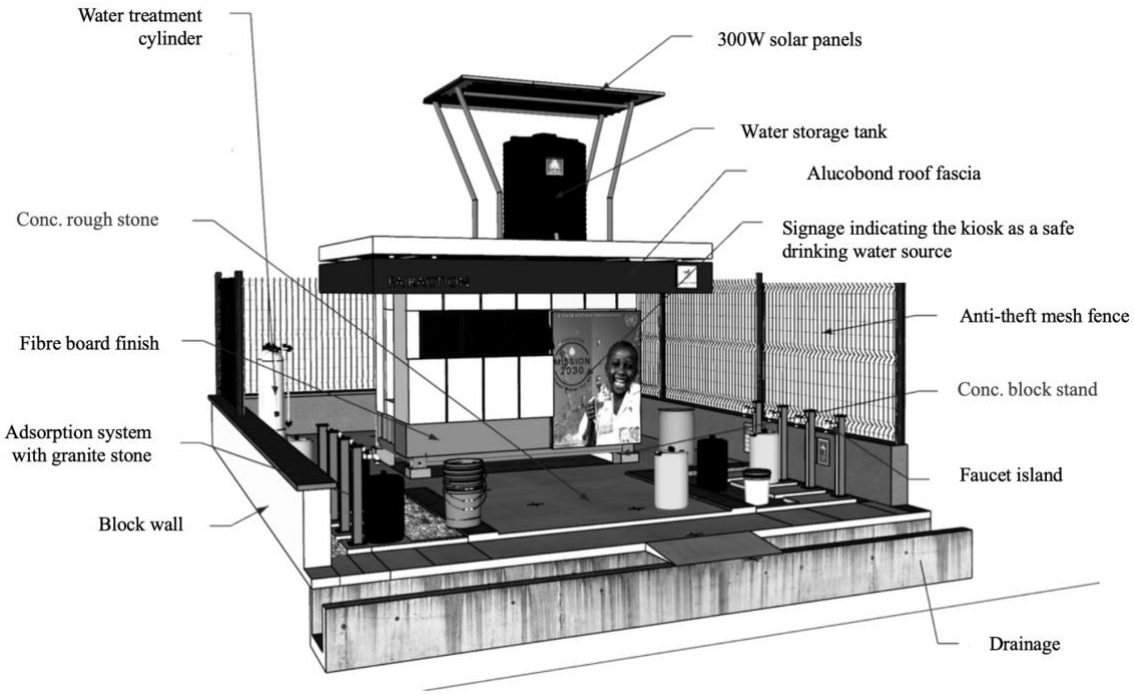


Figure 8-1: Architectural layout of smart water kiosks at Isale-Oja and Alabata showing treatment-ready infrastructure

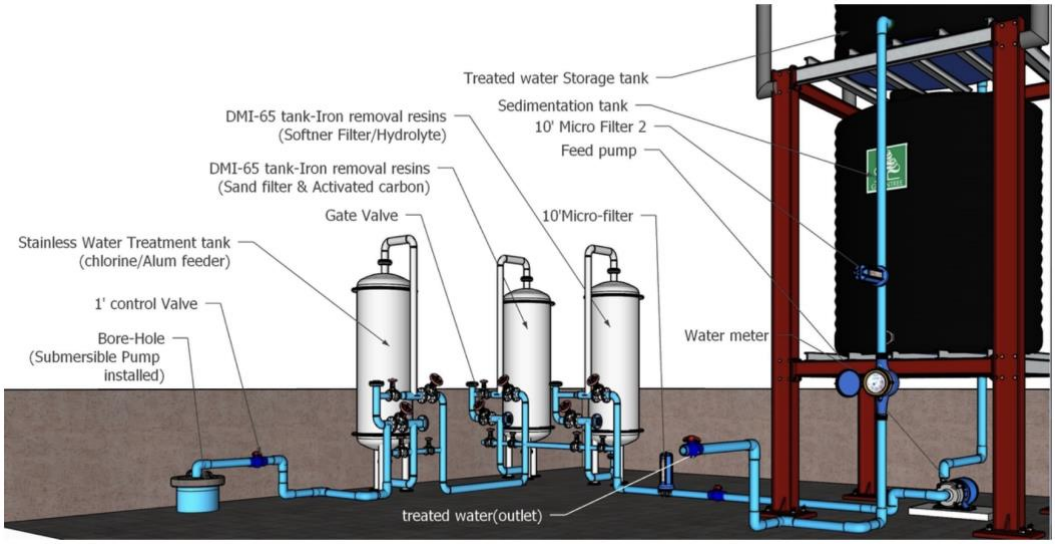


Figure 8-2: Schematic representation of the treatment process setup deployed at Isale-Oja and Alabata kiosks

The schematic in Figure 8-2 illustrates the sequence of treatment technologies from raw water intake to the final treated water storage. The configuration includes chemical dosing, multi-stage filtration, and micro-polishing components. A detailed explanation of each stage, including its purpose, operating function, and design parameters, is provided

in Section 8.2.4.3 (Treatment System Implementation), with additional details in Appendix 3, Section 1.

8.2.4. Method of Data Collection

8.2.4.1. Borehole Sampling and Laboratory Data

Data for water quality analysis were obtained through a combination of primary field sampling and secondary laboratory datasets:

- **Primary Data**: Five borehole samples were collected by the research team in May 2024 using sterile containers and cold chain transport. Analyses were conducted at a NiNAS-accredited, IPAN-registered laboratory following standard protocols.

- **Secondary Data**: Twelve additional test results were obtained from accredited laboratories after outreach to over 50 institutions. Most declined due to confidentiality, but participating labs shared data under anonymity agreements. All results were independently verified for NIS 554:2015 compliance.

All 17 borehole samples were collected from sources designed to supply the public with drinking water. This ensured the dataset reflects infrastructure intended to meet NIS 554:2015, rather than informal or visibly contaminated sources. Sampling conditions, source infrastructure, and inclusion criteria are described in Section 2 of Appendix 3. Full physicochemical and microbiological results are presented in Tables A3.1 and A3.2 of Appendix 3.

8.2.4.2. Sample Size Justification

The study's objectives are diagnostic, typological, and intervention focused. The 17 borehole samples analysed were sufficient to support these objectives, providing representative variation across diverse hydrogeological and socio-economic settings in four Nigerian states. Each sample was tested for 40 physicochemical and microbiological parameters, enabling in-depth contamination profiling and analysis of parameter interrelationships.

For Objective 1, the sample size was sufficient to (a) assess regulatory failure across functioning subset of public-use boreholes, (b) identify the most commonly failing parameters, and (c) conduct parameter-level correlation analysis and evaluate proxy indicator performance using rule-based predictive simulations.

For Objective 2, which involved piloting point-source treatment at two smart kiosks, the focus was on real-world implementation using full-scale field testing and regulatory evaluation.

The treatment evaluation was conducted as an embedded field case study with full pre- and post-treatment water quality assessment, operational feasibility testing, and regulatory benchmarking. This empirical structure, supported by the broader typological analysis of 17 boreholes, provides a methodologically sound basis for the study's findings and recommendations.

8.2.4.3. Treatment Intervention and Documentation

Data collection for the treatment pilot included scheduled sampling, technical documentation, and regulatory reference analysis:

- **Pre- and Post-Treatment Sampling**:

  Water samples were collected from the Isale-Oja and Alabata kiosks at two stages: pre-treatment in May 2024 and post-treatment in July 2024. All sampling followed sterile protocols as previously described, and laboratory analysis was conducted by an accredited testing facility.

- **Treatment System Implementation**:

  The treatment design was informed by baseline water quality analysis, which indicated elevated turbidity, total hardness, sulphate, iron, and microbial contamination. A multi-stage treatment system was installed at both kiosks, consisting of the following components:

- Chlorine and alum dosing was applied for disinfection, coagulation, and iron oxidation, using a mechanical dosing unit installed at the raw water inlet.
- Multi-grade sand filtration used silica media arranged in a fining-upward sequence: Grade 4 (coarse gravel), Grade 3, Grade 2, and Grade 1 (fine-grained sand), as specified in the treatment system supply (see Section 1 of Appendix 3).
- Activated carbon filtration was applied to remove residual chlorine and improve taste and odour, in accordance with the documented use of granular activated carbon in the process setup.
- Iron removal was achieved using INDION iron removal resin (ISR), a catalytic, non-regenerative media integrated into the filtration unit.
- Cationic and anionic resin filtration was incorporated prior to hydrolyte to support pH stabilisation and the removal of excess minerals such as calcium, magnesium, and sulphates.
- Micron filtration included two cartridge-based units, equipped with six replaceable filters, for final polishing prior to treated water storage. These units remove fine particulates before distribution.

The system is housed in food-grade stainless steel tanks and operates using solar-powered surface transfer pumps. Routine backwashing is conducted manually by trained kiosk attendants on a weekly basis, and filtration media are replaced according to each component's service life and site-specific water quality demands.

Further technical details, including treatment media specifications, filter sequencing, dosing mechanisms, backwashing procedures, and maintenance schedules, are presented in Section 1 of Appendix 3.

8.2.5. Method of Data Analysis

8.2.5.1. Contamination Characterisation

This analysis assessed the extent and complexity of borehole water contamination by evaluating regulatory compliance and interrelationships among failing parameters. A six-phase analytical process was applied:

- **Compliance Assessment**: Each of the 17 borehole samples was evaluated against NIS 554:2015 thresholds for 40 parameters, comprising 28 physicochemical and 12 microbiological. Binary compliance (pass/fail) was recorded for each parameter per sample.

- **Parameter Failure Frequency**: Frequency analysis was conducted on 35 of the 40 parameters. Five parameters—Appearance, Odour, Phosphate, Total Solids, and Total Suspended Solids—were excluded due to the absence of defined regulatory thresholds. The remaining parameters were categorised by presumed source: geogenic (e.g., iron, TDS) or anthropogenic (e.g., microbial indicators).

- **Descriptive Statistics**: For the 35 threshold-based parameters, summary statistics were calculated to assess the severity and variability of contamination. These included mean ($\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$) and standard deviation ($SD = \sqrt{\frac{1}{n-1}}\sum_{i=1}^{n}(x_i - \bar{x})^2$), along with minimum and maximum values.

- **Correlation Analysis**: Spearman's rank correlation coefficient (ρ) was applied to evaluate monotonic relationships among nine key water quality parameters: Turbidity, Total Plate Count, Total Coliforms, TDS, Hardness, Conductivity, pH, Iron, and Alkalinity. A total of 36 non-redundant pairwise combinations were assessed. This number derives from the formula for unique combinations:

  $Number\ of\ pairs \quad = \binom{n}{2} = \frac{n(n-1)}{2}$

  Each pairwise combination was analysed for rank correlation using the Spearman formula:

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

where d_i is the difference between the ranks of paired observation and n is the number of observations. Relationships were considered statistically significant where $\rho > 0.5$ and $p < 0.05$.

- **Predictive Simulation of Proxy Indicators**:
  While Spearman's correlation analysis identified significant relationships between parameters, predictive simulations were conducted to evaluate their utility as practical field proxies. Each simulation calculated the proportion of failing samples that would be detected using individual or combined parameter sets. The predictive overlap for a given proxy set is defined as:

  $$Predictive\ Overlap\ (\%) = \left(\frac{|F \cap P|}{|F|}\right) \times\ 100$$

  Where:

  - F is the set of all samples that failed any of the benchmark parameters,
  - P is the set of all samples that failed at least one parameter in the proxy set,
  - $F \cap P$ represents the intersection of sets F and P, that is, the samples that failed both the benchmark and the proxy parameters,
  - $|F \cap P|$ is the number of correctly identified failing samples (true positives), and
  - $|F|$ is the total number of failing samples in the benchmark set.

  This formula calculates the percentage of true failures that would be detected using just the selected proxy parameters. It allows comparison of different proxy combinations (e.g., Iron + Total Plate Count, Iron + Turbidity) based on how well they approximate full contamination screening in the field.

- **Contamination Typology:** Boreholes were manually classified into four contamination-based categories: Microbial Only, Geogenic Only, Mixed (Microbial + Geogenic) and Compliant, based on the specific pattern of parameter exceedances. Samples meeting all NIS 554:2015 thresholds were labelled as Compliant. A manual typology was chosen over algorithmic clustering (e.g., K-

means) due to the small sample size (n = 17), non-normal data distribution and the need for interpretable, policy-relevant groupings. This classification informed treatment prioritisation and regulatory recommendations.

8.2.5.2. Pilot Treatment and Regulatory Evaluation

A multi-layered analysis was applied to evaluate treatment effectiveness, regulatory suitability, and scalability challenges in low-resource settings:

- **Treatment Effectiveness:** Pre- and post-treatment water quality data from Isale-Oja and Alabata were compared against NIS 554:2015 thresholds. Priority was given to health-critical parameters (e.g., microbial indicators), while aesthetic parameters (e.g., hardness, sulphate) were assessed for residual exceedance.

- **Regulatory Suitability:** A multi-criteria decision analysis (MCDA) framework evaluated the practicality of enforcing NIS 554:2015 in rural contexts. Comparisons were made with the more lenient Federal Gazette limits based on NIS 554:2007 (National Environmental & Regulation Enforcement, 2011), for example sulphate (400 mg/L) and magnesium (150 mg/L) versus 100 mg/L and 20 mg/L under NIS 554:2015. The analysis considered whether phased compliance and relaxed thresholds for non-health-critical parameters could balance public health protection with technical and financial feasibility.

- **Barrier Analysis:** Thematic analysis of field observations and implementation logs, informed by systems thinking, identified structural barriers such as cost, technical complexity, and regulatory inflexibility.

8.3. Results and Discussion

8.3.1. Borehole Water Quality: Compliance, Contaminants, and Typologies

8.3.1.1. Widespread Non-Compliance with NIS 554:2015

The compliance assessment revealed that 15 of 17 borehole samples (88.2%) failed at least one of the 40 parameters set by NIS 554:2015, which comprises 28 physicochemical and 12 microbiological indicators. Only two boreholes, one in Lagos and one in Oyo,

achieved full compliance. This widespread non-compliance indicates a structural deficiency in Nigeria's water infrastructure. While national efforts to expand access continue, the neglect of safety requirements fundamentally undermines SDG 6.1's goal of universal and safe drinking water (UNICEF & WHO, 2021). Under the current delivery model, water infrastructure projects in Nigeria therefore cannot be regarded as fully advancing SDG 6.1.

8.3.1.2. Failure Frequency and Key Contaminants

Total Plate Count showed the highest non-compliance rate, failing in 10 of 17 samples (58.8%), followed by pH and iron (47.1% each), Total Coliforms (41.2%), and Hardness (35.3%). These patterns reflect a dual burden: microbial contamination from anthropogenic sources, and geogenic contamination from aquifer mineral dissolution. The recurrence of exceedances across parameters indicates a systemic water quality failure. Figure 8-3 presents a heatmap visualising the failure pattern, and Table A3.3 in Appendix 3 details the parameter frequencies.

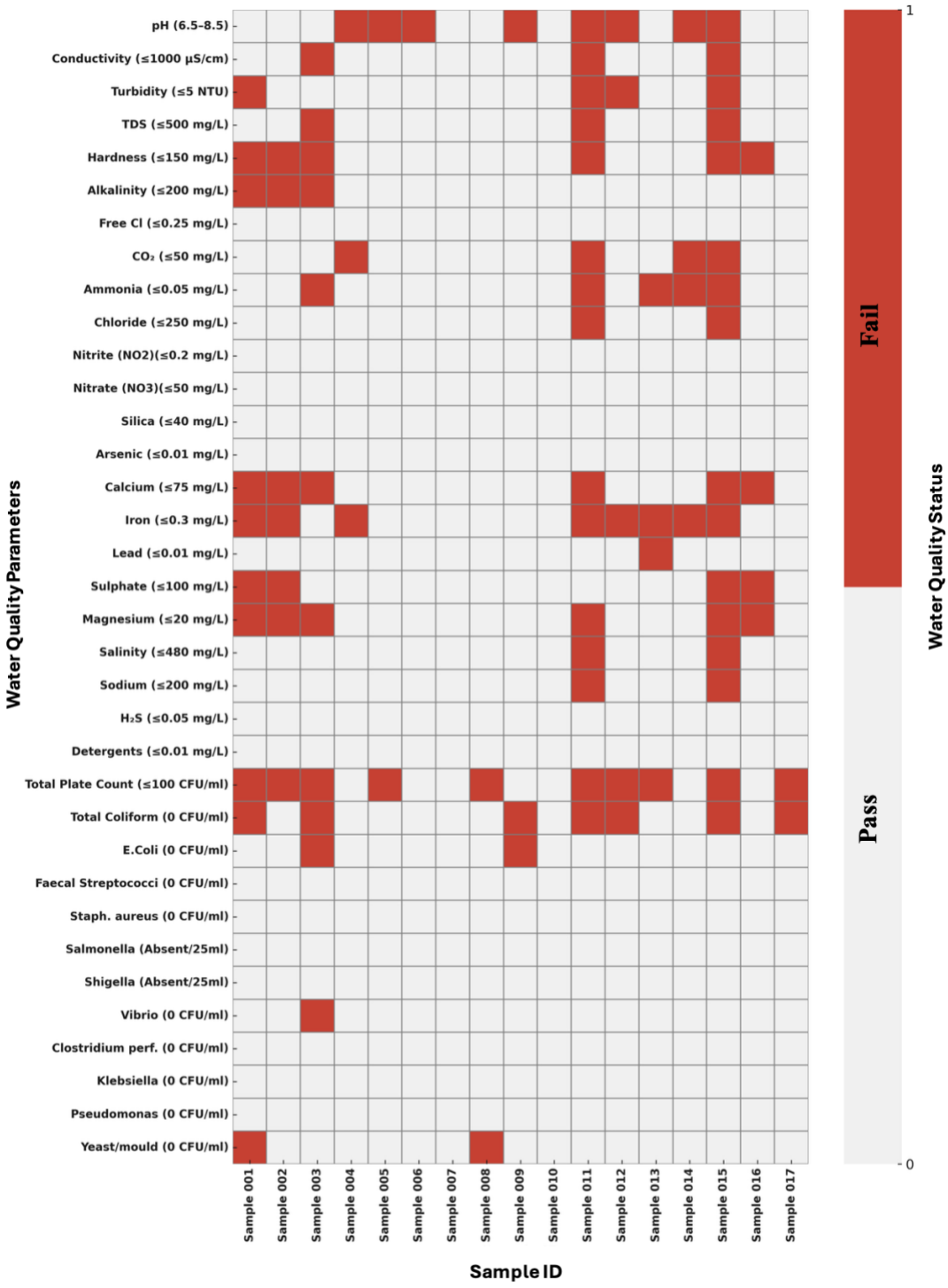


Figure 8-3: Heatmap showing the frequency and pattern of parameter exceedances across 17 borehole samples based on NIS 554:2015 thresholds

8.3.2. Descriptive Statistics and Parameter Variability of Borehole Water Quality

Descriptive analysis revealed marked variability across key water quality parameters, highlighting the inconsistency of borehole safety across sites. Turbidity exhibited the widest range, from 0 to 525 NTU (mean = 69.5; SD = 173.0), with multiple samples exceeding the NIS 554:2015 limit of 5 NTU. Electrical conductivity ranged from 54.6 to 1,736 µS/cm (mean = 507.8), indicating substantial variation in ionic content. Total dissolved solids (TDS) ranged from 27.3 to 868 mg/L (mean = 252.4), with several samples exceeding the 500 mg/L threshold. Hardness spanned 7.9 to 345.1 mg/L as $CaCO_3$ (mean = 117.8), with multiple exceedances above the 150 mg/L standard. pH values ranged from 5.4 to 7.6, with many samples falling below the acceptable lower limit of 6.5, increasing the risk of corrosivity and metal solubility. The 90th percentile further showed that upper-end water-quality conditions remained severe across several parameters, with turbidity reaching 266.64 NTU, conductivity 1326.50 µS/cm, TDS 663.40 mg/L, hardness 296.58 mg/L as $CaCO_3$, iron 39.92 mg/L, total plate count 362.20 CFU/ml, and total coliform 57.20 CFU/ml. These results confirm that exceedances are both widespread and severe, and that water quality varies significantly by location, reinforcing the need for site-specific diagnostics and tailored treatment strategies. Table 8-1 presents the detailed descriptive statistics.

Table 8-1: Descriptive Statistics and Parameter Variability of Borehole Water Quality

Parameter	mean	std	min	max	90th percentile
pH (6.5–8.5)	6.48	0.77	5.4	7.6	7.42
Conductivity (≤1000 µS/cm)	507.75	554.02	54.6	1736	1326.50
Turbidity (≤5 NTU)	69.51	173.00	0	525	266.64
TDS (≤500 mg/L)	252.38	279.30	27.3	868	663.40
Hardness (≤150 mg/L as $CaCO_3$)	117.84	117.98	7.9	345.1	296.58
Alkalinity (≤200 mg/L as $CaCO_3$)	112.04	110.97	10.8	423.5	219.16
Free Cl (≤0.25 mg/L)	0.00	0.00	0	0	0.00
CO_2 (≤50 mg/L)	35.28	24.63	3.6	81	79.20
Ammonia (≤0.05 mg/L)	2.04	4.78	0	18.9	5.90
Chloride (≤250 mg/L)	87.06	153.31	6.9	488.9	248.12

Nitrite (NO_2)(≤0.2 mg/L)	0.04	0.05	0	0.17	0.10
Nitrate (NO_3)(≤50 mg/L)	2.22	3.69	0.11	15.8	3.78
Silica (≤40 mg/L)	14.35	8.92	5.7	32.3	28.60
Arsenic (≤0.01 mg/L)	0.00	0.00	0	0	0.00
Calcium (≤75 mg/L)	47.62	46.94	3.2	138.3	118.92
Iron (≤0.3 mg/L)	11.56	30.31	0	92	39.92
Lead (≤0.01 mg/L)	0.00	0.01	0	0.03	0.00
Sulphate (≤100 mg/L)	42.52	64.24	0	177	141.48
Magnesium (≤20 mg/L)	17.19	17.17	0.8	50.3	43.20
Salinity (≤480 mg/L)	189.35	275.89	42.4	912.5	477.86
Sodium (≤200 mg/L)	56.76	99.14	4.4	316.8	160.74
H_2S (≤0.05 mg/L)	0.00	0.00	0	0	0.00
Detergents (≤0.01 mg/L)	0.00	0.00	0	0	0.00
Total Plate Count (≤100 CFU/ml)	156.47	137.80	10	418	362.20
Total Coliform (0 CFU/ml)	15.29	28.72	0	86	57.20
E.Coli (0 CFU/ml)	0.35	1.00	0	3	1.20
Faecal Streptococci (0 CFU/ml)	0.00	0.00	0	0	0.00
Staph. aureus (0 CFU/ml)	0.00	0.00	0	0	0.00
Salmonella (Absent/25ml)	0.00	0.00	0	0	0.00
Shigella (Absent/25ml)	0.00	0.00	0	0	0.00
Vibrio (0 CFU/ml)	0.65	2.67	0	11	0.00
Clostridium perf. (0 CFU/ml)	0.00	0.00	0	0	0.00
Klebsiella (0 CFU/ml)	0.00	0.00	0	0	0.00
Pseudomonas (0 CFU/ml)	0.00	0.00	0	0	0.00
Yeast/mould (0 CFU/ml)	2.24	7.60	0	31	2.80

8.3.3. Interrelationships Among Contaminants and Predictive Simulation for Proxy Parameter Selection

Spearman's rank correlation analysis was conducted on nine key water quality parameters: Turbidity, Total Plate Count, Total Coliforms, TDS, Hardness, Conductivity, pH, Iron, and Alkalinity, selected based on failure frequency, regulatory significance, and

mechanistic relevance to microbial or geogenic contamination (Chapelle, 2000b; Zhong et al., 2023). Strong correlations were observed across both contamination domains, microbial and geogenic. Turbidity was positively correlated with Total Plate Count ($\rho = 0.72$, $p < 0.01$) and Total Coliforms ($\rho = 0.69$, $p < 0.01$), supporting its utility as a proxy for microbial risk. Geogenic parameters were also interrelated: TDS and Conductivity were strongly correlated ($\rho = 0.96$), while Hardness correlated with both TDS ($\rho = 0.91$) and Conductivity ($\rho = 0.89$), reflecting shared mineral sources. Detailed results are presented in Table 8-2

To assess their practical application in proxy-based water quality monitoring, predictive simulations of 255 distinct combination of parameters were conducted to evaluate how effectively individual and combined parameters could detect non-compliant samples. Key findings include:

- Iron alone identified 53.3% of failing samples.
- Turbidity alone detected 26.7%.
- Iron + Total Plate Count detected 80%, the highest-performing two-parameter proxy.
- Iron + Turbidity detected 53.3%, offering simplicity and field accessibility.
- Iron + Turbidity + Conductivity detected 60%, providing a fully instrument-based, non-microbial proxy set suitable for field deployment in remote areas.

Although combinations like Hardness + pH + Total Plate Count achieved 100% detection, they were excluded due to scientific and operational limitations. For example, pH (53.3% predictive overlap), while relevant to solubility processes (Chapelle, 2000a), lacks diagnostic specificity: deviations from neutrality may reflect benign geochemical variation rather than harmful contamination (Verlicchi & Grillini, 2020). Similarly, Hardness (40%) is considered an aesthetic parameter and not a direct health risk (Standards Organisation of Nigeria, 2015; WHO, 2022a).

Proxy monitoring is critical in low-resource settings where laboratory-based microbial testing is impractical. While Iron alone achieved 53.3% predictive overlap, combining it with Turbidity provides a dual-domain proxy that strengthens interpretability and operational value. Iron captures geogenic risks, while Turbidity, although not increasing

detection rate in this dataset, offers insight into potential microbial contamination. Both parameters are field-testable with simple portable instruments. This combination supports a scalable, low-cost screening tool for prioritising boreholes for intervention, especially in areas where Total Plate Count cannot be measured in real time.

Table 8-2: Spearman's rank correlation (ρ) matrix for key water-quality parameters.

Parameter A	Parameter B	Spearman ρ	p-value	Significant (ρ>0.5 & p<0.05)
Turbidity (≤5 NTU)	Total Plate Count (≤100 CFU/ml)	0.72	0.0012	Yes
Turbidity (≤5 NTU)	Total Coliform (0 CFU/ml)	0.69	0.0024	Yes
Turbidity (≤5 NTU)	TDS (≤500 mg/L)	0.56	0.0205	Yes
Turbidity (≤5 NTU)	Hardness (≤150 mg/L)	0.4	0.1138	No
Turbidity (≤5 NTU)	Conductivity (≤1000 µS/cm)	0.53	0.0287	Yes
Turbidity (≤5 NTU)	pH (6.5–8.5)	-0.15	0.562	No
Turbidity (≤5 NTU)	Iron (≤0.3 mg/L)	0.74	0.0007	Yes
Turbidity (≤5 NTU)	Alkalinity (≤200 mg/L)	0.36	0.1552	No
Total Plate Count (≤100 CFU/ml)	Total Coliform (0 CFU/ml)	0.56	0.0192	Yes
Total Plate Count (≤100 CFU/ml)	TDS (≤500 mg/L)	0.69	0.0023	Yes
Total Plate Count (≤100 CFU/ml)	Hardness (≤150 mg/L)	0.58	0.0151	Yes

Total Plate Count (≤100 CFU/ml)	Conductivity (≤1000 µS/cm)	0.66	0.0042	Yes
Total Plate Count (≤100 CFU/ml)	pH (6.5–8.5)	0.16	0.5393	No
Total Plate Count (≤100 CFU/ml)	Iron (≤0.3 mg/L)	0.55	0.021	Yes
Total Plate Count (≤100 CFU/ml)	Alkalinity (≤200 mg/L)	0.55	0.0234	Yes
Total Coliform (0 CFU/ml)	TDS (≤500 mg/L)	0.54	0.0253	Yes
Total Coliform (0 CFU/ml)	Hardness (≤150 mg/L)	0.44	0.0764	No
Total Coliform (0 CFU/ml)	Conductivity (≤1000 µS/cm)	0.52	0.0305	Yes
Total Coliform (0 CFU/ml)	pH (6.5–8.5)	-0.02	0.9414	No
Total Coliform (0 CFU/ml)	Iron (≤0.3 mg/L)	0.41	0.0994	No
Total Coliform (0 CFU/ml)	Alkalinity (≤200 mg/L)	0.41	0.1027	No
TDS (≤500 mg/L)	Hardness (≤150 mg/L)	0.9	0	Yes
TDS (≤500 mg/L)	Conductivity (≤1000 µS/cm)	0.96	0	Yes
TDS (≤500 mg/L)	pH (6.5–8.5)	0.46	0.0628	No
TDS (≤500 mg/L)	Iron (≤0.3 mg/L)	0.54	0.0254	Yes
TDS (≤500 mg/L)	Alkalinity (≤200 mg/L)	0.93	0	Yes
Hardness (≤150 mg/L)	Conductivity (≤1000 µS/cm)	0.91	0	Yes
Hardness (≤150 mg/L)	pH (6.5–8.5)	0.63	0.0068	Yes

Hardness (≤150 mg/L)	Iron (≤0.3 mg/L)	0.57	0.0166	Yes
Hardness (≤150 mg/L)	Alkalinity (≤200 mg/L)	0.95	0	Yes
Conductivity (≤1000 µS/cm)	pH (6.5–8.5)	0.43	0.0841	No
Conductivity (≤1000 µS/cm)	Iron (≤0.3 mg/L)	0.6	0.0116	Yes
Conductivity (≤1000 µS/cm)	Alkalinity (≤200 mg/L)	0.92	0	Yes
pH (6.5–8.5)	Iron (≤0.3 mg/L)	-0.1	0.704	No
pH (6.5–8.5)	Alkalinity (≤200 mg/L)	0.65	0.0048	Yes
Iron (≤0.3 mg/L)	Alkalinity (≤200 mg/L)	0.43	0.0821	No

8.3.4. Contamination Typology and Treatment Implications

To guide intervention strategies, each borehole was classified by its contamination pattern into four categories: Mixed (Microbial + Geogenic), Microbial Only, Geogenic Only, and Compliant. Of the 17 samples, 10 (58.8%) showed mixed contamination, 4 (23.5%) were geogenic only, 2 (11.8%) microbial only, and 2 (11.8%) were fully compliant.

The predominance of mixed contamination underscores the need for multi-barrier treatment systems that integrate disinfection, filtration, and chemical conditioning, rather than single-focus interventions like chlorination alone.

This typology also shaped proxy monitoring recommendations:

- Combinations like Iron + Conductivity capture geogenic risks only
- Iron + Turbidity, by contrast, can detect both microbial and geogenic failures, making it more suitable for identifying mixed contamination

- Thus, proxy selection should reflect the contamination profile common to the setting

The classification supports evidence-based planning by helping policymakers and practitioners target boreholes for treatment, monitoring, or decommissioning based on contamination type.

8.3.5. Treatment Effectiveness

The post-treatment results confirm effective system performance. Pre- and post-treatment comparisons are summarised in Appendix 3 (Tables A3.4 and A3.5), and Figures 8-4 and 8-5 show parameters that failed before treatment and were brought within NIS 554:2015 limits for Alabata and Isale-Oja, respectively. At Alabata, treatment achieved full compliance with all NIS 554:2015 parameters. At Isale-Oja, treatment achieved full compliance for microbial and other health-critical parameters, but four aesthetic indicators (total hardness, calcium, magnesium and sulphate) remained above their respective NIS 554:2015 limits. Alkalinity also remained elevated at 273.7 mg/L.

Although the laboratory used 200 mg/L as a reporting reference for alkalinity, neither NIS 554:2015 nor the Federal Gazette specifies a numerical limit for this parameter. When the post-treatment results are evaluated against the Federal Gazette (2011), which reflects the earlier NIS 554:2007 standard, all parameters at Isale-Oja, including the four aesthetic indicators and alkalinity, fall within permissible limits for domestic use (see Table 8-3).

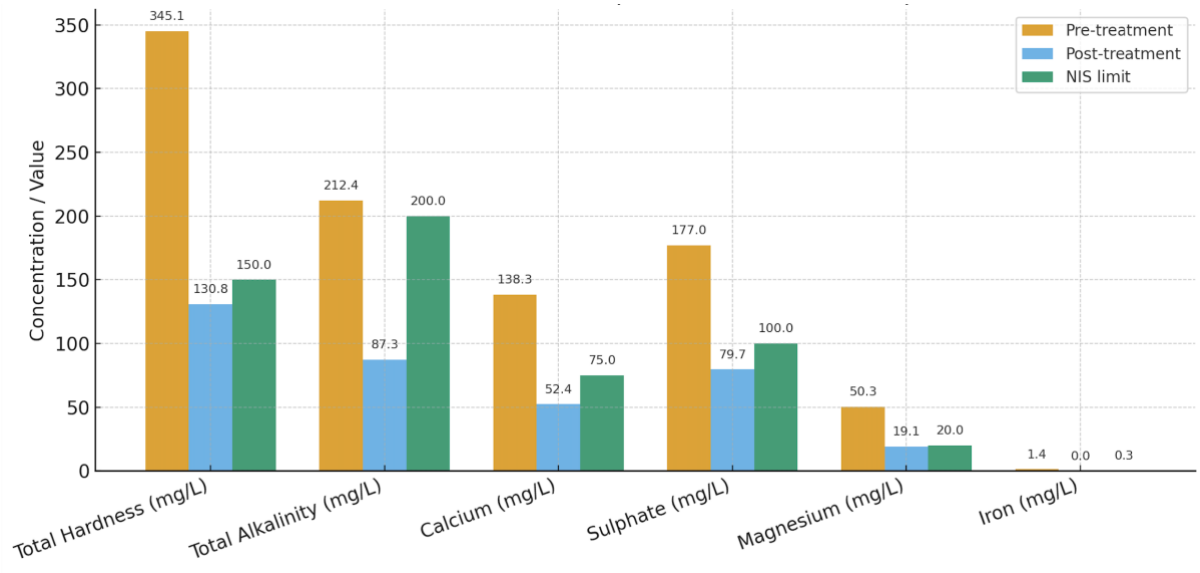


Figure 8-4: Alabata pre- and post-treatment results compared with NIS 554:2015 limits.

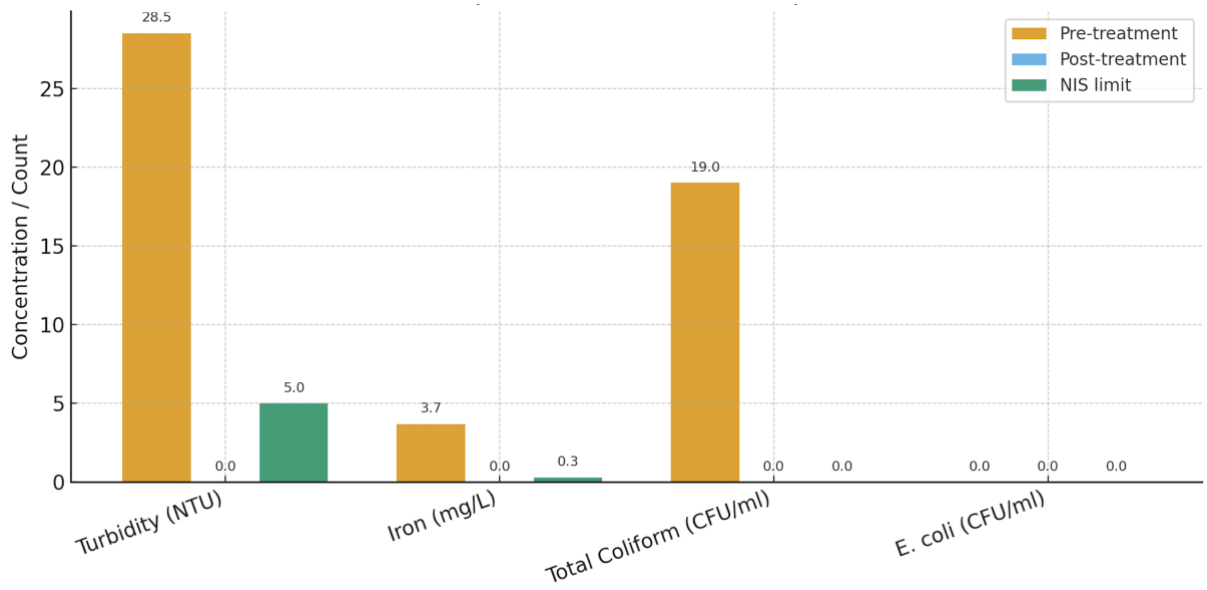


Figure 8-5: Isale-Oja pre- and post-treatment results compared with NIS 554:2015 limits.

Note: Figure 8.5 presents the Isale-Oja pre-treatment and post-treatment results for turbidity (NTU), iron (mg/L), total coliform (CFU/ml), and E. coli (CFU/ml), relative to the corresponding NIS limits. Post-treatment turbidity, iron, total coliform, and E. coli are all 0 and therefore coincide with the x-axis. For total coliform and E. coli, the NIS limit is also 0 CFU/ml, so the post-treatment value and standard limit overlap visually.

Table 8-3: Comparison of Isale-Oja Post-Treatment Results Against National Standards.

Parameter	**NIS 554:2015 Limit (mg/L)**	**Federal Gazette Limit (mg/L)**	**Isale-Oja Post-Treatment (mg/L)**
Hardness	150	500	349.5
Calcium	75	200	140.1
Sulphate	100	400	206
Magnesium	20	150	50.9
Alkalinity	No specified limit	No specified limit	273.7

Table 8-3 shows that all post-treatment values at Isale-Oja fell within the limits set by the Federal Gazette (2011), which references NIS 554:2007, indicating that the treated water is acceptable for domestic use under earlier national criteria. The testing laboratory nevertheless recommended reverse osmosis (RO) to achieve full compliance with the stricter NIS 554:2015 aesthetic thresholds. Introducing RO would substantially increase cost and technical complexity, undermining financial sustainability and limiting replicability in similar low-resource settings. These findings support a phased compliance model that prioritises immediate compliance with health-critical parameters while allowing conditional compliance with aesthetic parameters, calibrated to contextual and financial feasibility. Such an approach balances public health protection with implementation realities and is more compatible with scalable, sustainable safe water provision in underserved regions.

8.3.6. Barrier Analysis: Financial, Operational, and Design Constraints

The treatment pilot identified major constraints to scaling safe drinking water delivery in resource-constrained contexts. Financially, treatment accounted for 17.2% of total infrastructure costs in the pilot kiosk (see Appendix 3, Section 3 and Table A3.6). While this proportion may be acceptable in well-funded systems, it is prohibitive in low-budget settings. Achieving full compliance at Isale-Oja would have required reverse osmosis (RO) to address residual aesthetic exceedances (hardness, calcium, magnesium and sulphate). Integrating RO is estimated to increase treatment costs to 30 to 50% of the total

budget, creating serious challenges for financial sustainability under prevailing funding models.

Operationally, the treatment system requires routine backwashing and periodic replacement of components such as filtration media and resins to maintain performance. These activities introduce recurring costs, increase the maintenance burden and depend on the availability of trained personnel for technical tasks. In many rural settings, post-construction support systems are weak or absent. Without sustained technical oversight, even well-designed systems are at high risk of premature failure. This disconnect between operational demands and institutional capacity is a significant barrier to the long-term sustainability of treatment-integrated infrastructure.

From a design perspective, handpumps, which are widely used across the 434 boreholes identified by Adeoti et al. (2024b), lack the structural and functional capacity to support integrated treatment technologies or real-time monitoring. Their inability to facilitate post-construction oversight makes them incompatible with current water safety expectations and misaligned with the objectives of NIS 554:2015 and the broader mandate of SDG 6.1.

Overall, these empirical findings, together with the barriers to scaling treatment and the difficulty of enforcing a national standard that is both financially and technically viable, underline the need for regulatory and systemic reform.

8.4. Limitations

This study was limited by restricted access to laboratory test results. Although over 50 accredited laboratories were contacted, confidentiality constraints prevented most from releasing data, resulting in a total of 17 usable samples. While this dataset was sufficient for the study's objectives, a larger sample size would have supported more extensive statistical and regional analysis. Nonetheless, the samples analysed reflect diverse hydrogeological and socio-economic contexts. Combined with primary field sampling and embedded real-life treatment pilots, the study provides a robust empirical foundation

for assessing contamination risks, informing treatment strategies, and guiding regulatory reform in Nigeria.

8.5. Summary and Synthesis

This chapter extends the thesis from operational and behavioural performance (Chapters 6 and 7) to the domain of water quality and treatment feasibility. Using accredited laboratory analysis of 17 public boreholes across four Nigerian states, it assessed 40 physicochemical and microbiological parameters and found that 15 of 17 samples (88.2%) failed at least one NIS 554:2015 standard, with 58.8% exhibiting mixed microbial and geogenic contamination. Frequent exceedances included Total Plate Count, pH, iron and hardness. Correlation analysis and rule-based proxy simulations across 255 parameter combinations identified iron and turbidity as a practical proxy set for low-cost field monitoring and for prioritising contaminated boreholes for further testing and intervention.

Treatment pilots at Alabata and Isale-Oja demonstrated that basic point-source treatment can achieve health-critical safety in low-resource settings. At Alabata, all NIS 554:2015 parameters were met post-treatment. At Isale-Oja, all microbial and other health-critical parameters complied with NIS 554:2015, while four aesthetic indicators (total hardness, calcium, magnesium and sulphate) remained above their thresholds and would have required reverse osmosis (RO) for full compliance. A multi-criteria decision analysis showed that treatment represented about 17.2% of total project cost and could rise to 30 to 50% if RO were added. Given this cost profile, and the fact that all post-treatment parameters at Isale-Oja complied with the earlier NIS 554:2007 standard, the NIS 554:2015 thresholds for aesthetic parameters appear unrealistically strict for low-resource settings. These results support a phased compliance model that prioritises immediate adherence to health-critical parameters while allowing context-dependent compliance for aesthetic parameters, thereby balancing public health protection with technical and financial feasibility.

From a design perspective, the findings also show that handpump-equipped boreholes, which dominate rural supply (Adeoti et al., 2024b) lack the structural capacity to host

integrated treatment systems or real-time monitoring and are therefore poorly aligned with contemporary water safety expectations and the safe-water dimension of SDG 6.1.

Taken together, this chapter positions water safety, proxy-based monitoring, phased regulatory compliance and treatment-compatible infrastructure design as essential elements of a sustainable water service model. The next chapter (Chapter 9) builds on these results, together with the diagnostic, predictive, smart-system and behavioural findings from earlier chapters, to synthesise a life cycle sustainability framework that integrates safety, reliability, utilisation, financial viability and regulatory feasibility for advancing SDG 6.1 in Nigeria and comparable low-resource settings.

Chapter 9: Synthesis and Integrated Framework for Sustainable Water Infrastructure

9.1. Cross chapter synthesis of sustainability determinants

This chapter synthesises the empirical findings from Chapters 2, 4, 5, 6, 7 and 8. The empirical chapters collectively show that sustainability is not determined solely by the design or construction of infrastructure, but emerges from decisions made before, during and after construction. The 265 challenges identified in the systematic review cluster into seven domains that cut across the life cycle: technical integrity, financial viability, environmental stresses, social acceptance, institutional and governance arrangements, political context and data and information gaps. Mapping these challenges onto the pre-construction, construction and post-construction stages shows that weaknesses in the pre-construction stage, such as weak diagnostics, fragmented governance and non-transparent financing, create conditions that later technical, financial or other post-construction interventions cannot fully overcome.

The field diagnostics across 1,696 communities made this visible at scale. Within this sample, 844 communities had no improved water source, and 852 public boreholes were identified. Of these boreholes, 434 were functional and 418 were non-functional, revealing extensive service gaps and an almost 1:1 ratio of working to failed infrastructure. Failure trajectories differed by ownership, with community owned schemes showing lower failure rates than several externally managed alternatives, yet long term non-functionality remained widespread. Multidimensional poverty patterns at state level did not align with the spatial distribution of failures or service gaps, highlighting the need for community level mapping and diagnostics as a core element of the pre-construction stage.

The Predictive Iterative Sustainability Model (PISM) translates these determinants into pre-construction metrics. It uses 70 weighted indicators to calculate a Viability Rating (VR) and combines this with an income and expense model to estimate Sustainability Rating (SR) and Self Sustainability Rating (SSR). In the five water poor communities assessed, VR values clustered between 63.95% and 67.91%, setting an empirical baseline

for location viability for water projects, while predicted SR values ranged from 179% to 424%, meaning that projected income was about 1.79 to 4.24 times greater than operating and maintenance expenses. Communities that appeared similar in terms of water poverty and service deficits on the basis of VR therefore displayed very different financial sustainability profiles once expected demand, tariffs, costs and willingness to pay were taken into account. This demonstrates that location viability alone, as captured by VR, cannot predict sustainability outcomes.

Operational analysis of Smart Water Infrastructure (SWI) extends this insight to post construction performance. The Abeku kiosk demonstrated that high technical performance is achievable in low resource settings: 97.1% reliability over 1,063 of 1,095 days, 1.67 million litres dispensed and 100% SR when external support covered all operation, maintenance and repair costs. At the same time, average daily usage was 1,526 L, only 7.63% of the 20,000 L per day design capacity, SSR during the paid period was 22% and NRW accounted for 41.24% of water dispensed. A 68.4% drop in usage when charges were introduced, and the collapse of SSR from 22% to 0% when an overlapping free source by another organisation was installed, revealed financial fragility due to uncoordinated aid efforts, which can undermine sustainability even under technically robust operation.

The underutilisation study quantified behavioural and spatial determinants of use in a separate SWI kiosk deployment. In a community classified as water poor, only 16.3% of households adopted the SWI for drinking, despite treated water being initially free, and 97.7% rated existing sources, including unprotected wells, as very good and free of health concerns. IoT data over 168 days recorded utilisation at 1.52% of design capacity. Proximity modelling showed that each additional minute of walking time to the kiosk reduced the odds of adoption by about 48% (adjusted odds ratio around 0.52, 95% confidence interval 0.34 to 0.81), with adopters typically 3 minutes closer than non-adopters. These results ground the Water Infrastructure Underutilisation Principle detailed in Chapter 7, which explains how perceived adequacy of existing sources and small accessibility differences can result in non-use of technically superior infrastructure.

Water safety and treatment feasibility form a further cross cutting determinant. Accredited laboratory tests on 17 public boreholes showed that 15 samples (88.2%) failed

at least one NIS 554:2015 parameter and 10 (58.8%) presented mixed microbial and geogenic contamination. Proxy simulations across 255 parameter combinations showed that iron plus turbidity detected 53.3%, providing a practical proxy set for low cost field monitoring. Treatment pilots at two SWIs demonstrated that multi barrier point source treatment can deliver full health critical compliance but calls for phased compliance approach in which health related parameters are prioritised and aesthetic parameters are addressed as financial and technical capacity permit. Conventional handpump schemes provide access but lack the structural and operational capacity for integrated treatment and monitoring, so they cannot reliably meet the combined safety and access expectations of NIS 554:2015 and SDG 6.1.

Across these strands, five core propositions emerge:

1. **Sustainability is a life cycle property.** For infrastructure to be sustainable, its performance is determined by decisions made in the pre-construction, construction and post-construction stages.

2. **Community level diagnostics are essential for siting and design.** Effective planning relies on community level mapping and diagnostics to identify water poverty, infrastructure condition and service gaps that cannot be resolved from state level poverty data or other generalised metrics.

3. **Smart Water Infrastructure is both an effective service model and a critical data platform.** SWI provides reliable water services while generating longitudinal IoT data on reliability, utilisation, non-revenue water and financial performance that support performance management, iterative system improvement and calibration of sustainability models in low resource settings.

4. **Pre-construction sustainability evaluation strengthens project design and post-construction performance.** Applying tools such as the Predictive Iterative Sustainability Model and the Water Infrastructure Underutilisation Principle integrates viability, expected utilisation, demand, tariffs and willingness to pay into location and configuration decisions.

5. **Water safety and treatment feasibility are integral to sustainability.** Treatment ready design, proxy based monitoring and realistic, phased compliance with NIS 554:2015 enable borehole based systems to align access with safety expectations under SDG 6.1.

9.2. Integrated life cycle Sustainability Framework for Water Infrastructure

9.2.1. Pre-construction sustainability architecture

In the integrated framework, the pre-construction stage is implemented through three linked modules: community level mapping and diagnostic scoping, integrated viability and sustainability evaluation, and underutilisation risk screening and configuration.

1. Community level mapping and diagnostic scoping

At this stage, the framework requires community level mapping to understand the interrelated challenges faced by households and how a sustainable solution could work. The diagnostic focuses on information that directly guides design and sustainability, including:

- Water access profile: main sources used, travel time and effort, seasonality, queueing and reliability as experienced by households.
- Service condition**:** presence and functionality of improved sources and public boreholes, but only to the extent needed to decide whether to rehabilitate, complement or replace existing options.
- Household constraints: indicative affordability, competing expenditures and basic livelihood patterns that influence willingness and ability to pay.
- Risk context*:* obvious contamination risks, flood or drought exposure and any contextual factors likely to affect infrastructure operation (for example, security or physical access to sites).

2. **Integrated viability and sustainability evaluation**

The second module uses PISM to evaluate whether a proposed intervention in that diagnostic context is likely to be viable and financially sustainable. This evaluation is expressed through:

- Viability Rating (VR): a composite score based on the 70-indicator instrument, summarising governance, institutional, environmental and social conditions relevant to long term performance.
- Sustainability Rating (SR) and Self Sustainability Rating (SSR): projections of the income–expense balance under defined tariff and support scenarios.

3. **Underutilisation risk screening and configuration**

The third module integrates the Water Infrastructure Underutilisation Principle into pre-construction planning. Here, the focus is on whether the proposed configuration is likely to be used at the level assumed in PISM. Key considerations are:

- Relative accessibility: walking time and effort to the proposed SWI location compared with existing sources, using thresholds informed by the observed 48% reduction in adoption per additional minute of walking time.
- Perceived adequacy of existing sources: whether households regard current sources as “very good” or acceptable, even where technically unsafe, and how this perception interacts with tariffs and convenience.
- Competing and overlapping supplies: presence or likelihood of overlapping free or heavily subsidised alternatives that could displace demand from the proposed system.

9.2.2. Construction and configuration of sustainable infrastructure

In the integrated framework, the construction stage translates the pre-construction decision set into a concrete project through three linked processes: co-design with the community, technical configuration of a treatment-ready, monitored system, and alignment of governance, tariffs and support with the agreed service model.

1. **Co-design and service model definition**

At this point, the proposed intervention is developed through structured co-design with community representatives and relevant local institutions. Using the community diagnostic and pre-construction evaluation as inputs, this process:

- Confirms the service objectives (for example, primary drinking water, supplementary supply, or treatment point) and ensures they are culturally and socially appropriate.
- Agrees on site locations and access arrangements, taking into account proximity patterns and walking time sensitivities identified in the underutilisation analysis.
- Discusses tariff options, water credit and support mechanisms using the SR and SSR scenarios as boundary conditions,
- Defines local roles and responsibilities, such as kiosk attendants, committee structures and maintenance contacts, to support ownership and accountability.

2. **Technical configuration and treatment-ready design**

The second process specifies the physical system required to deliver the agreed service model. This includes:

- Setting design capacity and storage in line with realistic demand and utilisation ranges from the pre-construction evaluation, rather than nominal population values.
- Selecting the source, abstraction, storage and distribution layout to support reliable operation under local hydroclimatic and access conditions.
- Designing and installing a treatment configuration that can address the parameters that fail, with priority given to health-critical contaminants.
- Embedding a monitoring and data architecture, including metering and, where feasible, IoT devices at key points, so that volumes, reliability, non-revenue water and basic financial indicators can be captured from commissioning.

3. **Governance, tariffs, support and commissioning**

The third process formalises institutional and financial arrangements and verifies that the constructed system is ready to enter the post-construction phase. It involves:

- Documenting ownership and operational responsibility, reflecting lessons on the performance of different management models
- Setting tariffs and water credit rules within the envelopes tested in PISM, and recording any long-term support commitments needed to maintain SR and SSR at acceptable levels
- Establishing monitoring and reporting procedures for reliability, utilisation, non-revenue water, revenue and basic expenditure
- Undertaking commissioning checks, including construction quality verification, initial functional testing of treatment and monitoring components, and a baseline water-quality assessment against NIS 554:2015.

9.2.3. Post-construction performance and safety

In the post-construction stage, the framework is implemented through two linked processes: (i) operational and behavioural monitoring and reporting, and (ii) water safety and treatment monitoring.

1. **Operational and behavioural monitoring and reporting**

This process treats each SWI scheme as both a service and a data platform by:

- Using IoT data, or manual metering records entered by an operations representative, such as a kiosk attendant in the context of an SWI, into appropriate data systems to track reliability, volumes supplied, utilisation relative to design capacity, non-revenue water, income, expenditure and basic adoption and usage patterns
- Applying standardised reporting formats so that operators, support organisations and regulators can review performance against the expectations defined in the pre-construction stage

- Using the resulting data to adjust operation and configuration, and to improve SR, SSR and utilisation so that performance moves towards the defined sustainability targets
- Using accumulated operational data from multiple schemes to refine key assumptions in pre-construction tools such as PISM, including demand, utilisation and willingness-to-pay parameters

2. **Water safety and treatment monitoring**

This process maintains alignment with the safety dimension of SDG 6.1 and the requirements of national drinking water standards by:

- Implementing proxy-based field testing at defined intervals as a low-cost screen for potential non-compliance
- Undertaking periodic full laboratory analyses on selected samples to verify proxy results and identify changes in contamination patterns over time
- Checking treatment performance under operating conditions, confirming that health critical parameters remain within acceptable ranges, and carrying out routine maintenance in line with the operating and maintenance schedule for the treatment system

9.3. Cross-cutting enablers for implementation

The Sustainability Framework developed through this thesis is supported by three enablers: governance, finance, and data, ethics and capacity. While additional enablers may be required when adapting the framework to other contexts, these three represent the minimum conditions needed to implement the framework across the pre-construction, construction and post-construction phases.

- **Governance:** Establishes the authority, coordination and accountability required across the life cycle, from securing permissions for field diagnostics and formalising ownership and O&M responsibility prior to construction, to managing service delivery, oversight and compliance during operation. It also supports

coordination across agencies and organisations to reduce overlapping or conflicting interventions and to maintain alignment between planning decisions and post-construction management.

- **Finance:** Enables implementation and continuity by ensuring that each phase has a viable economic basis. Resources are allocated to collect and manage data, build and maintain infrastructure, fund preventive maintenance, and sustain affordability through structured tariffs, subsidies and water credit mechanisms. Financial settings are aligned with SR and SSR targets so that post-construction performance remains consistent with the sustainability expectations established during pre-construction evaluation.

- **Data, ethics and capacity:** Provides the information and operational competence needed for evidence-based action. Data are captured through IoT systems where feasible or through verified manual records uploaded to a data management platform, such as the Target 6.1 Map used in Chapter 6. Operational evidence is then used to monitor performance, interpret deviations and adjust practice, including assumptions applied in pre-construction planning. Quality assurance, traceability and privacy safeguards support reliable analysis and ensure that implementation remains adaptive and accountable.

The integrated framework is consolidated in Table 9.1, which summarises the framework across the pre-construction, construction and post-construction phases described in Sections 9.2.1 to 9.2.3, together with the associated inputs, metrics and decision outputs.

Table 9-1: Integrated life cycle Sustainability Framework for Water Infrastructure in Nigeria

Life cycle stage / module	Core objective	Key inputs / tools	Core metrics / indicators	Main decisions / outputs
Pre-construction: community level mapping and diagnostic scoping	Characterise community level water access constraints and context to identify appropriate interventions	Household and community mapping; water access surveys; observations on source condition and reliability; basic health and risk information	Source types and locations; travel time and effort; hours and reliability of supply; perceived quality and safety; seasonal variation	Community water poverty profile; indicative intervention type (rehabilitation, SWI, treatment point); communities taken forward to PISM and underutilisation assessment
Pre-construction: integrated viability and sustainability evaluation (PISM)	Assess location viability and financial sustainability under realistic demand and cost assumptions	Community diagnostic profile; PISM or an equivalent multi-indicator sustainability assessment tool; local cost data; candidate tariff levels and anticipated external support (for example, subsidies or operating grants)	Viability Rating (VR); Sustainability Rating (SR); Self Sustainability Rating (SSR); baseline O&M cost estimates	Viability classification; recommended tariff and support ranges; indicative system scale; decision to proceed, re-scope or defer investment
Pre-construction: underutilisation risk screening and configuration	Assess risk of underuse and refine configuration and siting	Mapped walking times to proposed and existing sources; perceived adequacy of existing sources; information on competing or overlapping supplies; indicative willingness to pay	Relative accessibility (walking time differences); qualitative adoption risk; presence of free or heavily subsidised alternatives	Configuration and siting adjustments (for example, outlet locations, capacity band, service model); demand band for design; in high-risk cases, decision not to implement a full supply scheme

Construction: co-design and service model definition	Align service model and configuration with community priorities and pre-construction constraints	Community diagnostic and mapping; PISM outputs; underutilisation assessment; structured engagement with community and local institutions	Agreed service objectives (for example, primary drinking water, supplementary supply, treatment point); agreed access arrangements; indicative affordability and support preferences	Culturally and socially appropriate service model; agreed site locations; initial tariff, water credit and support arrangements; local roles and responsibilities for operation and oversight
Construction: technical configuration and treatment-ready design	Specify a treatment-ready, monitorable system consistent with demand, water quality and service model	Agreed service model; demand and utilisation band from pre-construction; hydrogeological and water-quality information; energy and land constraints	Design capacity and storage volume; abstraction, storage and distribution layout; treatment configuration aligned with failed parameters; monitoring and data architecture (meters, IoT where feasible)	Detailed engineering design and specifications; construction drawings and bill of quantities; defined treatment and monitoring layout suitable for the local context
Construction: governance, tariffs, support and commissioning	Establish institutional and financial arrangements and verify readiness for operation	Design package; SR and SSR scenarios; co-designed governance structure; agreements with operators, authorities and support organisations	Ownership and O&M responsibility; approved tariffs and water credit rules; committed external support level; commissioning test results (functional checks, initial water-quality assessment, monitoring system validation)	Implemented governance and O&M arrangements; confirmed tariff and support structure; commissioned system meeting baseline functional and health-critical requirements and ready for post-construction monitoring
Post-construction: operational and	Track technical and financial	IoT data or manual metering records entered by	Reliability (% days in service); utilisation (% of	Adjusted operation, maintenance schedules, tariffs

behavioural monitoring and reporting	performance and user response, and generate feedback for future pre-construction planning	operations representatives; income and expenditure records; basic user feedback or usage summaries	design capacity); non-revenue water (%); realised SR and SSR; adoption and usage patterns	and support; configuration changes where needed (for example, outlets, service arrangements); refined demand, utilisation and willingness-to-pay assumptions for use in subsequent pre-construction evaluations
Post-construction: water safety and treatment monitoring	Maintain alignment with SDG 6.1 safety expectations and national drinking water standards	Proxy based field tests; periodic full laboratory analyses; treatment system operating and maintenance records	Proxy compliance flags; pass/fail status for health-critical and aesthetic parameters under national standards; treatment performance under operating conditions	Confirmation of safe operation; treatment adjustments or maintenance actions; where health-critical parameters fail, temporary restrictions or alternative supply and review of treatment or source options

Chapter 10: Conclusion and Recommendations

10.1. Conclusion

This thesis developed and empirically validated a life cycle Sustainability Framework for Water Infrastructure in Nigeria, aligned with SDG 6.1 and its dual requirements of safe and affordable drinking water. The conclusions are organised below in the sequence of the seven research objectives set out in Section 1.5.2, so that each strand of evidence is mapped explicitly to the objective it addresses. Objectives 1 to 5 are realised through the empirical chapters summarised here, Objective 6 is realised through the integrated framework presented in Chapter 9, and Objective 7 is addressed through the practice, governance, and policy recommendations developed in Section 10.2, and through the future research directions developed in Section 10.3.

- Objective 1. Systematic investigation of factors influencing sustainability. The PRISMA-guided systematic literature review synthesised the sustainability evidence base for Nigeria. It identified 265 sustainability challenges spanning technical, financial, environmental, social, political, institutional and data limitations, and demonstrated that these factors operate across pre-construction, construction and post-construction stages. To navigate this complexity, the review established the need for a Sustainability Framework for Water Infrastructure that encompasses all stages of water infrastructure development and provides a structured basis for advancing SDG 6.1 in Nigeria and comparable developing contexts. The review thereby addressed Objective 1 by mapping how technical, institutional, political, environmental, behavioural, and social factors interact across the project life cycle, and by establishing the analytical foundation that the subsequent empirical chapters extend and validate.
- Methodological foundation (cross-cutting). The transdisciplinary methodology underpinned the thesis and enabled the Sustainability Framework to be empirically tested and refined under Nigerian field conditions. The research design was structured as an iterative cycle that links evidence synthesis with predominantly primary data collection, producing an integrated evidence base across planning, implementation and operation. This included community mapping and field diagnostics, household surveys, IoT and metering records from pilot infrastructure, clinic records, and accredited

laboratory water-quality testing. These inputs were combined with modelling, real-life implementation, monitoring and refinement to enable planning-stage evaluation to be validated against longitudinal operational evidence and to support iterative improvement using observed performance data. This methodological architecture is the connective tissue across the thesis, ensuring that diagnostic, predictive, operational, behavioural, and water-quality evidence is generated through a coherent transdisciplinary research design rather than as isolated case studies.

- Objective 2. Diagnostic and field-based research on barriers to sustainability. The large-scale field diagnosis provided a multi-factor assessment of rural water infrastructure conditions and failure progression. The analysis quantified service gaps and failure at scale across 1,696 communities, where 844 (49.8%) had no improved water source, and identified 852 public boreholes with near parity between functional (434) and non-functional (418) assets. It further reported failure-state distribution consistent with a sequential trajectory, including 28.05% failed but repairable, 20.66% failed beyond repair, and only 0.35% under repair. This supported the interpretation that infrastructure progresses from full function through repairable failure to failure beyond repair and abandonment when maintenance and governance responses are weak. In addressing Objective 2, this work also showed that community-owned schemes failed at a markedly lower rate (21%) than schemes governed by federal, state, local government or NGO arrangements (37% to 48.1%), and that state-level Multidimensional Poverty Index values did not predict community-level water poverty. These findings establish that diagnostic targeting must operate at the community scale and incorporate ownership and management arrangements, local demand, and maintenance capacity, not merely state-level aggregates or generalised indicators of deprivation.

- Objective 3. Pilot interventions generating real-time evidence on utilisation and reliability. The longitudinal smart water kiosk evaluation assessed smart water management effectiveness under longitudinal operating conditions and identified sustainability limitations that are not visible without structured, extended performance monitoring. Over 1,095 days of monitoring, the smart water kiosk achieved 97.1% reliability and 100% SR with external support, while average use was 1,526 L/day, only 7.63% of the 20,000 L/day design capacity, highlighting underutilisation as a critical sustainability challenge. Self-sustainability rating (SSR) was 22% during the paid

period before dropping to 0% following installation of an overlapping free source by another organisation, identifying aid overlap as a sustainability challenge. Usage also declined by 68.4% after tariff introduction, demonstrating that strong technical performance can coexist with weak SSR when pricing, competing supply and aid coordination are not aligned. The operational dataset quantified non-revenue water (NRW) of 41.24% as a distinct operational efficiency issue that reduces the conversion of water dispensed into revenue-generating volume, highlighting the importance of accurate metering and operational control in communal supply systems. In addressing Objective 3, the longitudinal SWI pilot also established that pilot infrastructure should be designed as a dual artefact, delivering services while functioning as an embedded research platform, so that real-time IoT telemetry generates the post-construction evidence required to validate planning-stage assumptions over time.

- Objective 4. Sustainability metrics and diagnostic tools for adaptive planning. The predictive modelling for water infrastructure sustainability planning study introduced the Predictive Iterative Sustainability Model (PISM) to address planning-stage gaps in sustainability evaluation. PISM integrates Viability Rating (VR) and Sustainability Rating (SR) within a cyclical pre-construction assessment process. Field data across five communities produced VR scores of 63.95% to 67.91%, establishing a benchmark for readiness assessment, while predicted SR values of 179% to 424% quantified large differences in sustainability potential across apparently similar settings. This result demonstrated that viability conditions alone do not predict sustainability outcomes without explicit modelling of demand, costs, affordability and operational realities. It also positioned PISM as a practical pre-construction planning tool, with predictive accuracy strengthened by iteratively updating model assumptions using observed SR data from real-life projects. The sensitivity analysis reported in Section 5.3.3 further showed that predicted SR is most responsive to willingness-to-pay parameters and recurrent expense assumptions, providing the evidential basis for risk-aware investment screening called for in Objective 4.

- Objective 4 is further advanced through the behavioural modelling of underutilisation, which established the Water Infrastructure Underutilisation Principle as a diagnostic explanation for why technically sound and sustainably managed systems may fail to

achieve expected impact in water-poor settings. Using household survey data, IoT flow monitoring, clinic records and logistic modelling, the study quantified underutilisation: 16.3% adoption for drinking among 86 households, representing about 1.5% of design capacity, and a 48% reduction in adoption odds per additional minute of walking time (AOR 0.52, 95% CI 0.34 to 0.81). The analysis identified a threshold dynamic where perceived adequacy of existing sources and spatial convenience dominate adoption decisions, and established that behavioural predictors should be embedded into planning-stage eligibility, siting and configuration decisions to reduce waste and strengthen sustainability in pursuit of SDG 6.1. This contribution converts behavioural and spatial evidence into planning-stage heuristics that can be applied before construction, complementing PISM's financial and viability assessment.

- Objective 5. Water quality assurance and treatment feasibility within the sustainability framework. The water quality and treatment assessment examined water safety constraints in Nigeria's public boreholes as a barrier to SDG 6.1. Using a mixed-methods design, the study assessed contamination in 17 public boreholes across four states through accredited testing of 40 parameters, and piloted treatment at two Smart Water Kiosks in Oyo State to evaluate treatment feasibility under NIS 554:2015.

  The results showed that 15 of 17 boreholes (88.2%) failed at least one NIS 554:2015 requirement and 10 of 17 (58.8%) exhibited mixed microbial and geogenic contamination, indicating that multi-barrier treatment readiness is required where safe supply is expected. Proxy analysis also supported the feasibility of low-cost monitoring approaches in low-resource settings, including proxy combinations such as iron plus turbidity detecting 53.3% of failing samples within the proxy simulation dataset (255 parameter combinations).

  Treatment pilots demonstrated that health-critical compliance can be achieved under field conditions, and the feasibility assessment supported regulatory and investment pathways that prioritise health-risk reduction while recognising implementation constraints for aesthetic parameters. The findings also showed that conventional handpump-based infrastructure is generally unsuited to integrated treatment and monitoring required for safe water compliance, whereas Smart Water Kiosk configurations can more readily integrate treatment and performance monitoring,

supporting a national sustainability framework that embeds water safety and bridges policy and field realities in progressing SDG 6.1. In addressing Objective 5, this evidence supports a phased compliance pathway in which health-critical parameters are prioritised immediately and aesthetic parameters are scheduled as financial and technical capacity allow, embedding water-quality assurance within the wider sustainability framework rather than treating it as a separate concern.

- Objective 6. Integration into a comprehensive life cycle sustainability framework. Chapter 9 synthesised the empirical findings from the systematic review, field diagnostics, predictive modelling, smart infrastructure monitoring, behavioural analysis, and water-quality assessment into an integrated life cycle Sustainability Framework for Water Infrastructure in Nigeria. The framework is structured across pre-construction, construction and post-construction phases. It links community-level diagnostics, PISM-based viability and sustainability assessment, underutilisation risk screening, co-designed service configuration, treatment-ready infrastructure design, governance and tariff arrangements, operational monitoring, and water-safety feedback loops. In addressing Objective 6, the thesis moves from individual empirical findings to an integrated decision architecture that can guide planning, implementation, monitoring and refinement of water infrastructure under complex Nigerian conditions. This synthesis is the principal integrative contribution of the thesis, because it consolidates the empirical evidence into a life cycle decision architecture that links diagnosis, planning, design, operation, behavioural uptake, financial performance, and water safety within a single sustainability framework.

- Objective 7. Evidence-based recommendations for practice, governance and policy. The thesis provides a foundation for recommendations directed at engineering practice, governance and policy. The evidence indicates that sustainable water infrastructure delivery in Nigeria requires a shift from asset provision to life cycle service assurance. Engineering practice must incorporate viability assessment, treatment-ready design, monitoring architecture and post-construction feedback. Governance arrangements must clarify ownership, O&M responsibility, coordination among implementing organisations and mechanisms to reduce aid overlap. Policy must support routine use of metrics such as VR, SR, SSR, reliability, utilisation, NRW and water-quality compliance in project approval, monitoring and evaluation. In addressing Objective 7,

the thesis establishes the empirical basis for the practice, governance, and policy recommendations developed in Section 10.2, and the future research directions developed in Section 10.3.

Viewed alongside the wider Nigerian evidence base, the thesis findings are consistent with established accounts that rural water infrastructure failure is shaped by multi-domain sustainability constraints across planning, delivery and post-construction management. The further contribution of the thesis is to show that these established explanations do not fully account for what happens once infrastructure enters real operation. The field diagnostics showed that state-level poverty indicators were insufficient for explaining community-level water infrastructure deprivation, while longitudinal smart-monitoring and operational data revealed mechanisms not documented in the reviewed literature, including aid overlap, persistent infrastructure underutilisation, the SR/SSR gap, and NRW patterns that remained broadly unchanged across free and paid service periods. This showed that tariff introduction alone did not materially reduce NRW, and that metering, operational controls and smart monitoring are central to managing water losses in communal supply systems. These findings demonstrate the value of a framework that is diagnostic before construction and adaptive after implementation. The life cycle framework developed in this thesis therefore links pre-construction assessment with post-construction feedback, enabling sustainability decisions to be refined through lived service experience and observed system performance.

Building from this evidence, the thesis advances a novel life cycle Sustainability Framework for Water Infrastructure as its central contribution. The framework positions sustainability in communal water infrastructure as a life cycle property, emerging from the interaction of technical, financial, behavioural, institutional and governance decisions before, during and after construction. It synthesises evidence from the systematic review, large-scale field diagnostics, PISM modelling, longitudinal smart monitoring, underutilisation analysis and water-quality assessment into a single decision architecture for planning, delivery and post-construction monitoring. Within this framework, the thesis embeds four interlocking analytical contributions: PISM as a pre-construction predictive instrument; the Water Infrastructure Underutilisation Principle as an explanation of persistent non-use of technically functional systems; the sequential failure trajectory as a Nigerian-specific account of infrastructure deterioration; and the SR/SSR gap as a construct that separates operational reliability from financial self-sustainability.

Together, these contributions reposition sustainability from a general aspiration into a structured, metric-driven and testable framework for understanding how communal water infrastructure performs, persists or fails. The framework has been implemented in five Nigerian communities through Smart Water Infrastructure deployments that currently provide safe and sustainable water access for approximately 5,000 people, demonstrating its practical value for water agencies and delivery partners seeking to advance SDG 6.1. Its empirical validation is strongest for groundwater-centred communal systems, particularly borehole-based and smart-kiosk configurations. However, many of the sustainability mechanisms identified in the thesis, including planning quality, governance, financing, community behaviour, monitoring, maintenance and water-safety assurance, are not exclusive to groundwater systems. The contribution is therefore both substantive and methodological: it provides a tested Nigerian framework for borehole-based communal systems and a transferable life cycle research architecture that can be adapted, through context-specific testing, recalibration and longitudinal validation, to other complex water-infrastructure settings similar to Nigeria and to other water-source configurations, including surface-water, rainwater harvesting, dam-fed, household-level and hybrid systems.

10.2. Recommendations for engineering practice, governance, and policy

The empirical chapters of this thesis surfaced practical implications at each stage of the water infrastructure life cycle. These implications are consolidated below into a single set of recommendations for engineering practice, governance, and policy, organised by life cycle stage. They draw on the integrated framework in Chapter 9 and are addressed to water agencies, regulators, and funders responsible for water infrastructure delivery in Nigeria.

10.2.1. Pre-construction

- Site selection should rest on community-level mapping. Mapping captures the spatial distribution of households, existing water sources, walking times, settlement layout, and local hydrogeological and access conditions, and is the only practical basis for matching infrastructure scale, configuration, and siting to actual demand and accessibility. The Community Level Mapping and Diagnostic Scoping module of the

integrated framework (Section 9.2.1) should be applied before any site is approved for capital expenditure.

- PISM should be used to test location viability and projected sustainability before construction. Pre-construction appraisal should not rely on water need or location viability alone. It should combine the Viability Rating with predicted Sustainability Rating and clearly stated assumptions about demand, willingness to pay, tariff level, operating costs, maintenance costs, repair costs, and expected external support. This allows agencies and funders to decide whether a proposed project should proceed, be redesigned, receive structured support, or be deferred before capital is committed.
- Underutilisation risk should be screened alongside PISM before construction. While PISM assesses location viability and projected sustainability, the Water Infrastructure Underutilisation Principle should be used to test whether the demand assumed in the PISM assessment is likely to translate into actual use. This requires checking relative walking time, perceived adequacy of existing sources, affordability, and the presence of competing free or subsidised supply. Where underutilisation risk is high, the project should be reconfigured before construction through improved siting, revised service models, adjusted tariff assumptions, stronger community engagement, or structured external support.

- Ownership, operational capacity, and maintenance arrangements should be agreed at site selection, not after handover. Site selection, ownership structure, maintenance planning, and local operational capacity should be treated as core design variables from the outset of project development.

10.2.2. Construction

- New communal infrastructure should be designed from the outset to support treatment and monitoring. This includes provision for treatment units, treated-water storage, metering, sampling points, maintenance access, and IoT-based or verified manual monitoring where feasible. Handpump-only schemes may improve access, but they are poorly suited to integrated treatment and routine performance tracking. Where safe drinking-water compliance is required, treatment-ready configurations should be considered during design rather than left to later retrofitting.

- Tariffs, water-credit arrangements, and external-support commitments should be agreed at commissioning, not later. They should be calibrated to the SR and SSR scenarios produced by PISM during appraisal and recorded as part of the commissioning package.

- Training of local technicians, kiosk attendants, and community committees should be a condition of project handover. The lower failure rate of community-owned schemes reflects operational capacity and local accountability, not technology choice.

10.2.3. Post-construction

- Post-construction monitoring should function as an adaptive management mechanism rather than a retrospective reporting exercise. IoT telemetry, or verified manual records where digital monitoring is not feasible, should be used to track reliability, utilisation, non-revenue water, revenue water, water credit, expenditure and water-quality indicators against the assumptions established during pre-construction appraisal and commissioning. Deviations from expected performance should trigger defined responses, including maintenance intervention, tariff review, demand reassessment, NRW investigation, treatment adjustment or revision of service arrangements.

- A phased compliance pathway should be formalised for applying NIS 554:2015 in low-resource communal water systems. Health-critical parameters, particularly microbiological indicators and contaminants with direct public-health implications, should be treated as immediate compliance requirements. Parameters that are primarily aesthetic or operational, such as hardness-related exceedances, should be managed through staged improvement plans where full compliance requires technologies that may be financially or technically prohibitive at commissioning. This approach preserves public-health protection while recognising the implementation constraints that shape sustainable service delivery in resource-constrained settings.

- Proxy-based field monitoring should be incorporated into routine water-quality monitoring as a risk-based prioritisation mechanism. It should complement accredited laboratory testing by providing an affordable way to identify schemes that require

confirmatory analysis, treatment review, or escalation. This approach would allow limited testing resources to be directed towards higher-risk systems while preserving the authority of formal compliance testing.

10.2.4. Cross-cutting

- Project approval should include a whole-of-life financing plan. Before construction, implementing agencies and funders should identify how operation, maintenance, repair, treatment-media replacement, monitoring, and any water-credit or subsidy commitments will be financed over time. The SR/SSR gap identified in Chapter 6 shows that, in water-poor communities, full cost recovery through user tariffs may not be realistic. Sustainability planning should therefore distinguish between costs that can reasonably be recovered through water sales and costs that require structured external support, such as major repairs, treatment replacement, or social water provision.

- Aid-overlap risk should be assessed before new water interventions are approved. Government agencies, NGOs, donors and implementing partners should coordinate planned projects using shared community diagnostics and infrastructure mapping, so that new interventions complement existing systems instead of unintentionally displacing demand or weakening cost recovery. The aid-overlap effect identified in Chapter 6 shows that uncoordinated provision of parallel free or subsidised sources can undermine otherwise functional infrastructure and reduce long-term sustainability.

- National frameworks such as the Partnership for Expanded Water Supply, Sanitation and Hygiene (PEWASH) should be operationalised through the life cycle decision architecture developed in Chapter 9. In addition to measuring infrastructure access, sector reporting should incorporate behavioural and spatial indicators, including actual use, walking time, perceived adequacy of existing sources, reliability, affordability, and water-safety status.

Taken together, these recommendations consolidate the practical implications of the empirical chapters into actions that can be adopted by water agencies, regulators, and funders responsible for water infrastructure delivery in Nigeria.

10.3. Recommendations for future research

Building on the practice-oriented recommendations in Section 10.2, this section identifies the future research directions that arise from the empirical boundaries and analytical contributions of the thesis. The framework was empirically substantiated through five Smart Water Infrastructure deployments in South West Nigeria, providing evidence of its applicability within the conditions in which it was developed. Further research is needed to test the framework beyond this initial validation context, determine where its decision rules and thresholds remain robust, identify where recalibration is required, and examine how its core modules can be adapted across diverse water-service contexts.

External validity and transferability of the framework

Building on this initial validation context, future research should examine whether the framework's modules, indicators and decision rules retain their explanatory and decision-support value when applied to different water-service settings. This should include additional Nigerian geopolitical zones and comparable low-resource settings in Africa and South Asia, where hydrogeology, settlement patterns, institutional capacity, affordability conditions and water-use behaviour may differ from those observed in this thesis. Each application should be designed as a structured replication, using a consistent indicator set to compare reliability, utilisation, SR, SSR, NRW, water-safety compliance and adoption outcomes. The analysis should identify which components can be transferred without modification, which require recalibration and which require redesign. This would define the boundary conditions of the framework and establish the extent to which it can support sustainable water-infrastructure planning beyond its original empirical setting.

Prospective calibration of PISM

PISM has been applied and tested at the planning stage across five communities. It has not been tested at the scale required to establish prediction error bounds, and its indicator weights have not been re-estimated against realised post-construction performance. Future research should compare pre-construction VR, SR, and SSR outputs with observed outcomes across a larger and more diverse sample of deployments, generating uncertainty bounds that can be

reported alongside point predictions and supporting risk-tiered investment decisions. Whether PISM's weighting structure remains appropriate across service configurations, including smart kiosks, treatment points, small piped networks, and hybrid systems, is a further open question. The contribution would be the transition of PISM from an internally tested planning instrument to a calibrated, uncertainty-aware decision-support tool.

Generalisation and causal evaluation of the Underutilisation Principle

The Water Infrastructure Underutilisation Principle provides a behavioural explanation for why reliable infrastructure may remain underused in water-poor communities. Future research should test the principle across wider geographic, socio-economic and governance contexts to determine which mechanisms remain stable and which require contextual refinement. Intervention-based studies should also examine whether underutilisation can be reduced through changes to siting, service configuration, tariff design, water-quality communication and community engagement. This would strengthen the behavioural theory of communal water infrastructure adoption and improve planning tools for anticipating underutilisation risk before construction.

Proxy-based water-quality monitoring across hydrogeological contexts

Chapter 8 demonstrated the practical value of proxy-based monitoring for identifying water-quality risks in low-resource settings. Future research should extend this work across broader hydrogeological contexts to assess how proxy indicators perform under different groundwater conditions, contamination profiles and treatment environments. Multi-site validation using larger datasets would strengthen understanding of sensitivity, specificity and reliability at scale, and support the development of risk-based monitoring protocols within a phased approach to national drinking-water compliance.

Institutional capacity, data governance, and AI-enabled WASH modelling

The recommendations in Section 10.2 depend on institutional conditions that enable evidence to be collected, interpreted, and acted upon at scale. Future research should therefore examine whether water agencies, local governments, community committees, and implementation partners have the technical, administrative, and organisational capacity required to use life

cycle metrics in routine planning and management. This includes research into training models, reporting standards, institutional incentives, and accountability mechanisms that can support consistent use of sustainability evidence across the water infrastructure life cycle.

A further research direction concerns the use of artificial intelligence and machine-learning approaches for large-scale WASH data modelling. As community diagnostics, IoT telemetry, water-quality records, clinic records, financial data, and infrastructure inventories expand, AI-enabled models could support the identification of failure risks, underutilisation patterns, water-quality priorities, anomalous NRW behaviour, and refinements to PISM assumptions. However, such models should be interpretable, locally validated, and governed by clear data-quality standards so that they strengthen decision-making without weakening accountability or producing contextually inappropriate recommendations.

Data governance should form part of this agenda. As IoT systems, manual reporting, and digital platforms become more central to water infrastructure management, research should address data quality, traceability, ownership, privacy, ethical use, and decision accountability, particularly in vulnerable communities where monitoring systems must support service improvement without creating risks of surveillance, exclusion, or data misuse.

Collectively, the future research directions outlined above build directly on the central achievements of this thesis. The thesis has developed and empirically substantiated a life cycle Sustainability Framework for Water Infrastructure through real-world implementation, predictive modelling, smart monitoring, behavioural analysis, and water-quality assessment in Nigerian water-poor communities. External validation would test the framework's transferability; prospective calibration would strengthen PISM as a predictive planning tool; wider testing of the Water Infrastructure Underutilisation Principle would deepen understanding of adoption behaviour; expanded proxy-monitoring research would improve the affordability of water-quality assurance; and institutional, data-governance, and AI-enabled WASH modelling research would support implementation at scale. In this way, future research can extend the thesis contribution from an empirically substantiated Nigerian framework into a broader decision-support pathway for accelerating safe, reliable, affordable, and sustainable water access in pursuit of SDG 6.

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Appendix 1

Table A1.1 Search strategies in databases

Databases	Search Keywords	Search Date	Related Article/Total
Scopus	TITLE-ABS-KEY (("water infrastructure" OR "water facility" OR "water supply") AND (sustainab* OR challenge* OR solution*) AND Nigeria)	27/04/2023	202/287
Google Scholar	("water infrastructure" OR "water facility" OR boreholes OR wells OR standpipes) AND (sustainab* OR "sustainable development" OR "sustainable solutions") AND Nigeria AND (fail* OR challenge* OR factor* OR barrier*) AND ("technical factors" OR "financial factors" OR "environmental factors" OR "social factors" OR "political factors" OR "institutional factors")	28/04/2023	86/598

Search Strategy

In conducting the systematic literature review reported in Chapter 2, the study adheres to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, which ensures a transparent, rigorous, and replicable review process (Moher et al., 2009; Page et al., 2021). The process began with an initial scoping search using Google to explore the existing literature and refine the research objectives and questions. This preliminary search informed the development of the search strategy and ensured a comprehensive approach to identifying relevant studies.

The primary electronic database search was conducted using Scopus due to its extensive collection of publications, its large peer-reviewed library (Burnham, 2006; Falagas et al., 2008), and its ability to capture publications from several developing countries, ensuring that sufficient studies on Nigeria are captured (Mongeon & Paul-Hus, 2016; Zhu & Liu, 2020). This comprehensive database provides wide coverage of scientific disciplines and ensures a diverse range of sources for systematic literature review. Relevant keywords and phrases were identified based on the research objectives and questions and used to screen titles and abstracts of articles in the database. Selected articles were then subjected to a full-text review for eligibility.

Alongside the electronic database search, hand-searching of pertinent article references and grey literature was also conducted. The hand-searching approach for grey literature followed Adeniran's (2022b) search strategy in his systematic literature review titled: "What is the state of water infrastructure governance research in Nigeria? A review", which focuses on the first 200-300 results from Google and Google Scholar, and the first 100 results from the UN and World Bank databases. By attempting to capture publications through a range of sources that includes grey literature (conference proceedings and working papers), the tendency for publication bias in systematic reviews is averted (Adams et al., 2016; Lilyea et al., 2016; Mahood et al., 2014). After completing the searches, eligible studies were included in the review, and relevant information was extracted and synthesised to address the research questions and objectives. This comprehensive search strategy ensured that a wide range of literature was considered and reduced the likelihood of bias in the review.

Inclusion and Exclusion Criteria

The researcher established a set of predefined inclusion and exclusion criteria to ensure the relevance and consistency of the studies included in the systematic review. These criteria help determine which studies to include in the review and which ones to exclude.

In the systematic review process, both mandatory and additional criteria play pivotal roles in the selection of articles. Criteria 1 to 7 in Table 2-1 are mandatory, forming the bedrock of the inclusion process. These criteria are designed to ensure that the selected articles align closely with the research topic, objectives, and questions, maintaining a rigorous focus on water infrastructure sustainability in Nigeria, particularly pertaining to groundwater sources.

However, during the search process, it was observed that there were limited articles explicitly focusing on the entirety of the research topic or directly addressing all aspects of the research objectives and questions. This presented a challenge in finding sufficient literature to form a comprehensive review.

To overcome this, Criteria 8 and 9 were introduced as additional filters to refine the selection process. These criteria delve deeper into specific facets of the research area, such as community participation, climate change impact, water resources management, and their relationship to water infrastructure sustainability. They were designed to ensure the inclusion of articles that, although may not cover the entire research objective explicitly, could still provide valuable insights to help answer the research questions.

These additional criteria allowed for a broader perspective, enabling the inclusion of articles that contribute to the understanding of water infrastructure sustainability in Nigeria, even if they approach the topic from a different angle or context. Thus, they ensured a sufficient body of literature was selected for the review while maintaining relevance to the research objectives and questions.

The integration of mandatory and additional criteria provides a robust and adaptive framework for article selection. It ensures that the systematic review remains tightly focused on the primary research question, while also permitting the exploration of specific themes and sub-questions that emerge as the review progresses. This approach accommodates the dynamic nature of systematic reviews, allowing for a comprehensive and nuanced exploration of Nigeria's water infrastructure sustainability literature.

Data Extraction and Synthesis

Data extraction and synthesis for the systematic review are conducted methodically to ensure a comprehensive analysis of the included studies, directly addressing the research objectives and questions.

Data Extraction: Using a custom-made Microsoft Excel form, systematic data extraction is carried out. This form is designed to draw out significant details from each study, such as the study's objectives, applied theoretical frameworks, utilised methodology, and key findings that align with the research objectives and questions. The extraction primarily focuses on factors

contributing to water infrastructure failure in Nigeria, including technical, financial, environmental, social, political, and institutional aspects, and the sustainable solutions proposed or implemented.

The data extraction form is composed of the following categories: Article ID, Title, Authors, Year of Publication, Journal/Source, Study Location, Study Objectives, Factors Identified (Technical, Financial, Environmental, Social, Political, Institutional), Theoretical Frameworks, Methodology, Key Findings, Sustainable Solutions Proposed or Implemented, Implications for Research, Limitations, Opportunities for Future Research, and Quality Assessment. Each category serves a specific purpose in the analysis. The “Implications for Research” column summarises how each study's findings contribute to the research objectives, while “Quality Assessment” provides a critique of each article's quality.

Data Synthesis: An integrated approach that combines thematic analysis, narrative synthesis, and content analysis is employed to synthesise the extracted data. This approach facilitates the identification of common themes, the exploration of relationships and findings across the studies, and the quantification of the frequency of certain responses or factors. Summary tables/charts are created to present the synthesised findings, highlighting key insights and trends.

Quality Assessment

The quality assessment tool used in this study included the following five questions: Does the study have a clear aim or objective?

1. Is the study design appropriate for the aim or objective?
2. Was the data collection method clearly described and appropriate?
3. Were the results clearly presented?
4. Were the conclusions supported by the results?

Each of the selected studies was evaluated against these criteria, with each question warranting a 'yes' or 'no'. Based on the number of affirmative responses, studies were rated as follows:

- Very High Quality: 5/5
- High Quality: 4/5

- Moderate Quality: 3/5
- Low Quality: 2/5
- Very Low Quality: 1/5

These ratings were recorded in the 'Quality Assessment' column of the data extraction form. Alongside this numerical rating, a narrative summary of each article's quality was provided in the same column. This combined approach enabled a nuanced and comprehensive evaluation of the methodological rigour of the selected studies, thereby ensuring that the conclusions drawn from the systematic review were predicated on high-quality evidence.

Table A1.2 Overview of Chosen Studies

S/ No	Author(s) and Year	Title	Publication Type	Geographical Setting	Geographical Location	Study Aim	Water Source	Study Approach
1	(Adeniran et al., 2021)	Water infrastructure development in Nigeria: Trend, size, and purpose	Article	National	Nigeria	Aims to analyse historical water infrastructure development in Nigeria with a specific focus on dams and standpipes	Ground Water & Surface Water	Qualitative
2	(Andres et al., 2018b)	Why are so many water points in Nigeria non-functional?: an empirical analysis of contributing factors	Article	National	Nigeria	To identify the extent, timing, and reasons for the failure of water points in Nigeria	Groundwater	Quantitative
3	(Popoola et al., 2021)	Household Water Stress, Adaptation and Resilience in Some Selected Peri-urban and Rural	Conference Paper	Peri-urban and rural	Oyo State	To examine the state of potable water infrastructure and resilience in rural areas of Oyo State, Nigeria	Groundwater & Surface Water	Mixed

		Communities of Oyo State, Nigeria						
4	(Shiru et al., 2020)	Challenges in water resources of Lagos mega city of Nigeria in the context of climate change	Article	Urban	Lagos	To assess the challenges facing the water resources of Lagos, from availability and anthropogenic impacts to the efforts towards attaining sustainable management.	Groundwater, surface water	Mixed
5	(Olajuyigbe , 2016)	Community participation and sustainability issue: An evaluation of a donor-driven water sector in Ikaram millennium village project, Nigeria	Article	Rural	Ondo	Investigate the factors affecting the sustainability of water projects	Groundwater	Mixed
6	(Oyegoke et al., 2012)	The challenges of water supply for a megacity: a case study of Lagos Metropolis	Article	Urban	Lagos	Address water supply challenges in Lagos State	Groundwater and Surface Water	Not Stated

7	(Oyekale & Ogunsanya, 2012)	Factors Influencing Households' Access to Portable Water in Rural Nigeria	Article	Rural	Nigeria	To determine the factors that influence access to improved water sources in rural Nigeria	Groundwater and Surface Water	Quantitative
8	(Ugwu et al., 2022)	Does economic policy in Nigeria enhance sustainable water and sanitation facilities?	Article	National	Nigeria	To analyse the impact of economic policy on sustainable water and sanitation facilities in Nigeria	Note Stated	Quantitative
9	(Adeoti, 2008)	Determinants of households' participation in the collective Maintenance of publicly provided water infrastructure in Oyo State, Nigeria	Article	Rural	Oyo	Evaluate participation in collective maintenance of boreholes and factors that influence it in Oyo state.	Groundwater	Quantitative
10	(Andres et al., 2018a)	An evaluation of the contributing factors of water scheme failures in Nigeria	Article	National	Nigeria	To identify the extent and timing of the failure of water schemes in Nigeria and the factors affecting it		Quantitative

11	(Cronk & Bartram, 2017)	Factors influencing water system functionality in Nigeria and Tanzania: a regression and Bayesian network analysis	Article	National	Nigeria & Tanzania	To explore factors influencing the functionality of 82,503 water systems in Nigeria and Tanzania.	Groundwater	Quantitative
12	(Emmanuel & Bamidele, 2013)	Sustainability of borehole water schemes through community participation in Ejigbo, Osun state	Article	Rural	Osun	Evaluate the contributions of community efforts to the borehole water supply schemes in Ejigbo LGA.	Groundwater	Quantitative
13	(Khan et al., 2018)	Ensuring sustainability and improving functionality of water supply facilities through VLOM in Nigeria–from pilot to national strategy	Conference Paper	Rural	Nigeria	To implement a sustainable operation and maintenance strategy for rural water supply via Village Level Operation and Maintenance (VLOM)	Groundwater	Not Stated

14	(Oloruntade et al., 2014)	Assessing the sustainability of borehole as an alternative to pipe-borne water supply in some selected communities in Akoko area of Ondo State, Nigeria	Article	Rural	Ondo	The aim of the study is to assess the sustainability of boreholes for potable water supply in selected communities in Akoko Area, Ondo State, Nigeria.	Groundwater	Mixed
15	(Otun et al., 2011)	Issues and challenges of decaying urban water infrastructure in Nigeria	Conference Paper	Urban	Nigeria	Highlight and discuss the issues and challenges of decaying water assets in PWUs in Nigeria	Not Stated	Qualitative

Table A1.3 Empirical Findings of Selected Studies

S/N	Study	Empirical finding
1	Adeniran, Daniell & Pittock (2021)	National overview of trend, size and purpose of water-infrastructure development (esp. dams/standpipes); discusses finance and recurrent malfunctioning; does not estimate a south–north failure gradient.
2	Andres et al. (2018b)	National analysis shows non-functionality is associated with technology type, regional location, promoter and management practices; early failure probabilities are high.
3	Popoola et al. (2021)	Peri-urban/rural Oyo surveys report high household water stress and reliance on coping strategies, indicating persistent infrastructure/service gaps.
4	Shiru et al. (2020)	Lagos case combining field observations, samples and interviews documents compounded water stress from rapid urbanisation and climate variability.
5	Olajuyigbe (2016)	Community study shows weak government support and low local economic capacity undermine donor-driven project sustainability.
6	Oyegoke, Adeyemi & Sojobi (2012)	Lagos megacity case documents supply shortfalls and operational/monitoring weaknesses, arguing for structural reform.
7	Oyekale & Ogunsanya (2012)	Econometric analysis finds distance, household wealth and health constraints significantly predict access to improved sources in rural Nigeria.
8	Ugwu et al. (2022)	National modelling indicates economic policy and unsafe sanitation conditions affect sustainability of water and sanitation facilities.
9	Adeoti (2008)	Household survey in Oyo shows education, distance, income and rule enforcement increase participation in collective borehole maintenance.
10	Andres et al. (2018a)	Using the 2015 National Water & Sanitation Survey, around 46% of schemes are non-functional; timing and

		determinants point to design, implementation and operational levers.
11	Cronk & Bartram (2017)	Regression/Bayesian analysis (Nigeria & Tanzania; >82k systems) shows functionality relates to technical, financial and social determinants, incl. management and tariffs.
12	Emmanuel & Bamidele (2013)	Osun case finds greater community participation is associated with better borehole condition.
13	Khan et al. (2018)	Presents VLOM as an O&M approach; descriptive strategy rather than outcomes evaluation.
14	Oloruntade et al. (2014)	Ondo survey reports high failure rates for both hand-pump and motorised/solar boreholes, especially 5–10 years after construction.
15	Otun, Oke & Oguntuase (2011)	Highlights ageing and poor management of urban public water utilities and declining service quality.

Table A1.4. Sustainable Solution Proposed Summary

S/No	Author(s) and Year	Sustainable Solutions Proposed
1	(Adeniran et al., 2021)	Prioritise sustainable water resources development by optimising water infrastructure use, adopting modern rural–urban development approaches, keeping infrastructure development options flexible for an uncertain future, and understanding power relations and political dimensions of water infrastructure development.
2	(Andres et al., 2018b)	Improve the design, implementation, and operational stages of water points and choose the right extraction technology to prevent failure over the medium and long term.
3	(Popoola et al., 2021)	Increase cooperation towards the maintenance of water facilities among communities, strategically locate the capital city and LGAs to promote access to governance and improve

		project management to eliminate unnecessary maintenance costs from faulty water infrastructures in rural areas.
4	(Shiru et al., 2020)	Implement infrastructural development, stricter laws and regulations, public education, and integrated water resource management.
5	(Olajuyigbe, 2016)	Actively involve the community and the local government in activities to achieve sustainable development.
6	(Oyegoke et al., 2012)	Propose comprehensive changes in water supply project design and implementation, incorporating cost-effectiveness, technical innovation, environmental protection, and community participation. Utilise performance indicators and increase private sector involvement in water supply provision.
7	(Oyekale & Ogunsanya, 2012)	Government should implement awareness programmes to sensitise rural households on the need to treat their water before use.
8	(Ugwu et al., 2022)	Ensure proper monitoring and funding of WASH projects, maintain clean toilet campaigns, and improve water policies for better infrastructure.
9	(Adeoti, 2008)	Improve adult education and training for management teams on both repair work and administrative tasks to increase trust and participation, leading to better maintenance of boreholes.
10	(Andres et al., 2018a)	Give top priority to design, implementation, and operational stages to drastically reduce failure rates. Increase the role of WASHCOMs in the maintenance of water schemes throughout the country.
11	(Cronk & Bartram, 2017)	Improve water system monitoring, use different modelling techniques for data analysis, and inform evidence-based decision-making for better water system management.
12	(Emmanuel & Bamidele, 2013)	Improve community participation, government involvement, and maintenance procedures, along with increased funding and sensitisation programmes to ensure borehole sustainability.

13	(Khan et al., 2018)	Implement the VLOM strategy involving institutional arrangements, financial planning, technical support, data collection, social mobilisation, capacity building, partnership with private sector, and effective monitoring system.
14	(Oloruntade et al., 2014)	Enhance the sustainability of boreholes by institutionalising water management at the local government level and fostering community involvement in borehole management.
15		Implement a detailed asset management program for PWUs to improve operational decisions and plan for future repairs and replacements of all water infrastructures.

Table A1.5. Consolidated summary of the 52 themes and associated issues identified across the reviewed studies

Category	**Theme**	**Number of identified issues**	**Description of issues**
Technical	Deterioration of Infrastructure	10	Systemic malfunctioning, ageing water schemes, and poor infrastructure development and management.
Technical	Poor Material and Construction Practices	4	Poor workmanship, poor construction materials, and design failures.
Technical	Poor Operation and Maintenance	9	Lack of preventive maintenance knowledge, poor maintenance of water sources, and technical issues related to management.
Technical	Choice of Technology and Equipment	6	Inappropriate technology choice, equipment failure, and wrong pump-type selection.

Technical	Water Supply Issues	5	Groundwater overdraft, uneven water distribution, and shallow wells that cannot provide all-year-round supply.
Technical	Spare Parts Availability and Quality	7	Limited availability and poor quality of spare parts and supplies.
Technical	Impact of External Factors	5	Vandalism, contamination, lack of electricity, and other external disruptions affecting infrastructure.
Technical	Overuse and Lack of Proper Planning	3	Exceeding intended use and wear and tear arising from poor planning.
Technical	Inadequate Knowledge and Resources	6	Poor knowledge of the Nigerian geological terrain, non-existent literature on infrastructure functionality, and large maintenance backlogs.
Technical	Specific Technology Issues	3	Functionality problems associated with manual pumps, hand pumps, and pump failure.
Technical	Infrastructure Collapse	1	Infrastructure collapse due to poor drilling.
Financial	Insufficient Funding/Budget Allocation	7	Infrastructure financing challenges, dwindling finances, deprioritising water supply, insufficient funding, and declining budget allocations.
Financial	Cost of Infrastructure and Maintenance	8	High costs of production, distribution, maintenance, and replacement components, including solar panels.

Financial	User Fees and Willingness to Pay	7	Absence of user fee collection, inability to pay, and unwillingness to pay charges.
Financial	Government Funding and Allocation	5	Weak or absent state and local government allocations and unsustainable public-sector spending.
Financial	Household Income and Poverty	6	Poverty-related inability to meet financial responsibility, purchase potable water, or connect to formal water services.
Financial	External Funding	4	Dependence on external funding and inefficient use of such funds.
Environmental	Water Scarcity	4	Scarcity linked to poor water management and increasing demand pressures.
Environmental	Pollution	3	Environmental pollution, contamination, and deforestation.
Environmental	Climate Change Impacts	4	Climatic variability and broader climate change effects on water resources.
Environmental	Population Growth	2	Pressure on water infrastructure from population growth and internal migration.
Environmental	Hydrogeology	5	Sparse village locations, clay soils, rocky terrain, and hydrogeological constraints affecting functionality.
Environmental	Insufficient Ground Water	2	Declining groundwater storage and inadequate aquifer yield for specific boreholes.
Environmental	Drought	2	Drought-related disruption to water infrastructure and supply reliability.

Social	Community Involvement	13	Weak community participation, poor cooperation, neglect of rural water supply, and limited public involvement in management.
Social	Population and Migration	8	Pressure on infrastructure from population growth and internal migration, especially in rapidly growing urban areas.
Social	Socio-Economic Factors	10	Effects of sex, education, age, and broader socio-economic conditions on access, maintenance, and sustainability.
Social	Ownership and Management	9	Influence of management model, women's participation, and community organisation on infrastructure performance.
Social	Rural-Urban Inequality	2	Unequal water access between rural and urban areas.
Social	Water Conflict	1	Disputes over water use and management.
Social	Access to Water Sources	2	Distance to source, availability of systems, and logistical constraints affecting water use and system functionality.
Social	Attitude and Corruption	2	Corruptive attitudes, theft of parts, and behavioural factors undermining sustainability.
Social	Environmental Considerations	1	Influence of environmental conditions on social dynamics around water infrastructure.
Political	Policy Misalignment	6	Functional misfits and implementation-level policy mismatch.

Political	Political Instability	5	Instability arising from complex political structures and discontinuity.
Political	Government Commitment	8	Weak government commitment, poor continuity of projects, and lack of political will.
Political	Corruption & Noncompliance	5	Executive corruption, lack of accountability, and policy non-compliance.
Political	Geographical Politics	8	Geographical location and local government politics affecting access, allocation, and functionality.
Institutional	Infrastructure Planning and Management	10	Weak planning, ad hoc initiatives, decentralisation problems, and poor service-delivery performance.
Institutional	Policy and Regulation	6	Incomplete or unsustainable projects and lack of clear operational and maintenance guidance.
Institutional	Institutional Capacity	8	Disjointed responsibility, low institutional capacity, and lack of trained mechanics.
Institutional	Monitoring and Quality Control	7	Inadequate project monitoring, poor quality control, and inefficient monitoring systems.
Institutional	Community Engagement and Transparency	6	Weak community participation, limited transparency, and poor institutional motivation.
Institutional	Corruption and mismanagement	7	Corruption, lack of accountability, and institutional mismanagement.

Institutional	Resource Allocation	6	State-level spatial inequalities and weak allocation of investment and resources.
Institutional	Definition and Research	2	Lack of widely agreed definitions for water infrastructure and sustainability functionality, and limited research grounding.
Institutional	Overarching Problems	4	Broad structural problems, including modernisation and urbanisation linked to the neglect of rural areas.
Other	Geographical factors	5	Distance-related challenges, including proximity to administrative centres and water sources.
Other	Vandalism/Theft	3	Damage and theft affecting infrastructure.
Other	Demographic Factors	1	Demographic pressure, including population growth, not fully captured within the main categories.
Other	Age Factors	1	Influence of household head age on financial contribution and participation.
Other	Methodological Factors	1	Weak approaches by developers and deficiencies in thorough feasibility studies.
	Total	**265**	52 themes across seven major categories**.**

Appendix 2

Section 1 - Sample Space Calculation

The sample space calculation detailed below for Aponmode Community exemplifies the approach used to determine the sample size for all five communities studied. This standardised methodology ensures consistency and comparability across different locations within our research.

Sample Space Calculation for Aponmode Community:

Population: 3000 - 3500.
Estimated people per household: 6 - 9
Estimated household per house: 3 - 6

Taking the averages:

Population = 3250
Estimated people per household = 7.5
Estimated household per house: = 4.5

Total number of households in the community:

Total households = Total population / Average people per household = 3250 / 7.5 = 433.33

Round up to the nearest whole number:

Total households = 433

The total number of houses in the community:

Total houses = Total households / Households per house = 433 / 4.5 ≈ 96.296

Round up to the nearest whole number: Total houses = 96

The unadjusted sample size using the adjusted Cochran's formula for a finite population, assuming a 95% confidence level (Z = 1.96), a 5% margin of error (E = 0.05), and an estimated proportion (p) of 0.5:

n = [(1.96^2 * 0.5 * (1-0.5)) / 0.05^2] / [1 + (((1.96^2 * 0.5 * (1-0.5)) / 0.05^2) - 1) / 433] =

[(1.96^2 * 0.5 * (1-0.5)) / 0.05^2] = 384.16

[1 + (((1.96^2 * 0.5 * (1-0.5)) / 0.05^2) - 1) / 433] = [1 + (383.16) / 433]

= 1 + 0.8848 = 1.885

n = 384.16/1.885 = 203.79
Round up to the nearest whole number:
n = 204 households

The design effect (DE) using the formula DE = 1 + (b - 1) * ICC, where b is the average number of households per house (4), and ICC is the intra-cluster correlation coefficient. We'll use an ICC of 0.1, as it's a common assumption when the actual ICC is unknown:
DE = 1 + (4.5 - 1) * 0.1 = 1.35

Adjust the sample size for the design effect:
n_adjusted = n * DE = 204 * 1.35 = 275.4

Number of houses to visit = 275.4/4.5 = 61.2

Round up to the nearest whole number: 61 houses

A minimum of 61 households in 61 different houses will be visited for surveys and interviews.

Section 2 – Likert-Scale Questions

Table A2.1 presents a subset of 10 questions from the full set of 70 Likert-scale questions used in this study. These sample questions are intended to provide readers with insight into the nature of the questionnaire designed for assessing the Location Viability Rating (LVR). Including only a selection of questions helps to keep the details provided here concise and respects the intellectual property associated with the full questionnaire. Readers interested in the complete list of questions should contact the author directly.

Table A2.1: Sample of Likert-Scale Questions Used for Location Viability Assessment

Community Water Poverty Rate Assessment

1. Does your household have access to safe water source for drinking?					
Response Options	**1.**	**2.**	**3.**	**4.**	**5.**
	Always access to safe water source	Mostly access to safe water source	Sometimes access to safe water source.	Rare access to safe water source	No access to safe water source
Score					

Researchers Comments					
2. What is the primary water source used by your household for drinking purposes, classified as either an improved or unimproved source?					
Response Options	**1.**	**2.**	**3.**	**4.**	**5.**
	Completely improved source	Mostly improved source	Moderately improved source	Somewhat improved source	Unimproved source
Score					
Researchers Comments					
3. How long does it take to reach the drinking water source from your house?					
Response Options	**1.**	**2.**	**3.**	**4.**	**5.**
	Have drinking water piped into home	Less than 5 minutes	5-15 minutes	15-30 minutes	More than 30 minutes
Score					
Researchers Comments					
4. What is the primary water source utilised for non-drinking purposes, categorised as either improved or unimproved?					
	1.	**2.**	**3.**	**4.**	**5.**

Response Options	Completely improved source	Mostly improved source	Moderately improved source	Somewhat improved source	Unimproved source
Score					
Researchers Comments					
5. How long does it take to reach the water source utilised for non-drinking purposes?					
Response Options	**1.**	**2.**	**3.**	**4.**	**5.**
	Have drinking water piped into home	Less than 5 minutes	5-15 minutes	15-30 minutes	More than 30 minutes
Score					
Researchers Comments					
6. What is the frequency at which households fetch water from far away water source?					
Response Options	**1.**	**2.**	**3.**	**4.**	**5.**
	Never, we have access to water through pipes	Rarely, once a week or less	Sometimes, a few times a week	Often, almost every day	Very often, several times a day
Score					
Researchers Comments					
7. What is your perception on the quality of water from your current water source?					

Response Options	**1.**	**2.**	**3.**	**4.**	**5.**
	Excellent quality	Very good quality	Good quality	Fair quality	Poor quality
Score					
Researchers Comments					
8. What is your perception on the quantity of water from your current source?					
Response Options	**1.**	**2.**	**3.**	**4.**	**5.**
	Sufficient throughout the year	Sufficient during most months of the year	Sufficient during some months of the year	Somewhat insufficient throughout the year	Very insufficient throughout the year
Score					
Researchers Comments					
9. In your experience, how many months out of the year do you feel the water supply from your current source is adequate?					
Response Options	**1.**	**2.**	**3.**	**4.**	**5.**
	Adequate throughout the year	9-12 months	6-9 months	3-6 months	Less than 3 months
Score					

Researchers Comments					
10. How many months out of the year do you face water scarcity?					
Response Options	**1.**	**2.**	**3.**	**4.**	**5.**
	Never face water scarcity	Less than 3 months	3-6 months	6-9 months	More than 9 months
Score					
Researchers Comments					

Section 3 - Conceptual Development, Mathematical Formulation for VR, SR, Adjusted Factor, and Convergence of the Model

Mathematical Formulation for VR

$VR_i = \sum_{j=1}^{m} w_j \times Factor_{ij}$

where $Factor_{ij}$ represents the normalised score for the *j*-th factor of the *i*-th location, defined by:

$$Factor_{ij} = \frac{MeanFactorScore_{ij}}{Highest\ Possible\ Factor\ Score_j}$$

In this formula

- VR_i is the Viability Rating for the *i*-th location, calculated before project implementation.
- w_j is the weight assigned to the *j*-th factor, denoting its importance in assessing project viability.
- $MeanFactorScore_{ij}$ is the mean score of the *j*-th factor for the *i*-th location, obtained from survey responses.
- $HighestPossibleFactorScore_j$ (*HP Score*) is the maximum score achievable for the *j*-th factor.
- m = Total number of factors evaluated in the VR calculation.

This formulation ensures that each factor is weighted according to its significance and normalised against the highest potential score to facilitate an equitable contribution to the overall viability rating. The result, *VRi*, is thus a composite index reflecting the integrated assessment of multiple sustainability dimensions for the *i*-th location.

Mathematical Formulation for SR

Upon establishing a community's VR, the SR was evaluated. The SR incorporates financial projections, with the VR serving as a modifier to adjust for other sustainability factors. The model posits that the post-construction functionality of infrastructure relies on its installation in a viable location and maintaining a positive income-to-expense ratio.

Step 1: Initial Predicted Sustainability Rating (SR) Using VR

$$SR_{Predicted,i} = VR_i \times \left(\frac{PredictedIncome_i}{PredictedExpenses_i} \times 100\right)$$

$$SR_{Predicted,i} = VR_i \times \left(\frac{PI}{PE} \times 100\right)$$

Where:

- VR_i: Viability Rating for the *i*-th location.
- PI: Predicted Income, representing the expected revenue from the water project.
- PE: Predicted Expenses, summing up the operational cost $(COST_{op})$, maintenance cost $(Cost_{ma})$ and Repair cost $(COST_r)$.
- $PI = PSPH \times PHWP$

  Where:
- $PSPH$: Predicted Sales Per Household, which is the Average Water Demand per Household $(AWDH)$ in litres, multiplied by the Estimated Amount Household are willing to Pay per litre $(EAHWP)$. $PSPH = AWDH \times EAHWP$
- $PHWP$: Predicted Household to use the Water Project, which is the Total Water Project Supply Capacity by household $(TWPSCH)$, multiplied by the Proportion of Household Willing to Pay for Water $(PHWPW)$. $PHWP = TWPSCH \times PHWPW$

  Where:
- $TWPSCH$: Total Water Project Supply Capacity by Household, which denotes the total number of households the water project can serve, which is calculated as the Volume of Water Supply Capacity per day $(VWSC)$ divided by the Average litre of water demand per household $(AWDH)$. $TWPSCH = \frac{VWSC}{AWDH}$
- For $\frac{VWSC}{AWDH}$ to be used in the formula, its value must be $\leq$ Estimated Households in the Community (EHC_i). (EHC_i) represents the total number of households estimated to reside in the ith location. Consequently, the Predicted Income (PI) is defined as follows:

$PI = PSPH \times PHWP$

Substituting appropriate variables for $PSPH$ and $PHWP$:

$PI = (AWDH \times EAHWP) \times \left(\frac{VWSC}{AWDH} \times PHWPW\right)$ given that $\frac{VWSC}{AWDH}$ or TWPSCH is $\leq EHC$.

If $\frac{VWSC}{AWDH}$ or TWPSCH is $> EHC, then\ EHC\ replaces\ \frac{VWSC}{AWDH}\ in\ the\ formula.$

Consequently, the comprehensive formula for $SR_{Predicted,i}$ can be articulated, accounting for all the defined variables:

$SR_{predicted,i} = VR_I \times \left(\frac{AWDH \times EAHWP \times \left(\frac{VWSC}{AWDH} \times PHWPW\right)}{COST_{op}+COST_{ma}+COST_r} \times 100\right)$ for $\frac{VWSC}{AWDH}\ or$ TWPSCH $\leq$ EHC or

$SR_{predicted,i} = VR_I \times \left(\frac{AWDH \times EAHWP \times (EHC \times PHWPW)}{COST_{op}+COST_{ma}+COST_r} \times 100\right)$ for $\frac{VWSC}{AWDH}$ or TWPSCH > EHC

Step 2: Actual SR Calculation and Average aSR Assessment

The Actual Sustainability Rating (aSR_i) for a project 'i' post-implementation is determined by the formula:

$aSR_i = \left(\frac{ActualIncome_{\ i}}{ActualExpenses_i} \times 100\right)$

$Average\ aSR = \frac{1}{n} \sum_{i=1}^{n} aSR_i$

Where:

- $ActualIncome_i$ is the real income generated by the project.
- $ActualExpenses_i$ is the sum of the actual costs incurred for operation, maintenance, and repair.

The aSR exclusively addresses the financial aspects critical to sustaining the water project, assuming that the project is installed in a location determined to be viable.

Iterative Optimisation: Bridging Predicted and Actual SR with Adjusted Factors and Replacing VR with Averaged SRs

Transition to Using Average aSR for Refined Prediction

In light of the significant resources required for Viability Rating (VR) assessments, the study introduces a streamlined method to predict the Sustainability Rating (SR) using the average of all SRs as a multiplier. This transition simplifies sustainability evaluations by reducing reliance on extensive initial surveys and incorporating actual project data, thereby enhancing the efficiency of our assessment framework for future endeavours.

$$\begin{Bmatrix} V\,Ri \times \left(\frac{PredictedIncome_i}{PredictedExpenses_i} \times 100\right), & for\ initial\ predictions \\ Average\ aSR \times \left(\frac{ActualIncome_{\ i}}{ActualExpenses_i} \times 100\right), & for\ refined\ predictions \end{Bmatrix}$$

Then

$SR_{Predicted,i} = Average\ aSR \times \left(\frac{PredictedIncome_i}{PredictedExpenses_i} \times 100\right)$

To validate the claim that $VR = \frac{I}{n}\sum_{i=1}^{n} SR_i$ after n projects using mathematical expression from different angels:

Direct Relationship Proof:

- Assumption: Direct influence implies $VR_i = SR_i$.
- Averaging Over n Projects:

$\overline{VR} = \frac{I}{n}\sum_{i}^{n} VR_i$

$\overline{SR} = \frac{I}{n}\sum_{i}^{n} SR_i$

- Equality:

$\overline{VR} = \overline{SR}$

The Direct Relationship Proof posits that if each project's Viability Rating (VR) directly matches its Sustainability Rating (SR), then the average VR will equal the average SR when considering multiple projects.

Linear Relationship Proof:

- General Linear Relationship:

$VR_i = a \cdot SR_i + b$

- Averaging Over n projects:

$\overline{VR} = \frac{I}{n}\sum_{i}^{n}(a \cdot SR_I + b)$

- Distribution:

$VR_i = a \cdot \overline{SR_i} + b$

- Condition for VR to Equal Average SR:

$a \cdot \overline{SR} + b = \overline{SR}$

- Solving for a and b

a = 1

b = 0

$\overline{VR} = \overline{SR}$

The Linear Relationship Proof posits that when VR is linearly related to SR, characterised by a scaling factor a and an offset b, the conditions $a = 1$ and $b = 0$ indicate a direct equivalence between VR and the average of all SRs from real-life projects. Therefore, in practice, once these conditions are validated by data from actual real-life water project, the average of SRs

can replace VR for future sustainability predictions, thus refining the model over time with real-life SRs.

Statistical Regression Proof

- Regression Model:

$VR_I = \beta_0 + \beta_1 \cdot SR_I + \epsilon_i$

- Fitting Model:

Find β_0 and β_1 that minimize $\sum {\epsilon_i}^2$

- Predicted VR:

$\widehat{VR_\iota} = \beta_0 + \beta_1 \cdot SR_I$

- Average Predicted VR:

$\overline{VR} = \frac{1}{n} \sum_i^n \widehat{VR_\iota}$

- Condition for Model Accuracy

$\beta_0 = 0$

$\beta_1 = 1$

The regression model Proof posits that when VR (*VRi*) is a linear function of SR (*SRi*), with $\beta 0$ as the intercept and $\beta 1$ as the slope, achieving $\beta 0 = 0$ and $\beta 1 = 1$ allows for direct VR prediction from average of SRs.

In all three proofs above, VR equates to the average SR when a = 1 and b = 0 across n projects. If this isn't the case, we apply an adjusted factor to align VR with actual SRs, fine-tuning the model with real-world data for future sustainability predictions. The below demonstrates how to calculate this adjustment.

Adjusted Factor when a ≠ 1 or b ≠ 0

Proof:

- Average SR:

$$\overline{SR} = \frac{1}{n} \sum_{i=1}^{n} SR_i$$

- Average VR with Original Degree of Influence given $D > 0$:

$$\overline{VR_D} = \frac{I}{n} \sum_{i=1}^{n} D \cdot SR_i$$

- Adjusted VR:

$\overline{VR} = a \cdot \overline{SR}$

- Determine Adjustment Factor a:

To align $\overline{VR}_D$ with $\overline{VR}$, we set:

$a \cdot \overline{SR} = \overline{VR}_D$

Substitute $\overline{VR}_D$:

$a = \frac{\frac{1}{n}\sum_{i=1}^{n} D \cdot SR_i}{SR}$

- Linear Relationship Through Adjustment:

Apply the adjustment factor to the original VR:

$\overline{VR} = a \cdot \overline{SR}$

This adjusted *VR* now represents the linear relationship between VR and SR.

- Conclusion: The adjustment factor *a* is the ratio of the average VR with the original degree of influence to the average SR
- Applying *a* to each *SRi* aligns the VR to the SR, establishing a linear relationship between VR and SR through the adjusted factor.

In practice, this means if the degree of influence *D* is weak, indicating that the original VR's impact on the actual SR is minimal, the VR may not correlate well with SR. In such cases, the model can be adjusted with a factor *a*, allowing for a recalibrated VR that better reflects the average SR and adapts to actual project performance data.

Adjusting Predicted SR to Align with Actual SRs – The Overall Model

- $SR_{predicted,i} = VR_i \times \left(\frac{Projected\ Income_i}{Projected\ Expenses_i} \times 100\right) \longrightarrow for\ initial\ predictions$

$SR_{predicted,i} = \overline{aSR} \times \left(\frac{Projected\ Income_i}{Projected\ Expenses_i} \times 100\right) \longrightarrow for\ refined\ prediction$

- Mean Predicted SR:

$\overline{SR}_{predicted} = \frac{1}{n}\sum_i^n SR_{predicted,i}$

- Actual SR Calculation:

$aSR_i = \left(\frac{ActualIncome_i}{ActualExpenses_i} \times 100\right)$

- Mean Actual SR:

$\overline{aSR} = \frac{1}{n}\sum_{i=1}^{n} aSR_i$

- Adjusted Factor:

$a = \frac{\overline{aSR}}{\overline{SR}_{predicted}}$

Adjusted SR:

$SR_{adjusted,i} = a \times SR_{predicted,i}$

$SR_{predicted,i} = a \times \overline{aSR} \times \left(\frac{Projected\ Income_i}{Projected\ Expenses_i} \times 100\right)$

Iterative Refinement with adjusted factor *a* (repeated application using new actual data from each iteration):

For each iteration k:

$SR^{(k+1)}_{predicted,i} = a^{(k)} \times SR^{(k)}_{predicted,i}$ (where $a^{(k)}$ is recalculated for each iteration)

This methodological adjustment aligns the model's predictions more closely with actual project outcomes. By scaling initial SR predictions using the adjustment factor derived from the ratio of average actual SR to predicted SR, we ensure that our model reflects real-world financial sustainability more accurately. This approach not only enhances the reliability of the model for future predictions but also allows the model to evolve dynamically as more project data becomes available, making it a robust tool for assessing the sustainability of water projects.

Convergence of $SR_{adjusted,i}$ to aSR_i

$\lim_{n\to large} | SR_{\text{Predicted,i}} - SR_{\text{actual,i}} | \leq \text{Acceptable Error Margin}$

This convergence criterion is a key indicator of the model's maturation. When the absolute difference between predicted and actual ratings consistently falls within an acceptable range, the model is considered sufficiently calibrated for accurate future predictions, enhancing its practicality for sustainable project planning and implementation. Convergence is anticipated after refining the model with substantial real-life project data, particularly from projects conducted in locations that utilize VR and the average of SRs.

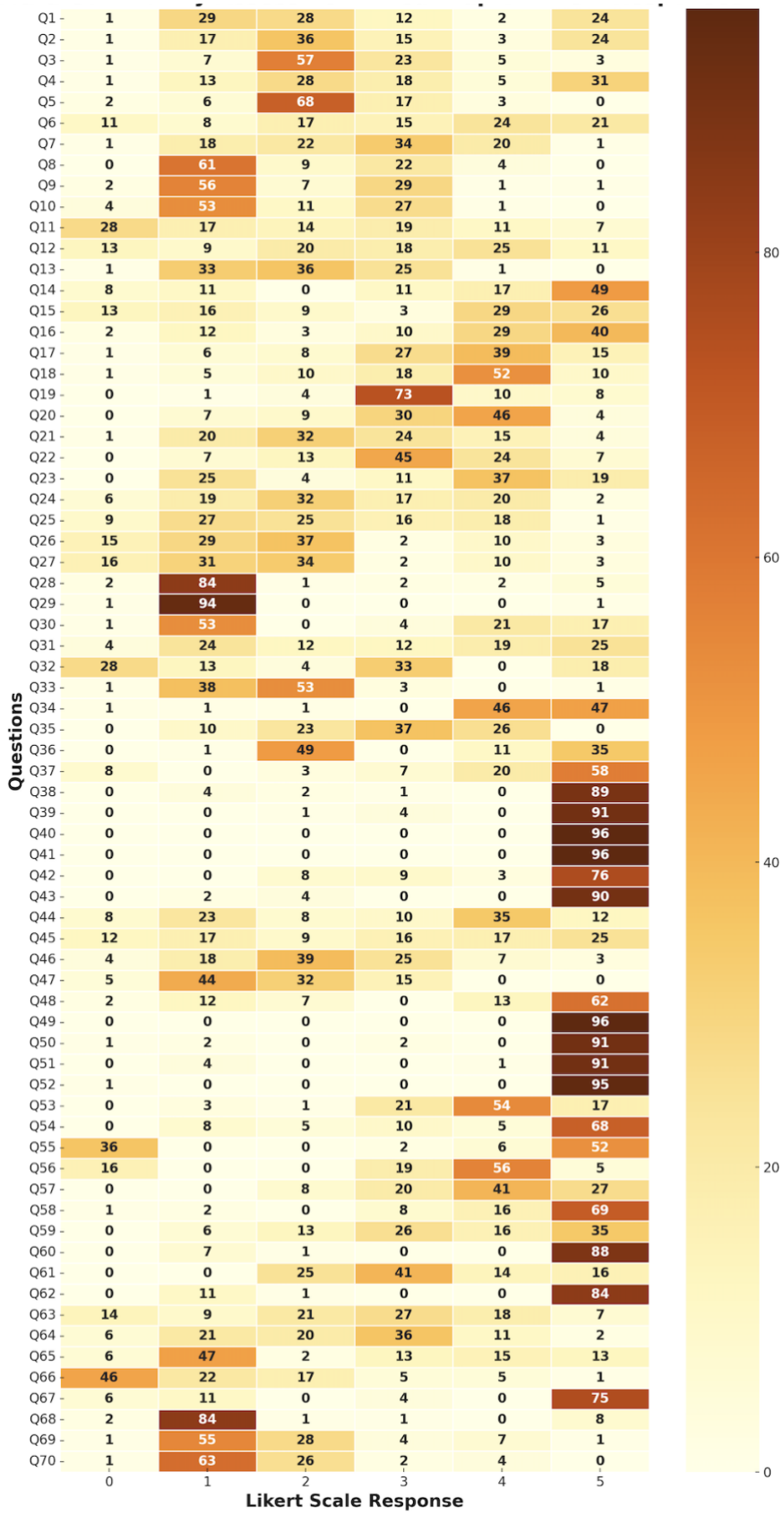


Figure A2.1: Alabata Community Assessment: Heatmap of Likert Responses

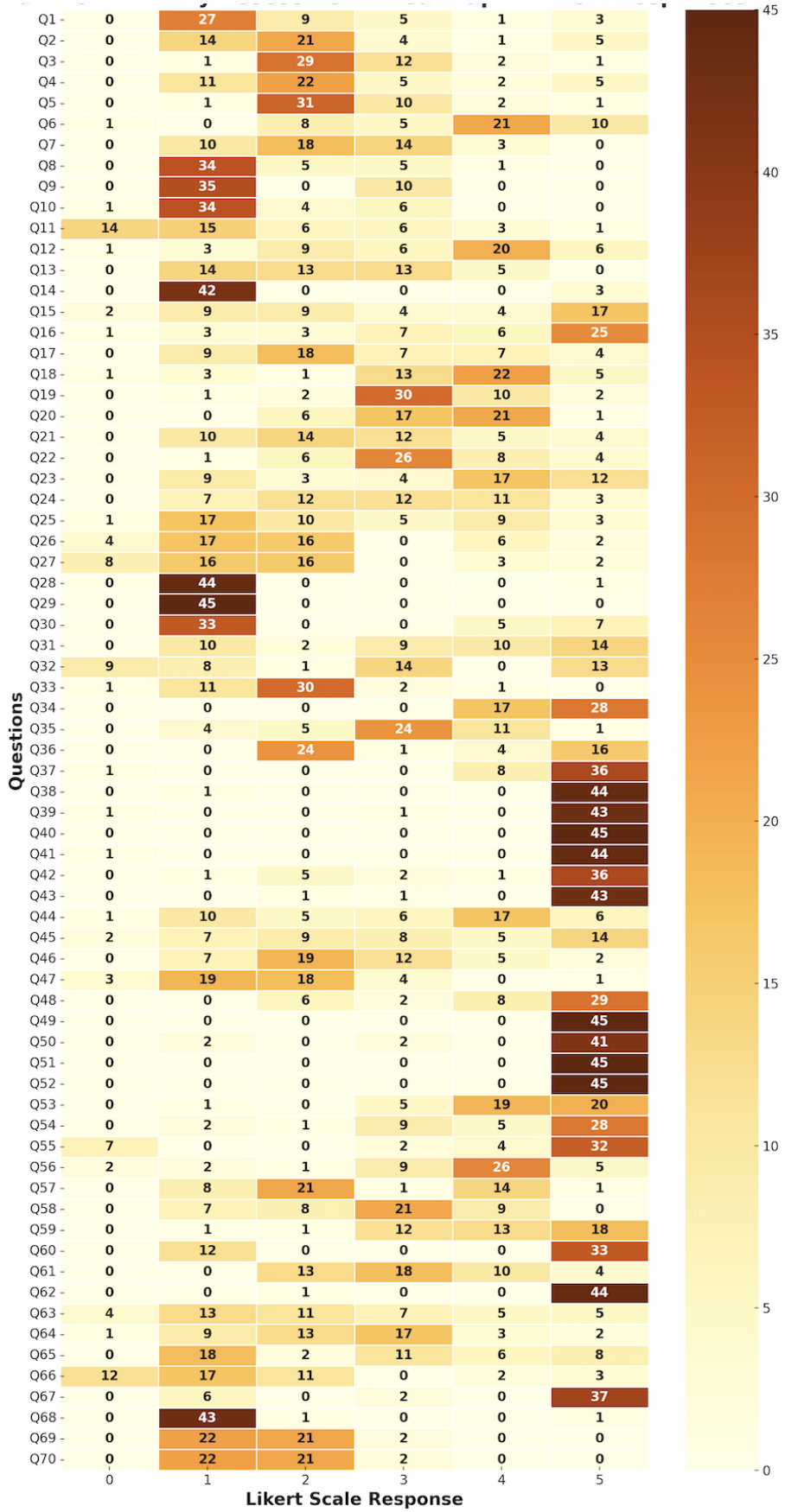


Figure A2.2: Omilabu Community Assessment: Heatmap of Likert Responses

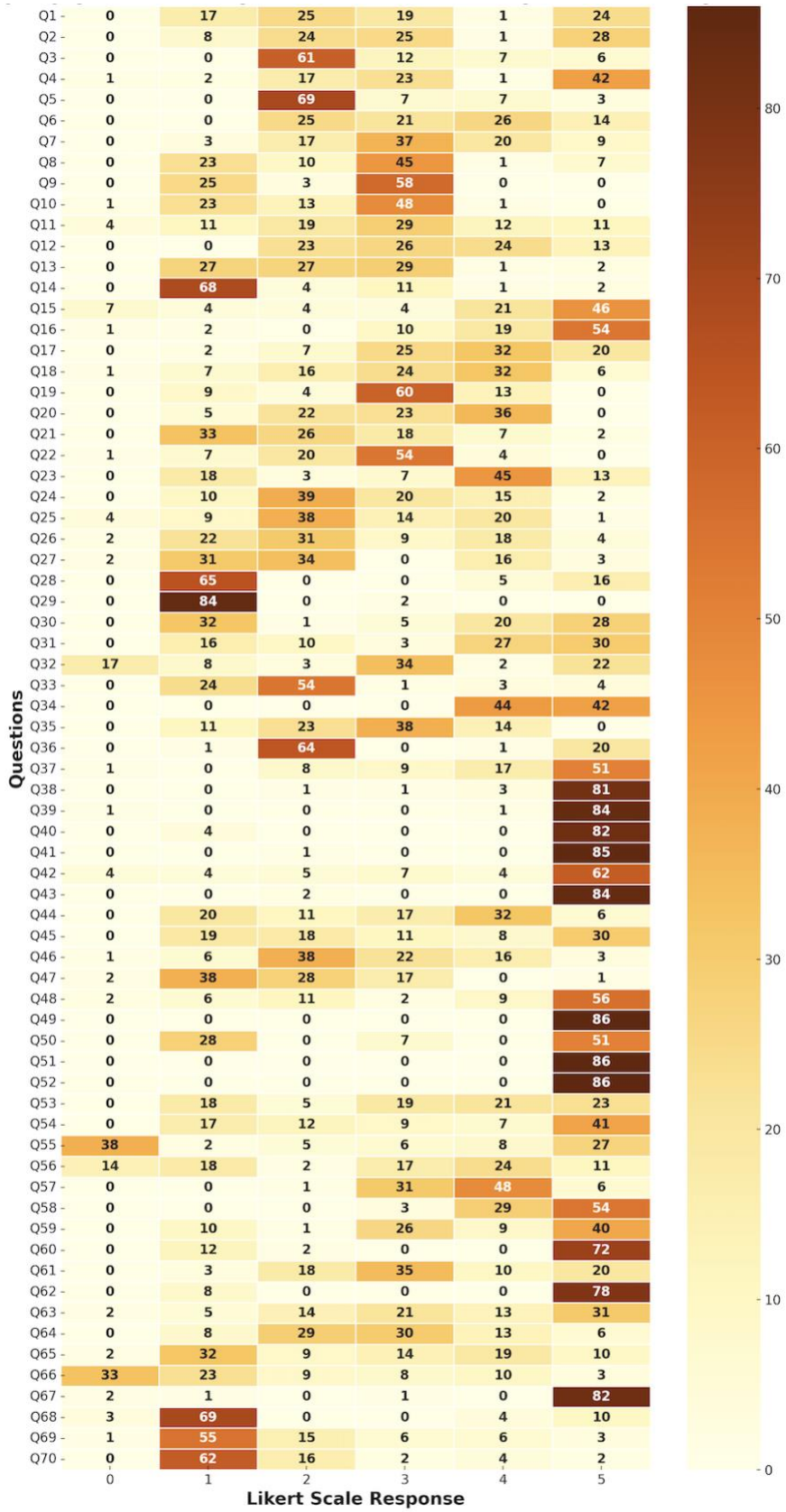


Figure A2.3: Isale-Oja Community Assessment: Heatmap of Likert Responses

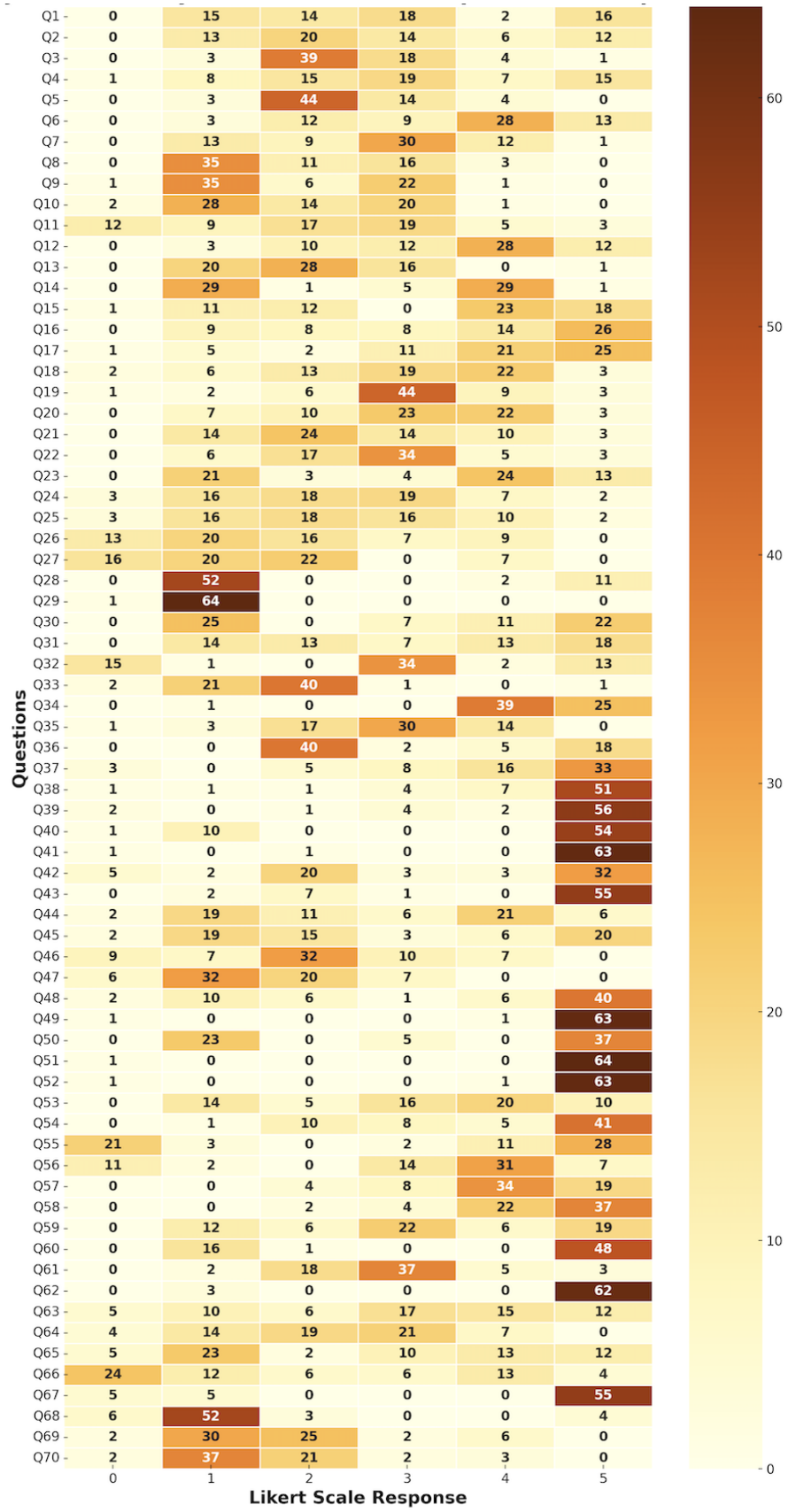


Figure A2.4: Ajila Community Assessment: Heatmap of Likert Responses

Appendix 3

Section 1

Treatment Processes, Purpose, and Design/Operating Parameters

This section provides a description of the treatment system deployed at the Isale-Oja and Alabata smart water kiosks, as illustrated in Figure 8-2 of chapter 8. The system is designed to address elevated concentrations of turbidity, iron, hardness, total dissolved solids, sulphates, and microbial contaminants identified during laboratory testing. The treatment process follows a sequential multi-barrier approach, combining chemical dosing, sedimentation, and physical filtration to produce safe water for public consumption.

1. Chlorine and Alum Dosing

- **Component**: Stainless Water Treatment Tank (with alum/chlorine feeder)
- **Purpose**: Disinfection and coagulation
- **Function**:
    - Chlorine pellets disinfect the raw water, oxidise iron from ferrous (Fe^{2+}) to ferric (Fe^{3+}) form for easier removal, and prevent microbial regrowth.
    - Alum (aluminium sulphate) facilitates coagulation of suspended solids and colloids, which aggregate into flocs that settle in the sedimentation tank.
- **Design/Operation**:
    - Chlorine and alum dosing occurs automatically as water enters the system.
    - Refilling of dosing chambers is carried out routinely by the kiosk attendant, typically once every six months depending on usage and dosage requirements.

2. Sedimentation Tank

- **Component**: Pre-filtration sedimentation chamber
- **Purpose**: Precipitation and settling of flocs
- **Function**:
    - The sedimentation tank receives chemically dosed water, where reactions between chlorine, alum, and impurities result in the formation of precipitates.

    - Flocs and heavier particles settle to the bottom, reducing the burden on the downstream filtration units.
- **Design/Operation**:
    - The tank is cleaned every six months by the kiosk team to remove settled sludge and maintain process efficiency.
    - Clarified water flows from the sedimentation tank into the filtration system.

3. Sand, Carbon, Resin, Hydrolyte, and DMI-65 Filtration

- **Component**: Two food-grade stainless steel filtration tanks
- **Purpose**: Multi-layer filtration and water softening
- **Function**:
    - Each tank contains a **fining-upward media sequence**, beginning with Grade 4 (coarse gravel), followed by Grade 3, Grade 2, and Grade 1 (fine sand), then activated carbon, cationic and anionic resins, hydrolyte, and DMI-65.
    - Activated carbon removes residual chlorine, organic matter, and odours.
    - **Cationic and anionic resins** are installed prior to the hydrolyte and serve as demineralisers to remove soluble cations and anions, thereby reducing water hardness.
    - Hydrolyte assists in stabilising pH and conditioning the water.
    - DMI-65 acts as a catalytic medium for iron removal.
- **Backwashing**:
    - Backwashing is conducted **once a week, every Wednesday**, by the trained kiosk attendant.
    - The process involves reversing water flow from bottom to top to dislodge and flush accumulated particulates from the media layers.
    - No chemical regeneration is required. Plain water is used for backwashing.
- **Media Maintenance**:
    - The resin media are non-clinker forming and retain catalytic activity over extended use.
    - Media replacement is typically required every 6 months, depending on contaminant load and treated volume.

4. Micron Filtration (Final Polishing)

- **Component**: Two 10” stainless steel microfilters
- **Purpose**: Removal of fine particulates and pathogens
- **Function**:
    - Provides final filtration, capturing particles as small as 1 to 5 microns prior to storage.
    - Ensures the treated water meets quality and safety standards.
- **Design/Operation**:
    - Filters are replaced approximately every three months, depending on water quality and usage volume. In practice, they are inspected regularly and replaced earlier if pressure build-up or reduced flow indicates clogging.

5. Treated Water Storage and Metering

- **Components**:
    - Treated water storage tank
    - Feed pump and gate valves
    - Water meter
- **Purpose**: Storage and monitoring of treated water
- **Function**:
    - The solar-powered feed pump regulates water flow into the filtration system.
    - Gate valves are used to manage flow direction and support maintenance activities.
    - The water meter monitors the volume of treated water dispensed and supports operational record-keeping

Section 2

Sampling Conditions, Source Infrastructure, and Inclusion Criteria

This section provides detailed contextual information for all 17 borehole water samples analysed in Chapter 8, including the nature of their construction, intended use, and the criteria guiding their inclusion. The objective is to ensure that the dataset reflects representative groundwater conditions from infrastructure designed to deliver safe drinking water to the public.

Primary Samples (n = 5)

Five water samples were directly collected by the research team from protected public-use boreholes located in Oyo State. All five boreholes were constructed as drilled and cased infrastructure intended to supply safe water to surrounding communities. The samples were obtained from smart kiosk installations and other secure public sources that are routinely accessed by residents. These samples were collected under direct field oversight, allowing for consistent sampling procedures and validation of infrastructure conditions.

Secondary Samples (n = 12)

Twelve additional samples were incorporated based on certified laboratory test results from boreholes located in Lagos, Ogun, Oyo, and Delta states. These boreholes serve public institutions such as schools, hotels, health centres, and commercial facilities. All were constructed as drilled boreholes with protective casings and surface-level access infrastructure, designed to supply safe water for drinking or domestic use. No sample was included from informal, unprotected, or temporary sources such as hand-dug wells.

The inclusion criteria ensured that only water sources intended to deliver safe drinking water to the public were analysed. This approach minimises confounding effects from poor infrastructure design or lack of protective features, allowing the findings to reflect actual groundwater quality rather than artefacts of inadequate system construction.

Coverage and Representativeness

The final dataset comprises 17 borehole samples drawn from four states—Oyo, Lagos, Ogun, and Delta. While the number of samples per state varies, the inclusion of multiple locations across southern Nigeria allows for a preliminary characterisation of borehole water quality in distinct geographic and institutional contexts. The dataset supports indicative analysis of contamination patterns and treatment considerations relevant to public-use boreholes across varied settings.

Table A3.1. Physical and Chemical Water Quality Parameters

Physical and chemical parameters for 17 borehole samples across Lagos, Oyo, Ogun, and Delta States. Parameters include pH, turbidity, TDS, conductivity, hardness, iron, sulphate, magnesium, and other included parameters, tested against NIS 554:2015.

Sample ID	Appearance (Clear)	Odour (Unobj.)	pH (6.5–8.5)	Conductivity (≤1000 µS/cm)	Turbidity (≤5 NTU)	TDS (≤500 mg/L)	Hardness (≤150 mg/L)	Alkalinity (≤200 mg/L)	Total Solids (mg/L)
Sample 001	Brownish and turbid	Unobjectionable	6.7	806	28.5	403.5	292.3	229.3	423.1
Sample 002	Slight brown	Unobjectionable	7.3	718	0	359.5	345.1	212.4	377.4
Sample 003	Slight yellow	Unobjectionable	7.6	1053.5	0	527	303	423.5	540.9
Sample 004	Slightly brown	Unobjectionable	5.4	57.2	0	29.1	10.2	10.8	41.2
Sample 005	Clear	Unobjectionable	5.7	66.7	0	33.4	8.1	12.4	48.1
Sample 006	Clear	Unobjectionable	5.4	77.7	0	38.9	7.9	20.6	49
Sample 007	Colourless	Unobjectionable	7.6	243.5	0	121.5	48	66.5	143.8
Sample 008	Colourless	Unobjectionable	7.1	341.5	0	171	79.6	134	183.3
Sample 009	Clear	Unobjectionable	5.9	54.6	0	27.3	9.9	12.1	51.8
Sample 010	Clear	Unobjectionable	7	67.5	0	33.6	24.2	25.1	51.4
Sample 011	Brownish & very turbid with tiny particles	Unobjectionable	5.9	1736	525	868	209.9	145.3	893
Sample 012	Brownish & turbid	Unobjectionable	6.24	90.5	94.4	45.2	27.4	37.6	80.3
Sample 013	Clear	Unobjectionable	6.8	470	5	258.5	134	143.1	283.5
Sample 014	Clear	Unobjectionable	5.6	160	0	28.5	18.2	13.9	103
Sample 015	Brownish & very turbid with tiny particles	Unobjectionable	5.9	1736	525	868	209.9	145.3	893

Sample 016	Colorless with particles	Unobjectionable	7.2	683	0	342	200	199.8	382
Sample 017	Colorless	Unobjectionable	6.8	270	3.8	135.5	75.5	73	147.8

Sample ID	Free Cl (≤0.25 mg/L)	CO_2 (≤50 mg/L)	Ammonia (≤0.05 mg/L)	Chloride (≤250 mg/L)	Nitrite (NO2)(≤0.2 mg/L)	Nitrate (NO3)(≤50 mg/L)	Silica (≤40 mg/L)	Arsenic (≤0.01 mg/L)	Calcium (≤75 mg/L)
Sample 001	0	20.6	0	57.2	0.06	2.1	16.5	0.001	117.2
Sample 002	0	15.4	0	70.6	0.17	0.33	26.8	0.001	138.3
Sample 003	0	19.5	18.9	61.6	0.01	0.28	23.8	0.001	121.5
Sample 004	0	61.4	0	14.4	0.02	0.17	6	0.001	4.1
Sample 005	0	21.8	0	7.1	0.01	1.2	9.6	0.001	9.7
Sample 006	0	19.2	0	21.5	0	1.2	15.1	0.001	3.2
Sample 007	0	3.6	0	17.1	0.02	0.11	32.3	0.001	19.2
Sample 008	0	19.5	0	35	0.06	2.8	15.9	0.001	31.9
Sample 009	0	26	0	7	0.01	3.5	5.7	0.0001	3.96
Sample 010	0	45	0	7	0.01	4.2	5.8	0.0001	9.7
Sample 011	0	81	5.9	488.9	0.05	1.4	9.5	ND	84.1
Sample 012	ND	28	ND	6.9	0.02	0.76	6.4	ND	11
Sample 013	ND	26	2.8	58.8	0.01	0.62	9.3	ND	53.7
Sample 014	ND	78	1.2	21.5	0.1	1.2	9.4	ND	7.3
Sample 015	0	81	5.9	488.9	0.05	1.4	9.5	ND	84.1
Sample 016	0	28	0	87.6	0.01	0.72	11	<0.001	80.2
Sample 017	0	25.8	0	28.9	0.1	15.8	31.3	0.001	30.3

Sample ID	Iron (≤0.3 mg/L)	Lead (≤0.01 mg/L)	Sulphate (≤100 mg/L)	Magnesium (≤20 mg/L)	Salinity (≤480 mg/L)	Sodium (≤200 mg/L)	H_2S (≤0.05 mg/L)	Detergents (≤0.01 mg/L)	Phosphate (mg/L)	TSS (mg/L)
Sample 001	3.7	0.001	123.4	42.6	133.2	37.1	0.001	0.001	0.43	19.6
Sample 002	1.4	0.001	177	50.3	157.5	45.8	0.001	0.001	2.1	17.9
Sample 003	0.1	0.001	86.9	44.1	141.2	32.4	0.001	0.001	4.3	13.9
Sample 004	0.37	0.001	0.46	1.5	55.9	9.3	0.001	0.001	0	12.1
Sample 005	0.05	0.001	3.7	3.5	106.8	27.6	0.001	0.001	0.43	23.5
Sample 006	0	0.001	0	1.2	68.9	14	0.001	0.001	0.87	10.1
Sample 007	0.01	0.001	7.7	7	60.8	11.1	0.001	0.001	0.87	Not Stated
Sample 008	0.1	0.001	0	11.6	93.2	22.7	0.001	0.001	4.8	12.3
Sample 009	0	0.001	0	1.4	42.5	4.5	0.0001	0.0001	0.43	Not Stated
Sample 010	0.1	0.001	0	3.5	42.5	4.5	0.0001	0.0001	0.43	Not Stated
Sample 011	92	ND	11.7	30.6	912.5	316.8	ND	ND	0.43	Not Stated
Sample 012	5.2	ND	6.2	4	42.4	4.4	ND	ND	0.43	Not Stated
Sample 013	0.37	0.03	17	19.5	136.3	38.1	ND	ND	1.7	Not Stated
Sample 014	0.7	ND	0.7	0.8	42.4	4.4	ND	ND	1.3	Not Stated
Sample 015	92	ND	117	30.6	912.5	316.8	ND	ND	0.43	Not Stated
Sample 016	0.18	<0.001	168.6	29.1	188.1	56.7	<0.001	<0.001	1.3	Not Stated
Sample 017	0.17	0.001	2.4	10.9	82.3	18.8	0.001	0.001	1.3	12.3

Table A3.2. Microbiological Water Quality Parameters

Microbiological parameters for 17 borehole samples across Lagos, Oyo, Ogun, and Delta States. Parameters include E. coli, Total Coliforms, Faecal Streptococci, Salmonella, Vibrio, Total Plate Count, and other included parameters, tested against NIS 554:2015.

Sample ID	E.Coli (0 CFU/ml)	Total Coliform (0 CFU/ml)	Faecal Streptococci (0 CFU/ml)	Staph. aureus (0 CFU/ml)	Salmonella (Absent/25ml)	Shigella (Absent/25ml)	Vibrio (0 CFU/ml)	Clostridium perf. (0 CFU/ml)	Klebsiella (0 CFU/ml)	Pseudomonas (0 CFU/ml)	Yeast/mould (0 CFU/ml)	Total Plate Count (≤100 CFU/ml)
Sample 001	0	19	0	0	Absent	Absent	0	0	0	0	31	198
Sample 002	0	0	0	0	Absent	Absent	0	0	0	0	0	211
Sample 003	3	38	0	0	Absent	Absent	11	0	0	0	0	119
Sample 004	0	0	0	0	Absent	Absent	0	0	0	0	0	10
Sample 005	0	0	0	0	Absent	Absent	0	0	0	0	0	105
Sample 006	0	0	0	0	Absent	Absent	0	0	0	0	0	73
Sample 007	0	0	0	0	Absent	Absent	0	0	0	0	0	94
Sample 008	0	0	0	0	Absent	Absent	0	0	0	0	7	317
Sample 009	3	7	0	0	Absent	Absent	0	0	0	0	0	49
Sample 010	0	0	0	0	Absent	Absent	0	0	0	0	0	17
Sample 011	0	86	0	0	Absent	Absent	0	0	0	0	0	418
Sample 012	0	1	0	0	Absent	Absent	0	0	0	0	0	325

Sample 013	0	0	0	0	Absent	Absent	0	0	0	0	0	158
Sample 014	0	0	0	0	Absent	Absent	0	0	0	0	0	23
Sample 015	0	86	0	0	Absent	Absent	0	0	0	0	0	418
Sample 016	0	0	0	0	Absent	Absent	0	0	0	0	0	11
Sample 017	0	23	0	0	Absent	Absent	0	0	0	0	0	114

Table A3.3 provides frequency of exceedance for each of the 35 water quality parameters with defined thresholds under NIS 554:2015, based on analysis of 17 borehole samples. The table presents the number and percentage of samples that failed each parameter,

Table A3.3: Parameter Failure Frequency

Failure Frequency	
Parameter	Number of Failures
Total Plate Count (≤100 CFU/ml)	10
pH (6.5–8.5)	8
Iron (≤0.3 mg/L)	8
Total Coliform (0 CFU/ml)	7
Hardness (≤150 mg/L)	6
Magnesium (≤20 mg/L)	6
Calcium (≤75 mg/L)	6
Ammonia (≤0.05 mg/L)	5
Sulphate (≤100 mg/L)	4
Turbidity (≤5 NTU)	4
CO_2 (≤50 mg/L)	4
Alkalinity (≤200 mg/L)	3
TDS (≤500 mg/L)	3
Conductivity (≤1000 µS/cm)	3
Chloride (≤250 mg/L)	2
E.Coli (0 CFU/ml)	2
Sodium (≤200 mg/L)	2
Salinity (≤480 mg/L)	2
Yeast/mould (0 CFU/ml)	2
Lead (≤0.01 mg/L)	1
Vibrio (0 CFU/ml)	1
Free Cl (≤0.25 mg/L)	0

H_2S (≤0.05 mg/L)	0
Nitrite (NO2)(≤0.2 mg/L)	0
Arsenic (≤0.01 mg/L)	0
Silica (≤40 mg/L)	0
Nitrate (NO3)(≤50 mg/L)	0
Faecal Streptococci (0 CFU/ml)	0
Staph. aureus (0 CFU/ml)	0
Salmonella (Absent/25ml)	0
Shigella (Absent/25ml)	0
Clostridium perf. (0 CFU/ml)	0
Klebsiella (0 CFU/ml)	0
Pseudomonas (0 CFU/ml)	0
Detergents (≤0.01 mg/L)	0

Table A3.4 provides Comparison of pre-treatment and post-treatment water quality results for the Alabata borehole site across 40 physicochemical and microbial parameters. Each parameter is evaluated against NIS 554:2015 compliance thresholds. The table illustrates substantial reductions in key contaminants—most notably total hardness, iron, sulphate, and microbial indicators—following treatment. All post-treatment values fall within regulatory limits, demonstrating the effectiveness of the applied multi-stage system in achieving both health-based and aesthetic water quality standards.

Table A3.4*:* Alabata Water Quality Comparison: Pre-Treatment vs Post-treatment

Parameter	**Pre-Treatment (Raw)**	**Post-Treatment (Treated)**	**Standard Limit**
Appearance	Slight brown	Clear	Clear (Visual)
Odour	Unobjectionable	Unobjectionable	Unobjectionable
Colour (TCU)	0	0	15 max
pH	7.3	7.2	6.5 – 8.5

Conductivity (µS/cm)	718	308.5	1000 max
Turbidity (NTU)	0	0	5 max
Total Hardness (mg/L)	345.1	130.8	150 max
Taste	Objectionable	Unobjectionable	Unobjectionable
Temperature (°C)	25.6	25.7	Ambient
Total Alkalinity (mg/L)	212.4	87.3	200 max
TDS (mg/L)	359.5	154.5	500 max
Total Solids (TS) (mg/L)	377.4	165.9	Not stated
Free Residual Chlorine (mg/L)	0	0	0.25 max
Free CO_2 (mg/L)	15.4	5.1	50 max
Ammonia (mg/L)	0	0	0.05 max
Chloride (mg/L)	70.6	28	250 max
Nitrite (mg/L)	0.17	0.01	0.2 max
Nitrate (mg/L)	0.33	0.47	50 max
Silica (mg/L)	26.8	11.2	40 max
Arsenic (mg/L)	0.001	0.001	0.01 max
Calcium (mg/L)	138.3	52.4	75 max
Iron (mg/L)	1.4	0	0.3 max
Lead (mg/L)	0.001	0.001	0.01 max
Sulphate (mg/L)	177	79.7	100 max
Magnesium (mg/L)	50.3	19.1	20 max
Salinity (mg/L)	157.5	80.6	480 max
Sodium (mg/L)	45.8	18.2	200 max
H_2S (mg/L)	0.001	0.001	0.05 max
Detergents (mg/L)	0.001	0.001	0.01 max
Phosphate (mg/L)	2.1	0.43	Not stated
TSS (mg/L)	17.9	11.4	Not stated
Microbial Parameter	**Pre-Treatment**	**Post-Treatment**	**Limit**
E. coli (CFU/ml)	0	0	0

Total Coliform (CFU/ml)	0	0	0
Faecal Streptococci (CFU/ml)	0	0	0
Staph. aureus (CFU/ml)	0	0	0
Salmonella (in 25ml)	Absent	Absent	Absent
Shigella (in 25ml)	Absent	Absent	Absent
Vibrio (CFU/ml)	0	0	0
Clostridium perf. (CFU/ml)	0	0	0
Klebsiella (CFU/ml)	0	0	0
Pseudomonas (CFU/ml)	0	0	0
Yeast/Mould (CFU/ml)	0	0	0
Total Plate Count (CFU/ml)	211	97	100 max

Table A3.5. Pre-treatment and post-treatment comparison of 40 physicochemical and microbial water quality parameters for the Isale-Oja (Ijaiye) borehole site. Parameters are benchmarked against NIS 554:2015 standards, with non-compliant values after treatment flagged. While treatment significantly improved overall water quality—eliminating all microbial contaminants and reducing several chemical parameters—post-treatment values for total hardness, alkalinity, calcium, sulphate, and magnesium exceeded permissible limits.

Table A3.5: Isale-Oja Water Quality Comparison: Pre-Treatment vs Post-Treatment

Parameter	**Pre-Treatment**	**Post-Treatment**	**Standard Limit**	**Failed Post-Treatment?**
Appearance	Brownish and turbid	Clear	Clear	
Odour	Unobjectionable	Unobjectionable	Unobjectionable	
pH	6.7	7.3	6.5 - 8.5	

Conductivity (µS/cm)	806	768	≤1000	
Turbidity (NTU)	28.5	0	≤5	
Total Hardness (mg/L)	292.3	349.5	≤150	**Fail**
Temperature (°C)	25.6	25	Ambient	
Total Alkalinity (mg/L)	229.3	273.7	≤200	**Fail**
TDS (mg/L)	403.5	384	≤500	
Total Solids (mg/L)	423.1	398.3	Not Stated	
Free Residual Chlorine	0	0	≤0.25	
Free CO_2 (mg/L)	20.6	6.7	≤50	
Ammonia (mg/L)	0	0	≤0.05	
Chloride (mg/L)	57.2	63.6	≤250	
Nitrite (mg/L)	0.06	0.01	≤0.2	
Nitrate (mg/L)	2.1	27.8	≤50	
Silica (mg/L)	16.5	17	≤40	
Arsenic (mg/L)	0.001	0.001	≤0.01	
Calcium (mg/L)	117.2	140.1	≤75	**Fail**
Iron (mg/L)	3.7	0	≤0.3	
Lead (mg/L)	0.001	0.001	≤0.01	
Sulphate (mg/L)	123.4	206.7	≤100	**Fail**
Magnesium (mg/L)	42.6	50.9	≤20	**Fail**
Salinity (mg/L)	133.2	144.8	≤480	
Sodium (mg/L)	37.1	41.2	≤200	
H_2S (mg/L)	0.001	0.001	≤0.05	
Detergents (mg/L)	0.001	0.001	≤0.01	
Phosphate (mg/L)	0.43	0.87	Not Stated	
TSS (mg/L)	19.6	14.3	Not Stated	
Microbial Parameter	**Pre-Treatment**	**Post-Treatment**	**Limit**	

E. coli (CFU/ml)	0	0	0	
Total Coliform (CFU/ml)	19	0	0	
Faecal Streptococci (CFU/ml)	0	0	0	
Staphylococcus aureus	0	0	0	
Salmonella (in 25ml)	Absent	Absent	Absent	
Shigella (in 25ml)	Absent	Absent	Absent	
Vibrio (CFU/ml)	0	0	0	
Clostridium perfringens	0	0	0	
Klebsiella aerogenes	0	0	0	
Pseudomonas aeruginosa	1	0	0	
Yeast/mould (CFU/ml)	31	0	0	
Total Plate Count (CFU/ml)	198	62	≤100	

Section 3

Infrastructure and Treatment Cost Breakdown

The water infrastructure deployed in this study follows a sustainability-oriented model developed through an iterative research and design process (Adeoti & Vigneswaran, 2024). Unlike conventional borehole projects in Nigeria, which are typically limited to water extraction and do not include treatment, monitoring, or staffing provisions, this infrastructure was designed to support long-term reliability. It incorporates multi-barrier treatment, real-time monitoring, and a fully employed kiosk attendant responsible for daily operations and maintenance at the infrastructure site.

Although the total infrastructure cost was higher than that of a typical borehole project, the treatment component alone accounted for 17.2% of the total project expenditure. This proportion reflects the investment required to integrate treatment into a system built for sustainability. In smaller or lower-budget implementations, the treatment cost proportion could be substantially higher, depending on the raw water quality and treatment requirements.

Table A3.6 presents the full cost breakdown for the smart water kiosk piloted in this study, with treatment-related costs highlighted in yellow. This breakdown distinguishes between treatment and non-treatment components, providing a clear view of the financial requirements associated with integrating water treatment into public water infrastructure.

Table A3.6. Cost Breakdown of Smart Water Kiosk Infrastructure and Treatment Components

Category	**Actual Cost in Naira (₦)**
Land Lease and Legal	**650,000**
Fabrication	
Water Tank Scaffold	1,525,000
Extra Solar Stand	210,000
10 FT Container	900,000
Structural Brace H-beam	186,000
Iron Plate	25,000
Tap Stand	170,000
Roofing Sheets	64,000
Square Pipe	75,000
Transportation	70,000
Generator and Fuel	43,000
Workmanship	280,000
Total Fabrication	**3,548,000**

Mason Works	
Interlocks	815,000
Stone Dust (10 tons)	135,000
Sharp Sand (10 tons)	75,000
Plaster Sand (10 tons)	40,000
Vinyl Floor	260,000
Granite (10 tons)	155,000
Concrete Block (400)	320,000
Cement (34)	357,000
Pigment & DPM	50,000
Extra Solar Stand Concrete	27,000
Mesh Wire	45,000
Coping & Casting	74,000
Tap Island Concrete	120,000
Workmanship	230,000
Total Mason Works	**2,703,000**

Plumbing	
Borehole Drilling & Fitting	2,230,000
Supply/Installation of Sub. Pump	375,000
3000L Water Tank	308,000
Plumbing Details	190,000
Workmanship	80,000
Total Plumbing	**3,183,000**

Cladding	
Alucobond	1,040,000
Fiber Cement Board (22)	395,000
Wall Profile	52,500
Corner Beat	16,800
Wall Angle (4)	4,400
Screws	6,000
Transportation From Lagos	190,000

Accessories For Fiber Boards	370,000
Workmanship	205,000
Total Cladding	**2,279,700**

Energy Installation	
Solar Power System	4,580,000
Electrical Fittings & Wires	62,000
Security Lights and Installation	69,500
Electrician (Workmanship)	55,000
Total Energy Installation	**4,766,500**

Carpentry	
Roofing Sheets	60,000
Water Tank Base Wood	39,000
Marine Board	75,000
Wood	65,000
Nail	10,000
Flash Band (Roof)	5,000
Workmanship	70,000
Total Carpentry	**324,000**

Perimeter Fencing	
Finger Free Mesh	992,000
Additional Pole	162,000
Entrance Gate (Mesh)	70,000
Workmanship	60,000
Total Perimeter Fencing	**1,284,000**

Miscellaneous	
Aluminum Windows (2)	178,000
Security Door	110,000
Screeding & Painting	260,000
Graphic Design & Print	250,000

Videographer & Photographer	300,000
Transportation Of Materials	390,000
Additional Welding Works	25,000
Mesh Roll (Tap Base)	15,000
IoT Installation	15,000
Fuel	15,000
Nail	5,800
Cleaning and other Expenses	34,000
Offloading of Interlocks	6,500
Sawmill Charge	5,000
Water and Drum	6,500
Borehole Flushing	155,000
Water Test (Microbial Examination)	150,000
Total Miscellaneous	**1,920,800**

Water Treatment Plant	
Food Grade Cylinders (2)	2,500,000
Activated Carbon (4)	40,000
Hydrolyte (2)	20,000
Filtration Media - Grade 4 (8)	8,000
Filtration Media - Grade 3 (8)	8,000
Filtration Media - Grade 2 (8)	8,000
Filtration Media - Grade 1 (8)	8,000
25Kg of Chlorine Pellets	85,000
Chlorine/Alum Manual Dispenser	78,000
Bag of Anionic Resin	35,000
Bag of Cationic Resin	35,000
Bag of Iron Removal Resin	42,000
50 Kg of Alum (Turkey)	195,000
Solar Surface Pump 1.5hp	500,000
Solar Panel 550 Watt (4)	840,000
DC Cable (12 meters)	81,600
Installation Rack 5mm Angle (8)	144,000

Transportation from Lagos	185,000
Plumbing Fittings and Workmanship	150,000
Treatment Plant Installation	650,000
Solar Installation	50,000
Welder Workmanship	30,000
Total Water Treatment Plant	**5,692,600**

Architect Inspection to Align Project with Architectural Design	**1,500,000**
Implementation Professional Fees (skills, time and effort) by YSG	**5,227,660**

Total Expenditure	**33,079,260**

% of Water Treatment in Overall Project Cost	**17.2%**