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Evaluating the effectiveness of smart water management systems in enhancing the resilience and sustainability of water infrastructure in Nigeria

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ABSTRACT

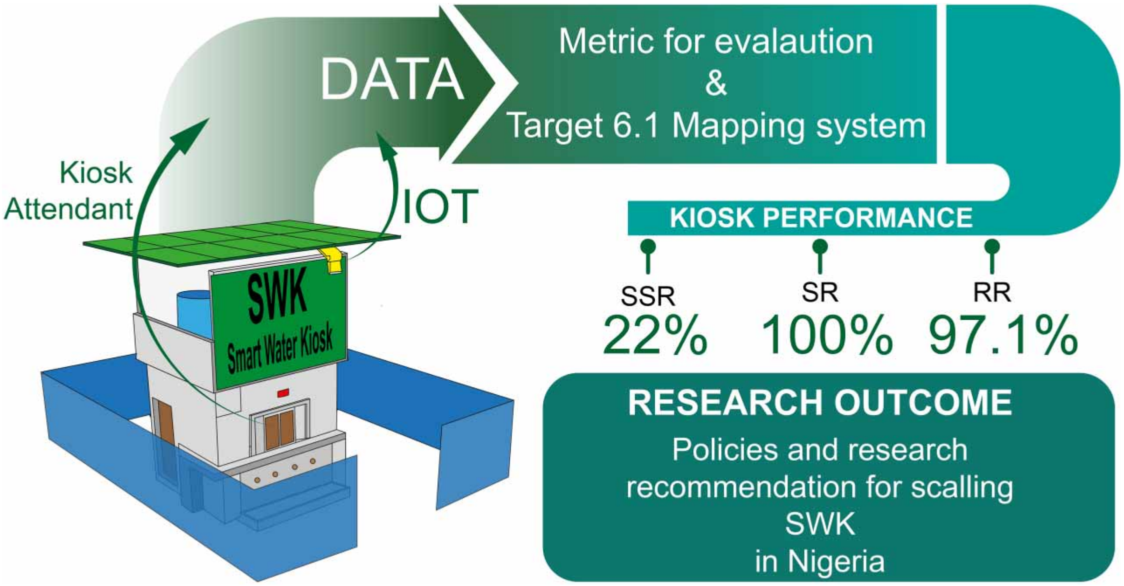
This study rigorously evaluates the effectiveness of smart water management systems in addressing prevalent water infrastructure failures, resilience, and sustainability challenges in Nigeria. Employing a transdisciplinary approach that integrates technological, social, and economic disciplines, along with industry and community insights, it analyses 1,095 days of operational data from a smart water kiosk. The data were processed employing Target 6.1 software for comprehensive comparative analysis, trend analysis, predictive modeling, and impact assessment. Initially, the kiosk achieved a 22% self-sustainability rating (SSR), which dropped to zero due to aid overlap – a novel challenge documented for the first time in the literature as a significant challenge to infrastructure sustainability. Additionally, the research highlighted infrastructure underutilization as a critical yet under-explored issue. Despite these challenges, the kiosk ultimately achieved a 100% sustainability rating (SR) with external support and maintained a high reliability rating of 97.1%. The findings of this study guide strategic research and policy recommendations, aiming to optimize the deployment of smart water management systems in Nigeria and other regions with similar socio-economic settings, thereby enriching the global discourse on sustainable water infrastructure.

Key words: infrastructure sustainability, IoT monitoring, Nigeria water infrastructure, smart water management, water kiosk

HIGHLIGHTS

- Assessed smart water management systems over three years, revealing key factors affecting infrastructure sustainability and resilience.
- Aid overlap on water infrastructure reduced sustainability ratings to 0%.
- Water pricing strategies do not significantly reduce non-revenue water.
- 97.1% reliability rating by effective maintenance and IoT-based real-time monitoring.
- Recommendations to enhance the deployment of smart water management systems.

GRAPHICAL ABSTRACT



INTRODUCTION

Ensuring access to safe and affordable drinking water is fundamental for sustaining life and supporting the global development framework (Bain *et al.* 2014). 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 (UN-Water 2016; Satterthwaite *et al.* 2020; Aly *et al.* 2022). However, escalating challenges from climate-induced droughts, floods, pollution, alongside rapid population growth and urbanization, intensify pressures on water infrastructure assets (Misra 2014; Sachidananda *et al.* 2016; Gupta *et al.* 2020). 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 revolutionize water management and distribution (Ramos *et al.* 2019; Singh & Ahmed 2021). Recent studies, including those by Fatehi-Nobarian *et al.* (2023), and Fatehi-Nobarian & Fard Moradinia (2024), highlight the effectiveness of advanced modeling techniques, such as wavelet–artificial neural network (ANN) hybrid models and harmony search algorithms. These models optimize 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 (Ramos *et al.* 2019; Adeoti *et al.* 2024a; Olatunde *et al.* 2024). 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, 2023, 2024a; 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 severely impacted by water management issues, serves as a pivotal case study. This context positions Nigeria as an ideal location to assess the efficacy of smart water management systems and gain insights into overcoming sustainability challenges in developing regions, underscoring the significance of our study.

Recognizing the multifaceted challenges to infrastructure sustainability, we adopted a transdisciplinary approach that integrates technical, environmental, social, and economic perspectives (Lawrence & Després 2004; Brandt *et al.* 2013). Utilizing ecological systems theory for nuanced community selection and Complex Adaptive Systems (CAS) theory for dynamic infrastructure design, our methodology facilitated a comprehensive framework that addresses socio-ecological interactions. Engagement with local experts ensured that our solutions were both innovative and culturally appropriate. This integrative approach resulted in the development of 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 (Andres *et al.* 2018; Adeniran *et al.* 2021; Adeoti *et al.* 2024a). 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 of this study were analyzed to achieve our research objectives. Utilizing 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 into addressing infrastructure deficits and failures in Nigeria and similar socio-economic regions.

The findings from our study are poised to significantly advance access to safe and affordable drinking water in Nigeria and have implications for similar global regions, 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.

METHODOLOGY

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

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.

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.* 2024b).

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 (NRW), water credit,

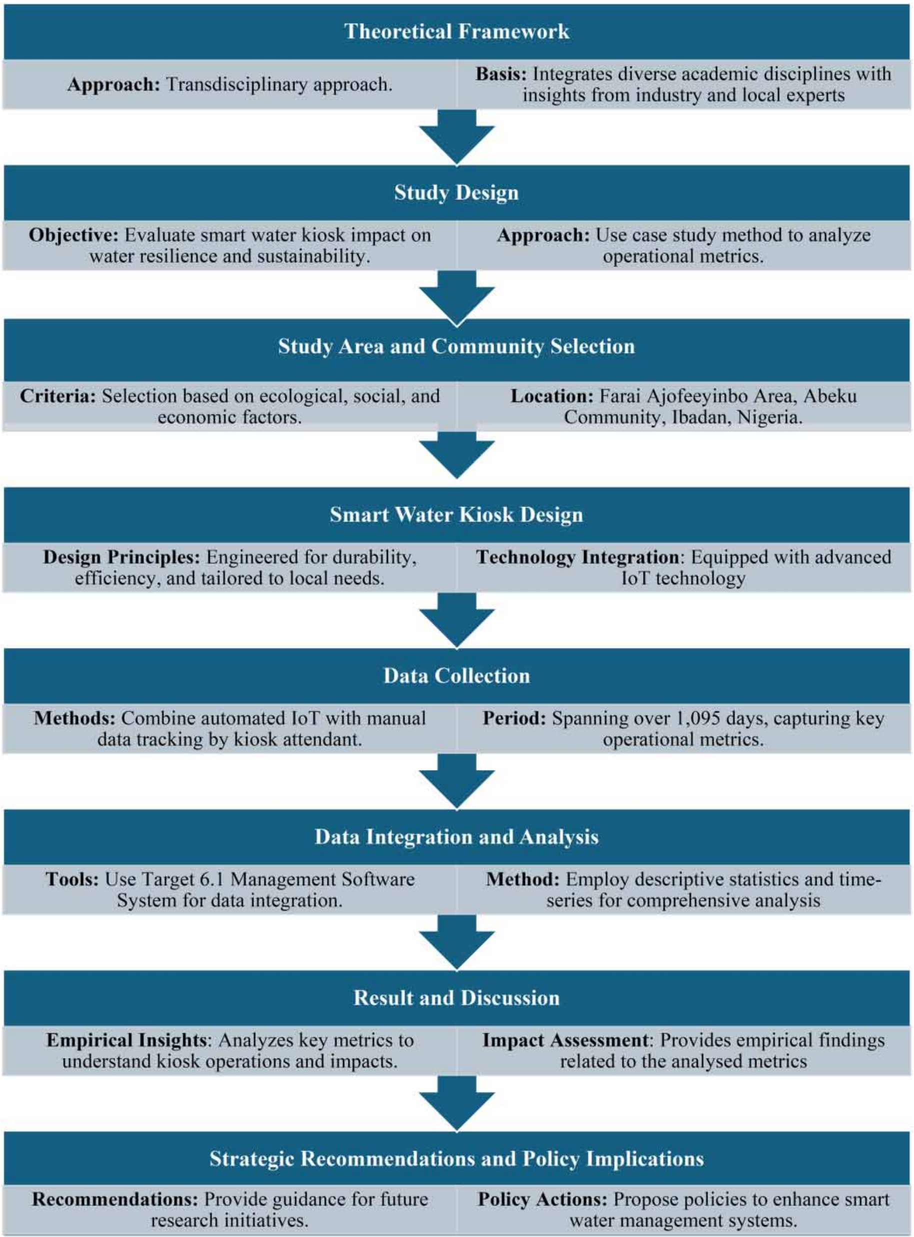


Figure 1 | Flowchart of the study's process.

overall water dispensed (WD), and overall kiosk usage, were meticulously 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.

Key performance metrics

- **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.

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

- **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

$$\left(\frac{\sum_N \text{Revenue water} + \sum_N \text{support}}{\sum_N \text{Expenses}}\right) \times 100$$

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

- **Revenue water:** Income from water sales over the period N.
  Expenses: Total cost of operation, maintainance & repair over the period N
  N: Total number of days in the period
- **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. Reliability rating $= \left(\frac{\text{Total operational days} - \text{days with interruptions}}{\text{Total operational days}}\right)$

Here,

- **Total operational days:** Total number of days in the period N
- **Days with interruptions:** Days of service disruption or failure during the N period

Additional metrics for comprehensive analysis

- **Overall WD:**

$$\sum_{n=1}^{N} (\text{Daily water dispensed})$$

- **Water credit:**

$$\sum_{n=1}^{N} (\text{Volume of free water})$$

- **NRW:**

$$\sum_{n=1}^{N} (\text{Total water dispensed} - \text{revenue water} - \text{water credit})$$

Study area and community selection

Utilizing the 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.* (2024a). 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.

Smart water kiosk design

Designed for adaptability and resilience, the smart water kiosk incorporates CAS theory and established civil engineering and environmental science practices (Chan 2001; Holden 2005). Referenced in Figure 2, its architectural and engineering features

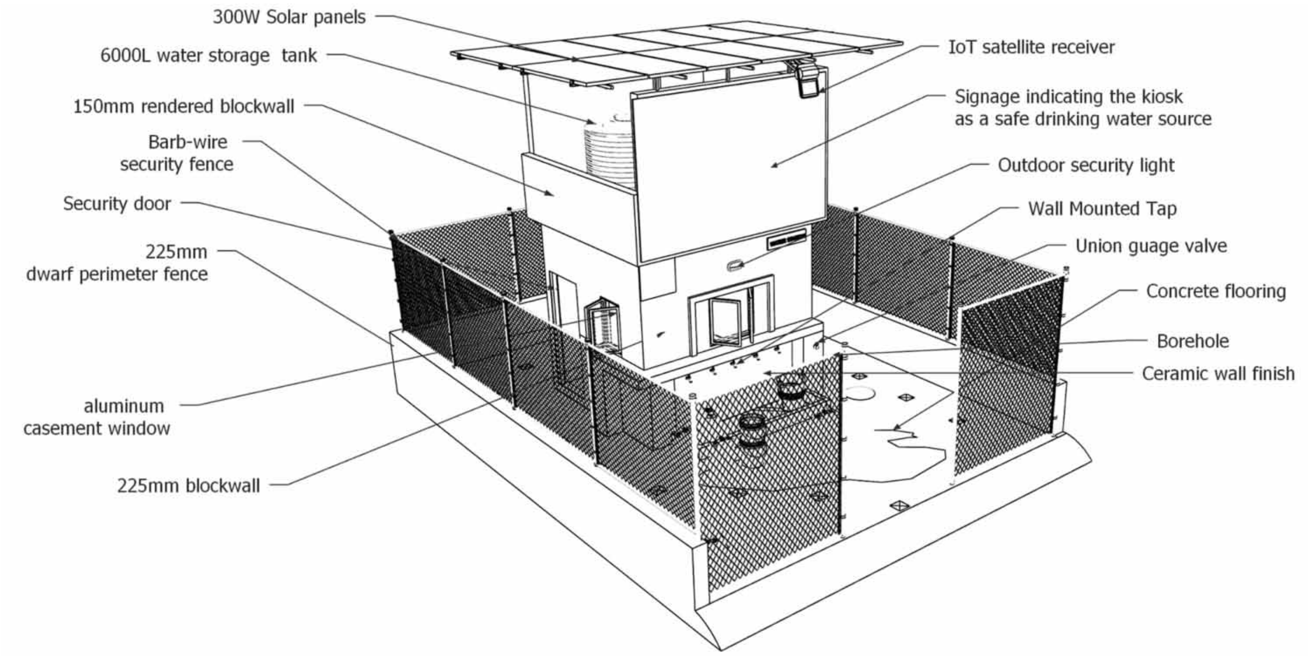


Figure 2 | Illustration of the smart water kiosk's architectural design, highlighting key components.

are based on Adeoti *et al.* (2024a)'s analysis of technical failures in Nigerian water infrastructure, providing crucial insights for constructing durable structures.

The kiosk utilizes advanced IoT technology and algorithmic software to remotely monitor and analyze 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 derived from Adeoti *et al.* (2024b)'s sustainability research. This study employed a Likert scale questionnaire to analyze 265 sustainability factors, forming a solid foundation for applying SSR and SR to assess infrastructure sustainability. The integration of rigorous, evidence-based frameworks with modern technologies and active collaboration with local experts and users validates the kiosk's scientific and practical relevance, exemplifying the transdisciplinary approach of this study.

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

Data collection

Data collection period: Data were systematically collected from the smart water kiosk over 1,095 days (3 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.

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, utilizing the Target 6.1 software with various statistical techniques for real-time analysis, are provided below.

Automated data collection: The smart water kiosk utilizes IoT technology provided by Farmbot, an Australian IoT company, to monitor and record key operational data such as the volume of WD, tank water levels, and overall system functionality. The data are 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 WD as recorded by IoT technology.

Anomaly detection and data integrity: When IoT data are unavailable, the Target 6.1 software employs the predictive formula outlined below to estimate WD 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 analyzed, 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 WD

$$\mathrm{WD} = (\mathrm{RW} + \mathrm{WC}) \times X \tag{1}$$

$$\mathrm{WD} = \mathrm{NRW} + (\mathrm{RW} + \mathrm{WC}) \tag{2}$$

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

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

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

$$\mathrm{Avg}\ (\mathrm{NRW\%}) = \frac{\sum \mathrm{NRW\%}\ \text{of each period}}{\text{Number of periods}} \tag{6}$$

where WD is the overall water dispensed; RW is the revenue water; WC is the water credit; NWR is the NRW; X is the adjustment factor needed to scale (RW + WC) up to the overall water dispensed.

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 minimizing IoT downtimes and relying on the synergy between formula-based predictions and IoT data, which collectively improve data accuracy and reliability.

Method of data analysis: This study utilizes the Target 6.1 software system, designed for comprehensive real-time analysis of various water management metrics such as revenue water, NRW, water credit, and total WD. 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 visualization 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 synchronized 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 analyzed to understand the surge's causes, enriching the dataset for ongoing analysis and offering insights into external factors impacting the kiosk's operation.

Optimizing 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 toward key performance indicators, specifically aiming to achieve a SSR of 100% and a high reliability rating. These metrics are fundamental in measuring the success and long-term viability of the kiosk.

RESULT AND DISCUSSION

The smart water kiosk utilization rate is 7.63% of its capacity

Figure 3 presents a time-series scatter plot of WD at the kiosk over 3 years, detailing both revenue water (paid) and water credit (free) periods. The peak daily usage was recorded at 7,267 L. Over the 1,095-day study period, the kiosk dispensed a total of 1,671,497 L, averaging 1,526 L per day, which is only 7.63% of the kiosk's designed capacity of 20,000 L 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 L per person per day (Howard *et al.* 2020), actual usage was significantly low, averaging about 7.63% of the total capacity. This notable underutilization underscores the discrepancy between potential and actual water use, reflecting a complex interplay of factors that influence consumption rates.

Factors contributing to kiosk underutilization

The investigation into the underutilization 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 underutilization across payment periods**: while usage dropped significantly during the paid period, underutilization persisted even during free periods. average daily usage was 1,898 L (9.49% of the kiosk's 20,000-L capacity) during

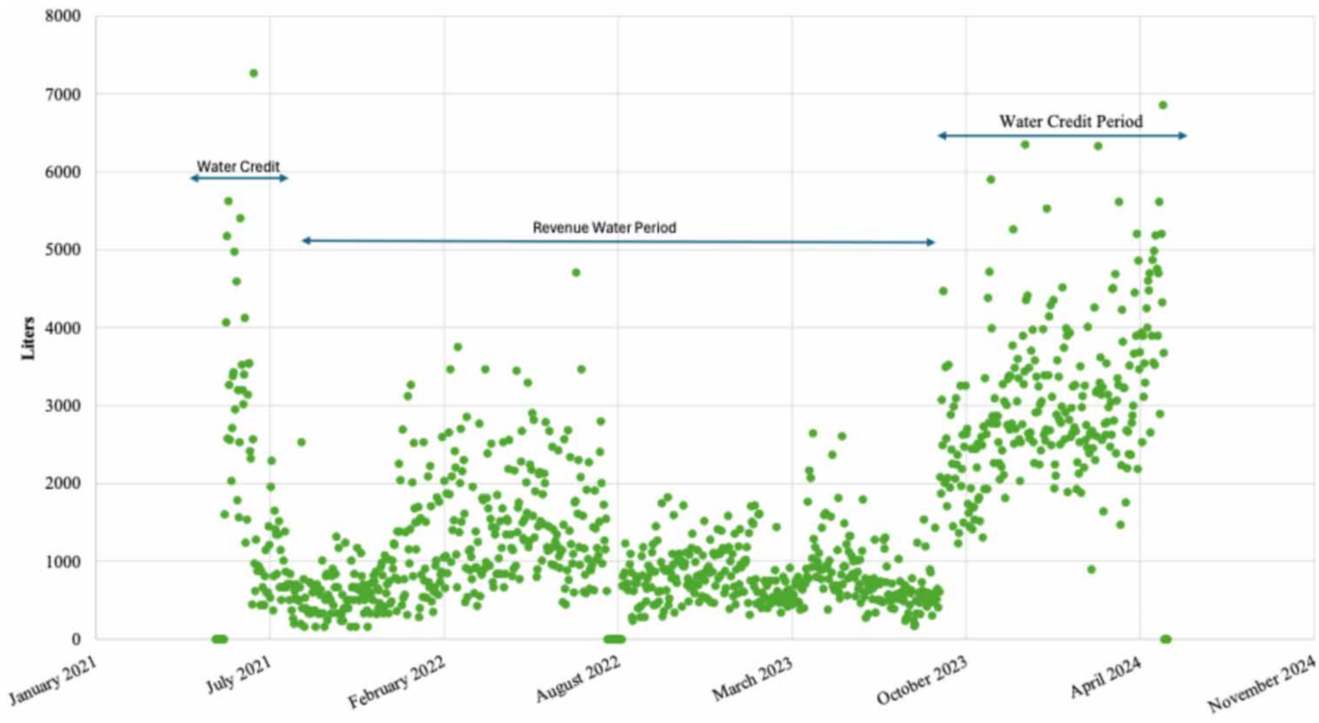


Figure 3 | Daily water usage trends at the smart water kiosk.

the initial free period, which fell to 578 L (2.89%) during the paid period, and rose slightly to 1,821 L (9.11%) in the final free period (see supplementary material, items 2 and 3, figures s2 and s3).

- **Dry and rainy seasons**: seasonal variations show slightly higher usage during the dry season (December to February), averaging 1,747 L per day (8.74% of capacity), compared to 1,454 L per day (7.27%) during the rainy season (March to November) (Kirk-Greene *et al.* 2024). Despite this increase, utilization remained significantly below capacity during both seasons (see Supplementary material, Item 1 and Figure S1).
- **Preference for unsafe alternative water sources:** Residents predominantly use unprotected wells, considered unsafe and unhygienic by national and UN standards for safe drinking water. These sources are favored 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.

Water usage decreased by 68.4% when charged compared to when free

As detailed in Items 2 and 3 of the Supplementary material, the estimated average daily water usage during the water credit period was 1,831 L, which decreased to 578 L during the paid period. This represents a 68.4% decrease in usage. This significant drop highlights the economic challenges within the community, with many residents either unable or unwilling to pay even the nominal fee of 25 Naira per 25-L jerrican (approximately $0.06 USD). 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.

22% SSR observed during revenue water period

The SSR of the kiosk was 22%, indicating that revenue from water sales accounted for 22% of its operational, maintenance, and repair costs, as depicted in Figure S4 of the Supplementary material. 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 subsidized 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.

Overlap of aid impact reduced SSR 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 utilization. During our 1,095-day study, significant shifts in water distribution occurred on the 833rd day, as depicted in Figure 4. 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 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.* 2024a). These dynamics underscore the need for coordinated strategies among aid organizations to ensure the long-term sustainability of infrastructure projects.

NRW constituted 41.24% of total WD

Figure 5 presents a time-series scatter plot displaying the total volume of WD (in green) and its associated NRW (in red) over the study period of 1,095 days. NRW accounted for 41.24% of the total volume, highlighting significant challenges in managing water losses. While the current underutilization of the kiosk moderates the immediate financial impact of this high

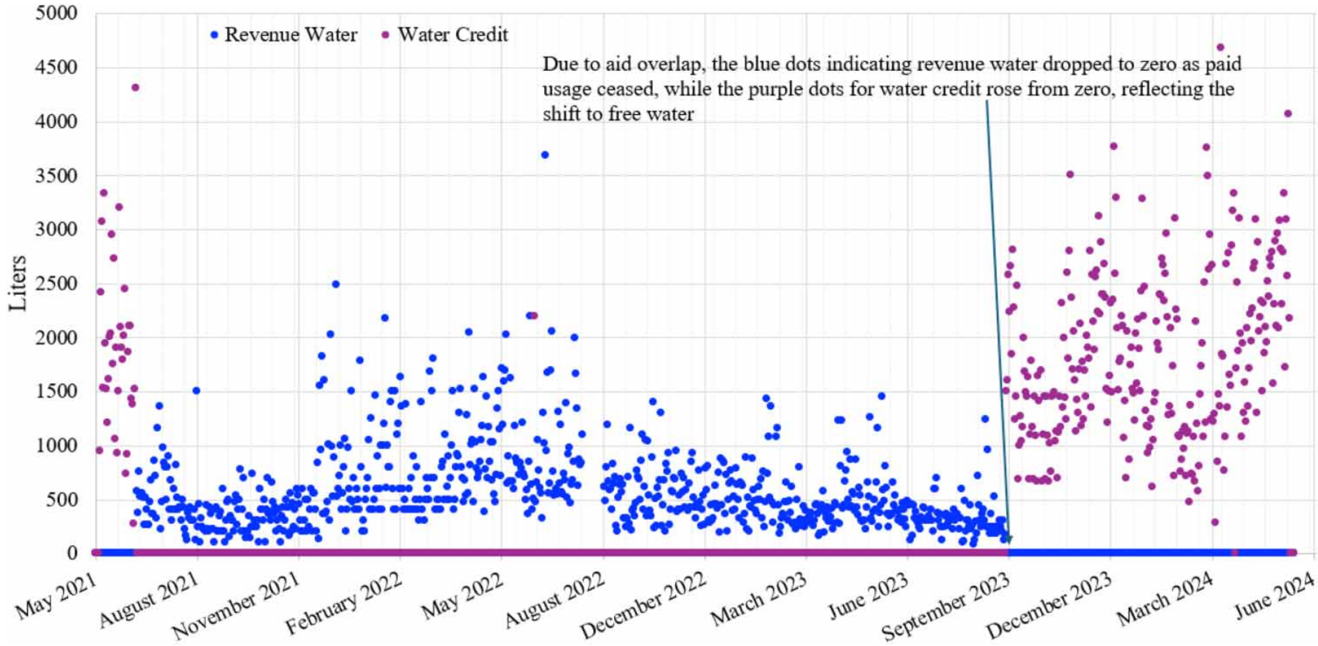


Figure 4 | Scatter plot illustrating the shift from revenue water to water credit due to aid overlap.

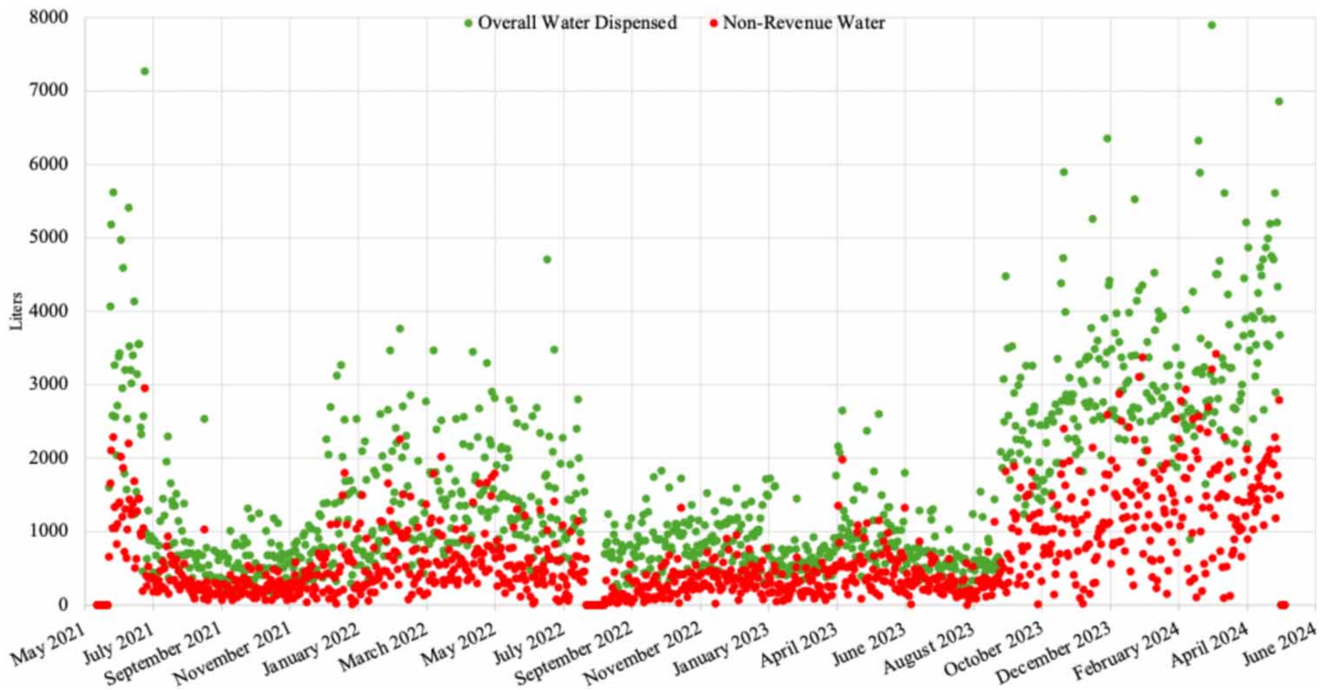


Figure 5 | Time-series scatter plot of WD and associated NRW.

NRW, such losses would become unsustainable should the infrastructure operate at its maximum utilization 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.

NRW consistency across pricing models

Analysis of NRW showed minimal variation between free and paid periods, with NRW remaining high at 40.75 and 41.8%, respectively, as detailed in Items 5 and 6 and Figures S5 and S6 of the Supplementary material. This consistency contradicts the assumption, argued by Liemberger & Farley (2005), that charging for water could significantly reduce water wastage. Our data suggest that NRW rates are consistent regardless of the pricing strategy, supporting Van den Berg's (2014) assertion that effective metering, not just pricing strategies, is crucial for managing NRW. Implementing technologies like 'Automatic Shutdown Devices' for accurate metering could offer a more effective strategy. Future pilots should explore the efficacy of such technologies in reducing NRW.

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 S7 of the Supplementary material. This trend suggests Monday as the optimal day for maintenance activities such as borehole flushing and tank washing, to minimize 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.

Smart water kiosk achieves 97.1% reliability and 100% SR

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 optimizing the timing for routine maintenance without service disruption, thereby ensuring minimal impact on system reliability.

Moreover, despite an initial drop to a 0% SSR due to aid overlap, meaning the kiosk cannot self-sustain without external support, the kiosk achieved a 100% SR supported entirely by external funding, covering all operational costs as detailed in Figure S8 of the Supplementary material.

Validation of smart water management models

The operational efficacy of IoT in our study aligns with the theoretical frameworks proposed by Lee *et al.* (2015), who advocate for integrating ICT with smart water grids to enhance urban water management systems. Similarly to our findings, Lee *et al.* (2015) suggest that ICT integration can significantly streamline operational processes and enhance efficiency in managing water resources within smart cities.

Moreover, the empirical results of our study serve as a practical benchmark for assessing theoretical models on smart water management systems. For instance, the models developed by Fatehi-Nobarian *et al.* (2023) have demonstrated effectiveness in optimizing hydraulic operations and predicting seepage in earth dams using advanced meta-heuristic and wavelet–ANN hybrid models in water management. Such theoretical models could leverage our methodology, which offers a practical framework for evaluating the effectiveness of theoretical models in real-life scenarios.

Overall, our research demonstrates the effectiveness of smart water management systems in enhancing the resilience and sustainability of water infrastructure by identifying new challenges such as infrastructure underutilization and aid overlap – phenomena previously undocumented in the literature – and providing empirical data for data-driven solutions. By leveraging these technologies, our study advances the discourse on integrating innovative solutions to enhance water infrastructure resilience and sustainability in Nigeria and similar socio-economic regions globally, offering strategic insights for policy development and further technological enhancements.

Implications and recommendations for policy, practice, and future research

Our extensive three-year study provides critical insights into the efficacy of smart water management systems, revealing essential strategies for their broader application. The findings highlight the necessity of diverse funding models, combining government subsidies, donations, and user fees for sustainability. Engaging communities in system design and operation is crucial to ensure that systems are well-adapted to meet local needs. Additionally, real-time IoT monitoring proves essential for prompt issue detection, enabling proactive repairs and infrastructure reliability. Findings on infrastructure underutilization suggest revising demand assessment methodologies to accurately identify water-poor communities and actual infrastructure needs.

Strategic and policy recommendations

- **Enhanced household-level demand analysis:** Develop techniques for precise demand analysis at the household level to prevent infrastructure underutilization and maximize resource efficiency. Predictive models should be utilized for accurate infrastructure demand forecasting (Adeoti *et al.* 2024b).
- **Institutionalizing smart water management:** Mandate smart system integration in national water projects to replicate the high reliability observed in this study.
- **Targeted financial support and subsidies:** Support water infrastructure that is unable to achieve 100% SSR, helping it reach 100% SR like the smart water kiosk in this study.
- **Iterative research and development:** Promote ongoing innovation in water management, treating each project as a pilot to refine practices based on empirical data and community feedback.

Future research directions

- **Infrastructure underutilization:** The phenomenon of water infrastructure underutilization and its impact on infrastructure sustainability is under-explored. There is a need for exploration into this topic and development of a framework to solve this challenge.
- **Advanced metering solutions:** Explore advanced metering technologies like automatic shutdown devices to improve water conservation and reduce NRW, offering alternatives to traditional pricing strategies that have shown limited efficacy in our findings.

CONCLUSION

This study rigorously evaluated the effectiveness of smart water management systems over 3 years, employing real-time data analytics at a smart water kiosk in an underserved Nigerian community. Initially, the kiosk achieved a 22% SSR, which subsequently dropped to zero due to overlapping aid efforts, a novel challenge identified in this research. Despite several obstacles, the kiosk attained a 100% SR through external support and maintained a high reliability rating of 97.1%. This research validates the effectiveness of smart water management systems in enhancing infrastructure resilience and sustainability by identifying previously undocumented challenges and proposed solutions based on empirical findings.

Our findings make a significant contribution to the discourse on sustainable water management, providing empirical evidence and practical insights vital for policy development, future research, and technological enhancements in the Nigerian water sector. The research highlights the potential of advanced technologies to address the complex challenges faced by water infrastructure in Nigeria and similar socio-economic regions.

One of the strategic recommendations from this study is to view each water project as a pilot within a continuous research and development framework, aiming to refine practices based on empirical evidence. Future research should explore the scalability of these systems across diverse geopolitical contexts utilizing our methodology to gather longitudinal data to ensure their broad applicability. This study establishes a foundation for further research to elaborate on the parameters of smart water management effectiveness and its integration into global sustainability practices, supporting global efforts to ensure access to safe and affordable drinking water.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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