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Sustainability framework for water infrastructure development in Nigeria: a modelling approach

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ABSTRACT

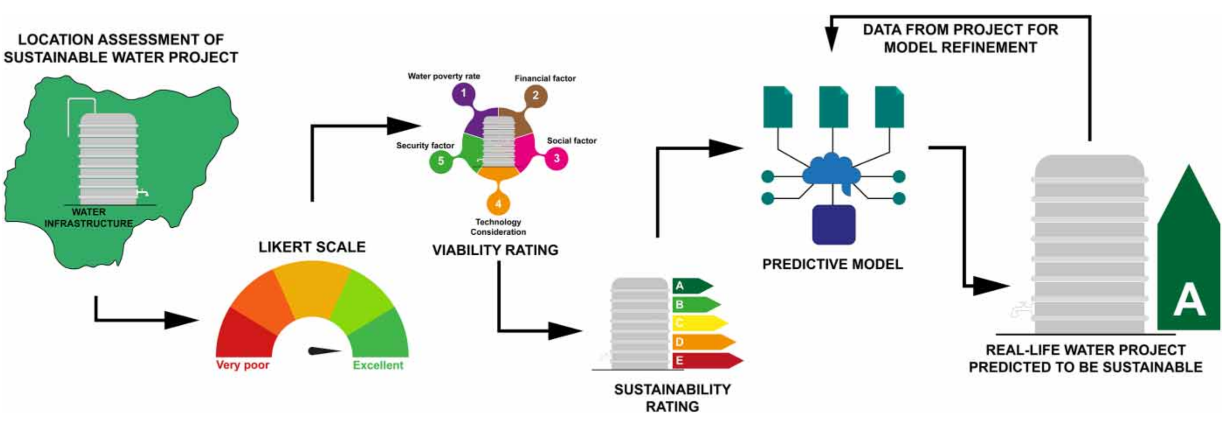
This study introduces the Predictive Iterative Sustainability Model (PISM), a tailored framework designed to enhance water infrastructure sustainability evaluations in Nigeria. PISM addresses the lack of localised, adaptable frameworks by integrating three key components: a Viability Rating (VR), a Sustainability Rating (SR), and a conceptual formula within a predictive iterative process. This integrated approach optimises project evaluation and planning. Empirical data were derived by evaluating responses to a survey with 70 Likert-scale questions covering 265 sustainability challenges. This data was used to assess community viability for sustainable water infrastructure in five Nigerian communities facing significant water poverty. The results reveal VR scores ranging from 63.95 to 67.91%, establishing a benchmark for viability. SR scores, on the other hand, vary substantially from 179 to 424%, illustrating the model's capacity to evaluate sustainability under diverse conditions and identify critical, high-impact projects that can mitigate infrastructure failure risks. As a dynamic and adaptable framework, PISM holds significant potential to improve water infrastructure sustainability in Nigeria and similar regions globally.

Key words: nigeria water projects, sustainability rating, sustainable development goal 6.1 (SDG 6.1), sustainable water infrastructure, viability rating, water infrastructure framework

HIGHLIGHTS

- Develops a model to enhance water infrastructure planning in Nigeria.
- Utilises Viability and Sustainability Ratings to predict project sustainability outcomes.
- Addresses the lack of a sustainability framework in Nigeria's water sector.
- Assesses community readiness for sustainable water infrastructure projects in water-scarce areas.
- Promotes the achievement of SDG 6.1.

GRAPHICAL ABSTRACT



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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.* 2014; 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 SDG 6.1 (Andres *et al.* 2018; Adeniran *et al.* 2021). 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.* 2024). 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 'Location Viability Rating' (LVR), a metric specifically designed to measure the unique circumstances of each community that impact the long-term success of water infrastructure projects.

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 (Dovers & Handmer 1992; Barbosa *et al.* 2014). This study specifically focus 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 to be durable, resilient to environmental changes, and capable of enhancing community well-being. It must remain functional throughout its designated lifespan, addressing challenges such as security issues, 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 (Oyegoke *et al.* 2012; Khan *et al.* 2018; Adeoti *et al.* 2023).

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).

Rigourous 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

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shortcoming when applying these frameworks to the developing countries like Nigeria. Addressing this disparity, our 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, our study represents a practical and strategic framework and tool for planning and executing water projects, significantly advancing the objectives of SDG 6.1 and contributing to the global water sustainability efforts. The innovative methodology used in this study has global significance as it is uniquely designed to predict infrastructure sustainability in the context of Nigeria, which is applicable to similar regions across Africa and the world, enhancing sustainable infrastructure implementation.

THEORETICAL FRAMEWORK: A TRANSDISCIPLINARY APPROACH

Introduction to the framework

This study introduces a novel, transdisciplinary framework for assessing water infrastructure sustainability in Nigeria. 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 rigour and practical application, exemplifying how a transdisciplinary method can bridge theoretical knowledge with real-world relevance.

Community selection: ecological systems theory

Bronfenbrenner's Ecological Systems Theory (1979), as applied to environmental contexts by Crawford (2020), forms the foundation for our community selection process. This theory recognises that the community well-being is shaped by complex interactions within environmental systems. We employed a standardised tool 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), informed by Adeoti *et al.* (2023)'s systematic review which identified 265 sustainability challenges. Adapting TPB principles, we use a Likert-scale format to assess community attitudes towards sustainable water infrastructure. This approach goes beyond simply predicting behaviour; by understanding community perspectives, we can develop a community VR for sustainable water infrastructure projects.

Location viability rating and sustainability rating

Complex Adaptive Systems Theory (Chan 2001; Holden 2005) informs the development of our VR and SR. This approach acknowledges the dynamic interplay of sustainability factors within communities. The VR and SR act as indicators for predicting the potential success of sustainable water infrastructure projects. Both theoretical foundations and real-world data from water projects inform the VR and SR. This adaptability ensures that our model remains responsive to the unique circumstances of each community, enabling a comprehensive evaluation of water infrastructure sustainability across diverse contexts.

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METHODOLOGY

Study area

This study investigates five communities within Oyo State, Nigeria, selected from the 1,696 communities assessed by Adeoti *et al.* (2024). Data from Adeoti *et al.* (2024) were thoroughly reviewed to identify the areas with most pressing water challenges. These communities, identified through precise GPS coordinates and enhanced by local insights, were chosen to represent a range of urban and rural water scarcity challenges. 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 ageing 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 semi-rural areas with no improved water sources, depending on rain and an unhygienic stream, which are often overlooked in water infrastructure planning.

SAMPLE SPACE

To ensure representative data collection across the five chosen communities, we employed Cochran's Formula and considered factors like population, household size, and house counts. 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, we surveyed more residents to strengthen the generalisability of our 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. Lastly, Ajila/Irepodun Idi Ayunre, with 367 households, required a sample of 56. Totally, 321 households required across all 5 communities.

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

Total number of households (H) in community

$$H = \frac{P}{A} \tag{1}$$

where:

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

Sample size using cochran's formula

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

where:

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

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- 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:

$$DE = 1 + (b - 1) \times ICC \tag{3}$$

Here:

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

Final number of houses to survey (n_final)

$$n_{\text{final}} = n_{\frac{\text{adjusted}}{b}} \tag{4}$$

where:

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

Detailed sample size calculation for Aponmode Community is provided in the Supplementary Information (SI). The same methodological framework was applied uniformly to the remaining four communities. This ensures transparency in our approach and clarity in our household interview selection process.

The Predictive Iterative Sustainability Model

The Predictive Iterative Sustainability Model (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 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 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 based on real-life project data. While the specifics of these enhancements fall outside the scope of this study, the conceptual formula guiding this iterative process is meticulously detailed in the SI material and subsequent sections of this methodology. This iterative process is crucial for perfecting the model's predictive capabilities, aiming to progressively improve its accuracy until it reaches a point of convergence.

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). The detailed questionnaire can be found in Table S1 of the supplementary information (SI). Responses were tallied under respective factors; each was assigned a weight reflecting its sustainability impact. These weighted responses were aggregated to calculate the LVR 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 1 succinctly presents the PISM approach to predicting water infrastructure sustainability. It begins by establishing the VR for each community, followed by a predicted 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

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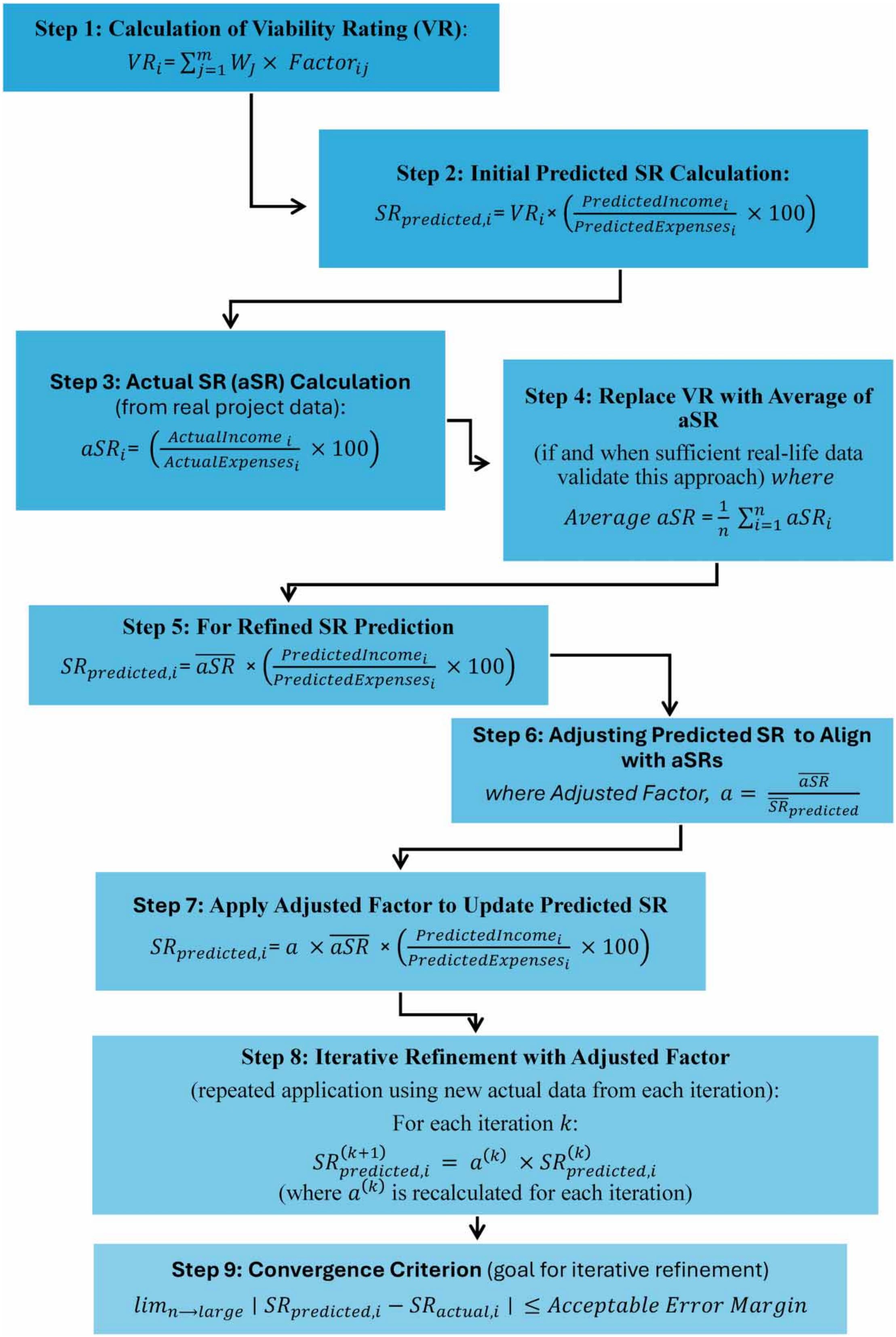

Figure 1 | Flowchart of the PISM methodology.

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coefficient, improving SR prediction practicality and accuracy by leveraging real-world project data. Figure 1 illustrates this transition, while the detailed conditions and mathematical proofs supporting it are elaborated in the Supplementary Information (SI). The SI provides a comprehensive breakdown of the PISM methodology, including the nuanced calculations and logical flow summarised in Figure 1.

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, the PISM demonstrates its effectiveness as a predictive tool for sustainability. The SR predictions for the five communities studied were meticulously informed by extensive surveys, reflecting actual conditions with accuracy. Therefore, the PISM, in its current state, represents a significant and influential framework with the potential to considerably enhance water infrastructure sustainability.

Methodological rigour and data integrity

Addressing methodological subjectivity

Our study's methodology, leveraging a transdisciplinary approach, integrated insights from both industry experts and academic researchers to ensure the validity of our survey instruments and data collection protocols. We standardised data collection 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, we initiated a rigourous verification process 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. Utilising Likert heatmaps, we meticulously reviewed each questionnaire response to identify potential anomalies, enabling us to make necessary corrections or exclude erroneous data to uphold the integrity and accuracy of our findings.

These methodological enhancements significantly improved the reliability of our results, providing a robust framework for assessing the sustainability of water infrastructure in the studied communities.

RESULTS AND DISCUSSION

Viability ratings of surveyed communities – Likert scale assessment

The VRs obtained from our Likert-scale questionnaire reflect comprehensive assessments across the five studied communities. The questionnaire, summarised in Table S1 of the Supplementary Material, 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, we collected responses from 380 households (88 in Aponmode, 96 in Alabata, 45 in Omilabu, 86 in Isale-Oja, and 65 in Ajila), exceeding the methodology's required sample size of 321.

Heatmaps were created to visualise the VR data for each community (Figure 2 and Figures S1–S5 in the Supplementary Material). These heatmaps show the distribution of responses across all 70 questionnaire items, highlighting variations in sustainability challenges and opportunities. For example, Figure 1 depicts the response patterns for Aponmode. Question 1 (Q1) on access to safe drinking water reveals a range of experiences. Total of 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 VR assesses crucial factors through a comprehensive analysis of all 70 survey questions.

Viability ratings scores of surveyed communities

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

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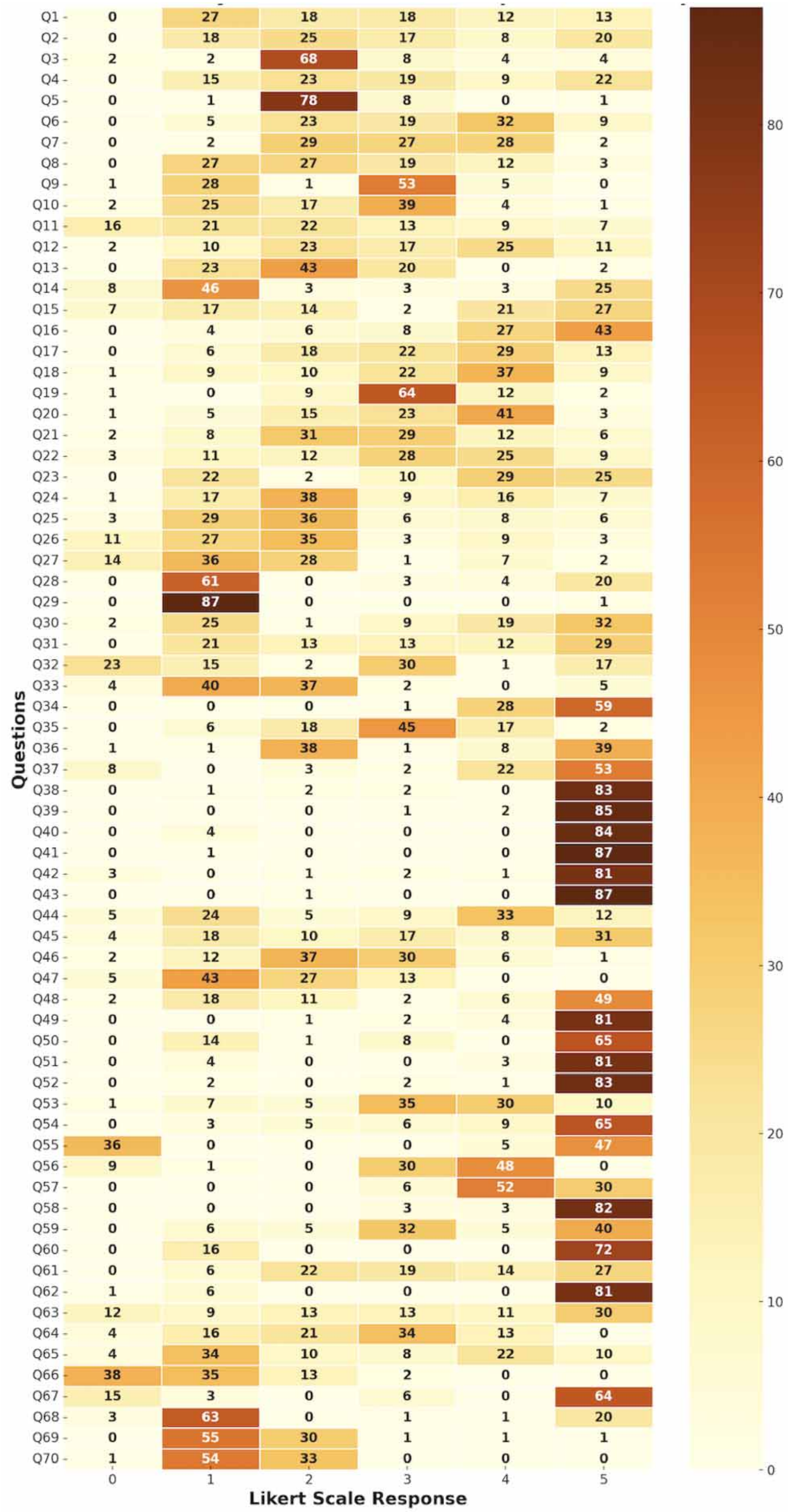

Figure 2 | Aponmode community assessment: heatmap of Likert responses.

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The VRs in Table 1 range from 63.95 to 67.91%, indicating a similar baseline viability for water projects across these communities despite their water needs. This similarity highlights that VR alone cannot predict sustainability outcomes. Instead, the VR serves as a springboard, influencing a model that predicts the SR. The community with the highest VR is expected to have the best predicted SR, suggesting a higher likelihood of successful sustainable infrastructure projects.

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

Predicted sustainability rating

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

SR prediction formula

$$SR_{\text{Predicted},i} = VR_i \times \left(\frac{\text{PredictedIncome}_i}{\text{PredictedExpenses}_i} \times 100 \right)$$

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 liter 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 total number of households (EHC), the formula adjusts to use EHC in place of VWSC/AWDH.

Table 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%	

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Hence the comprehensive formula use in obtain the SR becomes:

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

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

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 Supplementary Information (SI) material for further reference. Table 2 presents the determined SR for each of the five studied communites.

Delineating project viability through predicted sustainability ratings

Our analysis of Predicted SRs in Table 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.

Table 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%

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The PISM enhances the accuracy of SR predictions by leveraging the 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 over $3 billion has been lost to failed projects, hindering water access for millions of Nigerians (Otun *et al.* 2011; Andres *et al.* 2018; Adeniran *et al.* 2021). 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.

Model iteration and the path to convergence for accurate prediction

The iterative refinement of the PISM is designed to ensure that the predicted SR converges with the actual SR within an acceptable margin of error, represented by $\lim_{n\rightarrow \text{large}}|SR_{\text{Predicted,i}} - SR_{\text{actual,i}}| \leq$ 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: $a = \overline{aSR}/\overline{SR}_{\text{predicted}}$, 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 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. We propose replacing VR with the average SR of completed projects. This substitution leverages real-world data, potentially improving model accuracy while simplifying its application in water infrastructure planning.

The methodology section details an alternative method, iteratively refined for convergence, to enhance PISM's usability for water agencies. This method replaces VR with the average SR of completed projects. Since VR acts as a multiplier in SR prediction, this substitution could effectively adjust predictions and improve PISM's utility for strategic water infrastructure decisions. Convergence between predicted and actual SRs strengthens PISM's predictive power and underscores its value in water infrastructure execution. Continuous refinement and integration of real-world data will further enhance its forecasting capabilities, solidifying PISM as a crucial tool for achieving sustainable water infrastructure development.

Limitations

Refining the accuracy of PISM in Nigeria and similar 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. The primary challenge lies in overcoming potential financial constraints and obtaining long-term commitment from these key partners.

CONCLUSION

This study introduces the PISM, a novel framework designed to address critical gaps in sustainable water infrastructure development for Nigeria. PISM integrates VR and SR into a cyclical evaluation process, offering a valuable tool for assessing project sustainability during the early planning stages. Field data collected through surveys conducted across five communities established VR scores ranging from 63.95 to 67.91%, creating a robust benchmark for evaluating community readiness.

The wide range of SR scores (179–424%) highlights PISM's adaptability to diverse economic and operational realities, identifying projects with high sustainability potential. However, PISM's current strength lies in its predictive capabilities, which require real-world application for validation. Future research should focus on implementing PISM in actual projects to verify its predictions and refine its methods based on observed outcomes. Streamlining data collection and expanding its applicability to various contexts are crucial for enhancing PISM's practicality and scalability.

This study highlights the urgent need for collaboration among policymakers, institutions, and philanthropic organisations. By working together, they can effectively adopt and adapt innovative frameworks like PISM. Such collaboration is critical to

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addressing water poverty and infrastructure failures in Nigeria and other developing regions. Refining and implementing PISM in real-world projects are essential steps towards achieving SDG 6.1: ensuring universal access to safe and affordable drinking water.

The PISM's potential for global application offers a bright future for sustainable water infrastructure in developing regions. This research bridges the gap between academic discourse and practical solutions, empowering policymakers and practitioners in sustainable development. Integrating PISM into water projects and continuously refining it can turn the vision of universal access to safe water into reality.

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ETHICAL CONSIDERATIONS

This study was conducted in strict adherence to the ethical guidelines and standards set forth by the University of Technology Sydney, with ethics approval granted under UTS HREC REF NO. ETH23-7980. This approval underscores our commitment to responsible research practices, particularly when collecting data involving human participants.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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