An Integrated Performance Index for Decentralized Water Supply Systems: A Case Study of SiPAS in the Brantas River Basin

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Abstract: To develop and validate an Integrated Performance Index Model (IPIM) for evaluating Simple Water Supply Systems (SiPAS) in the Brantas River Basin, Indonesia. We surveyed, audited, and interviewed stakeholders at 31 SiPAS sites. Latent constructs were tested using SEM–PLS, and dimension weights were optimized with the Generalized Reduced Gradient method. The model explained system performance well (R^2 = 0.95) and showed high predictive reliability. The technical dimension exerted the strongest influence (72.10%), followed by managerial (26.70%) and social (15.10%) factors. The index differentiated low and high performing sites and was consistent with field audit findings. A companion mobile application enabled real time reporting and feedback to strengthen community participation. IPIM provides a concise, scalable framework for assessing decentralized water supply, prioritizing technical improvements while supporting managerial and social strengthening, and can inform investment and governance decisions for rural water services.

Keywords: GRG optimization; Performance index; Rural water governance; SEM-PLS; SiPAS

Introduction

Access to safe drinking water remains a pressing global challenge, with more than two billion people worldwide still lacking access to safely managed services (Nations, 2022). The problem is especially acute in rural and remote areas where centralized infrastructure is economically and technically unfeasible, undermining health, socioeconomic development, and progress toward SDG 6 (Domínguez et al., 2019).

This study introduces an Integrated Performance Index Model (IPIM) specifically tailored to decentralized water supply systems. The IPIM couples Structural Equation Modeling–Partial Least Squares (SEM–PLS) to validate latent constructs with Generalized Reduced Gradient (GRG) optimization to derive data-driven weights addressing the ad-hoc, single dimension emphasis common in prior frameworks (Goharian et al., 2018). Using data from 31 SiPAS installations across the Brantas River Basin, the model integrates technical, managerial, and social indicators to provide a context-sensitive diagnostic tool.

Decentralized, community driven systems are viable, flexible, and cost effective alternatives when centralized networks are infeasible (Maryati et al., 2022; Mvongo et al., 2021; Santikanuri et al., 2025). Evidence from Vietnam links strong community participation to service sustainability (Minh et al., 2024), while comparative analyses across ASEAN underscore the need for adaptive evaluation frameworks (Lawrencia,

2023). In Indonesia, the Simple Water Supply System (SiPAS) leverages local sources springs, rivers, and shallow wells and is supported by the Ministry of Public Works and Public Housing to expand equitable access (Hidayat & Andawayanti, 2024), many installations face deteriorating infrastructure, inadequate maintenance, limited financial planning, and weak institutional arrangements that threaten long term sustainability.

Beyond internal governance issues, SiPAS systems operate under external pressures, including environmental degradation, climate variability, and rising demand pressures that are pronounced in the Brantas River Basin, a critical watershed serving domestic, agricultural, and industrial needs (Kong et al., 2023). These dynamics heighten the urgency for adaptive, multidimensional tools to guide policy and investment decisions (Pandey et al., 2020).

Objective and importance. The research objective is to develop and validate a multidimensional performance index for SiPAS in the Brantas River Basin by integrating technical, managerial, and social dimensions. The resulting evidence base supports targeted governance reforms, strengthens community participation, and offers a scalable approach for evaluating decentralized water systems in comparable contexts.

Method

Study Area and Data Collection

This study was conducted in the Brantas River Basin, East Java, Indonesia, one of the country's most hydrologically significant and socioeconomically diverse regions. The basin features varied topographical, climatic, and demographic conditions, making it an appropriate area for evaluating decentralized water supply systems such as the Simple Water Supply System (SiPAS). A total of 31 SiPAS installations were purposively selected to represent diverse operational and contextual characteristics in rural and remote areas not served by Municipal Water Utilities (MWU). The selection criteria included exclusion from MWU service coverage, reliance on local natural water sources such as springs, rivers, and shallow wells, and the presence of community-based operational and maintenance structures. These criteria ensured that the selected sites accurately represented decentralized water systems typically found in underserved communities. The spatial distribution of these sites within the basin is shown in Figure 1.

To obtain comprehensive data, a mixed-method approach was employed, combining field observations, infrastructure audits, and structured questionnaires. The questionnaires were administered to SiPAS operators, community leaders, and institutional managers. A total of 26 Key Performance Indicators (KPIs) were measured across three core dimensions: technical (e.g., system reliability, water adequacy, maintenance frequency), managerial (e.g., financial transparency, institutional accountability, management capacity), and social (e.g., community participation, user satisfaction, social capital). Supporting water-quality monitoring references include national studies on suspended solids (TSS) using sentinel-2 imagery at estuaries (Yuliara et al., 2025). All indicators were scored using a 5-point Likert scale (1 = very poor to 5 = excellent) and normalized for subsequent analysis. These KPIs provided the foundation for constructing the Integrated Performance Index Model (IPIM).
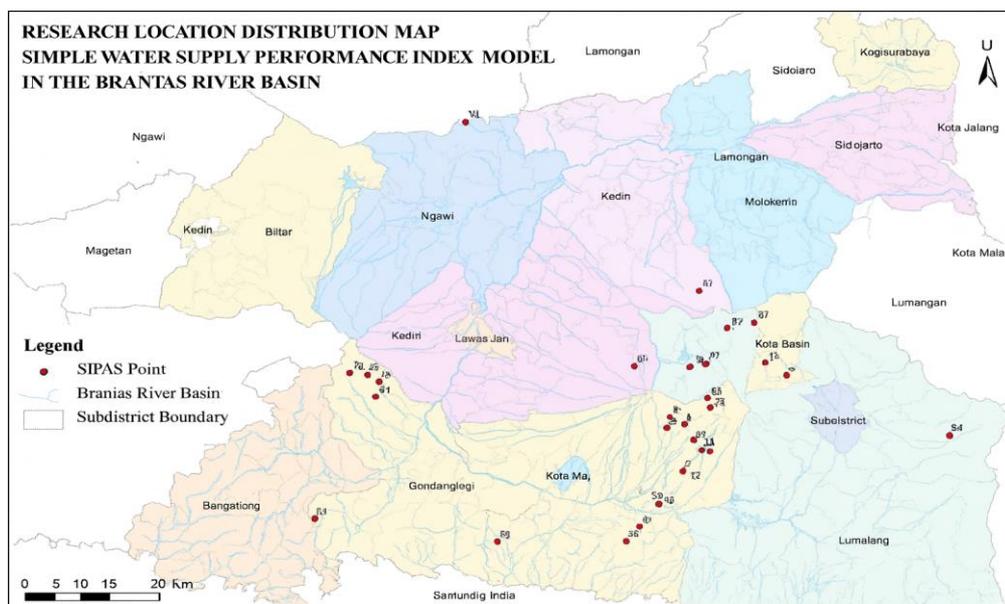

Figure 1. The Allocation of Research Locations within the Brantas River Basin

Structural Equation Modeling (SEM) - Partial Least Squares (PLS)

To construct the Performance Index Model, Structural Equation Modelling using Partial Least Squares (SEM-PLS) was applied to evaluate the multidimensional attributes of SiPAS performance. This approach was selected because it effectively models relationships between latent constructs and observed variables, even with non-normal data distributions and relatively small sample sizes, making it suitable for this study (Hair et al., 2017). The SEM-PLS framework enabled simultaneous modeling of the three dimensions technical, managerial, and social as latent constructs and their associated performance indicators. Each indicator was verified using an outer loading threshold of ≥ 0.70 to ensure validity, and only those meeting this criterion were retained in the model. Similar applications of SEM-PLS for evaluating decentralized water systems have demonstrated its reliability in performance assessment (Sukma & Leelasantitham, 2022). The relationship between each dimension and its indicators was expressed as:

$$Y = c_1x_1 + c_2x_2 + \cdots + c_nx_n \tag{1}$$

Where Y represents the overall performance index, and $c_1, c_2, \ldots, c_n$ are the gradient coefficients for the variables $x_1, x_2, \ldots, x_n$. This iterative process ensured that all selected indicators were reliable and consistent with their respective latent constructs, forming a robust foundation for calculating the Integrated Performance Index (Ramayah et al., 2018).

Generalized Reduced Gradient (GRG) Method

To optimize the Performance Index Model and account for nonlinearities in the data, the Generalized Reduced Gradient (GRG) algorithm was employed. GRG is a nonlinear optimization technique suitable for solving complex multivariable problems, making it appropriate for calibrating the performance index to reflect the diverse operational conditions of each SiPAS location (Lasdon et al., 1978). The GRG algorithm was used to assign optimal weights to the technical, managerial, and social dimensions, ensuring the model accurately captured the contribution of each dimension

to overall performance. Similar applications of GRG in optimizing water infrastructure such as sewer networks and decentralized water systems have demonstrated its effectiveness in improving performance and cost efficiency (Keawsriyong et al., 2025). The following formula was used to optimize the model:

$$f(x) \text{ subject to } g_i(x) = 0, i = 1, \ldots, m \tag{2}$$

Where x represents the vector of variables, and $g_i(x)$ are equality constraints that ensure the model meets precision requirements. The algorithm iteratively updates coefficients in response to performance feedback, thereby enhancing the predictive capability and robustness of the model. Prior applications of the GRG method in optimizing infrastructure systems such as sewer and water networks highlight its relevance in balancing performance with cost effectiveness.

Model Formulation and Validation

Once the Performance Index Model (IPIM) was developed, it was validated using cross validation techniques. Predictions generated by the model were compared with actual performance data from SiPAS installations that were not part of the training dataset. This approach tested the model's accuracy and generalizability in real world conditions. To statistically assess the consistency between the predicted and observed performance indices, a Student's t-test was conducted. The final Performance Index was expressed as a weighted linear model integrating the three dimensions:

$$IK = \alpha\, IK_{Technical} + \beta\, IK_{Social} + \gamma\, IK_{Management} \tag{3}$$

Where IK represents the overall performance index, and α, β, γ, are the respective weights for each dimension, with the constraint $\alpha + \beta + \gamma = 1$. These weights were derived from the GRG optimization process, reflecting the relative contribution of each dimension to overall system performance. Validation results showed no statistically significant difference between predicted and observed values (p > 0.05), confirming the model's robustness and suitability as a decision support tool for evaluating decentralized water systems (Montgomery & Runger, 2018).
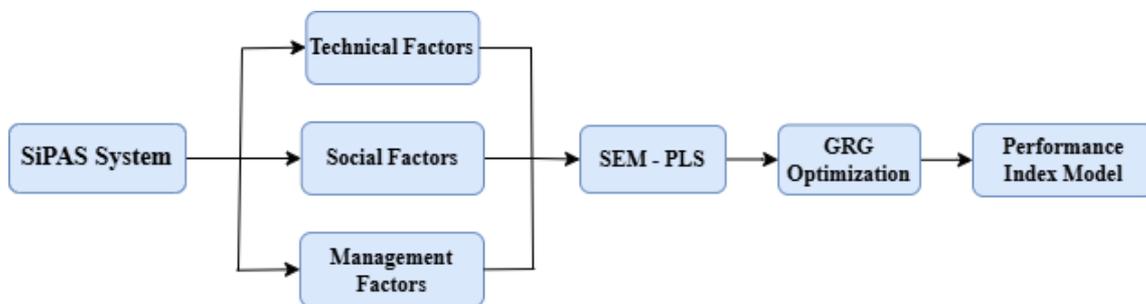

Figure 2. Methodology for developing the SiPAS performance index model

Result and Discussion

This study systematically investigates the performance of Simple Water Supply Systems (SiPAS) in the Brantas River Basin through the development of an integrated performance index model based on technical, managerial, and social dimensions. By utilizing Structural Equation Modeling–Partial Least Squares (SEM-PLS) and Generalized Reduced Gradient (GRG) optimization techniques, the research provides a rigorous quantitative framework for assessing and improving decentralized water supply performance in geographically and administratively complex regions.

Determination of Indicators Using the SEM-PLS Method

Data from 31 SiPAS installations in the Brantas River Basin were analyzed using Structural Equation Modeling–Partial Least Squares (SEM-PLS) to validate the selected performance indicators across technical, managerial, and social dimensions. SEM-PLS was chosen for its ability to model complex relationships between observed indicators and latent variables, making it highly suitable for multidimensional constructs in decentralized water systems. All indicators achieved outer loading values above 0.70, which is the minimum threshold for construct validity in SEM. This confirms that each indicator strongly represents its respective latent construct.

To further validate the model, we examined Average Variance Extracted (AVE) and Composite Reliability (CR) for the key latent constructs: physical infrastructure, service quality, human resources, and environmental impact. The AVE and CR values for all constructs were well above the conventional cut-off values. Specifically, AVE ranged from 0.61 for physical infrastructure to 0.84 for the economy. These results demonstrate the satisfactory convergent validity and internal reliability of the measurement model. Notably, the economy and institutional management constructs exhibited the highest explanatory power and internal reliability, suggesting their substantial influence on system performance and organizational success. The central hypothesis posits that all factors will surpass the established AVE threshold of 0.50 (Figure 3), confirming that the constructs account for sufficient variance from their indicators to demonstrate convergent validity. This threshold is widely accepted in the literature as a benchmark for ensuring that constructs explain more variance than measurement error, thereby reinforcing the model's robustness.

The results show values of Composite Reliability across constructs of Factorial analyses to be as close to can be expected throughout the board, with most factors over the level 0.70 and a few (Figure 4). This is a sign of strong internal consistency and suggests that the measurement model is strong and reliable with a broad application in all domains. Evidence from comparisons with earlier studies is provided that these CR scores are aligned with or higher than usually reported in behavioral and social science research, further guaranteeing confidence in the reliability of the model and appropriateness for adequate construct representation.
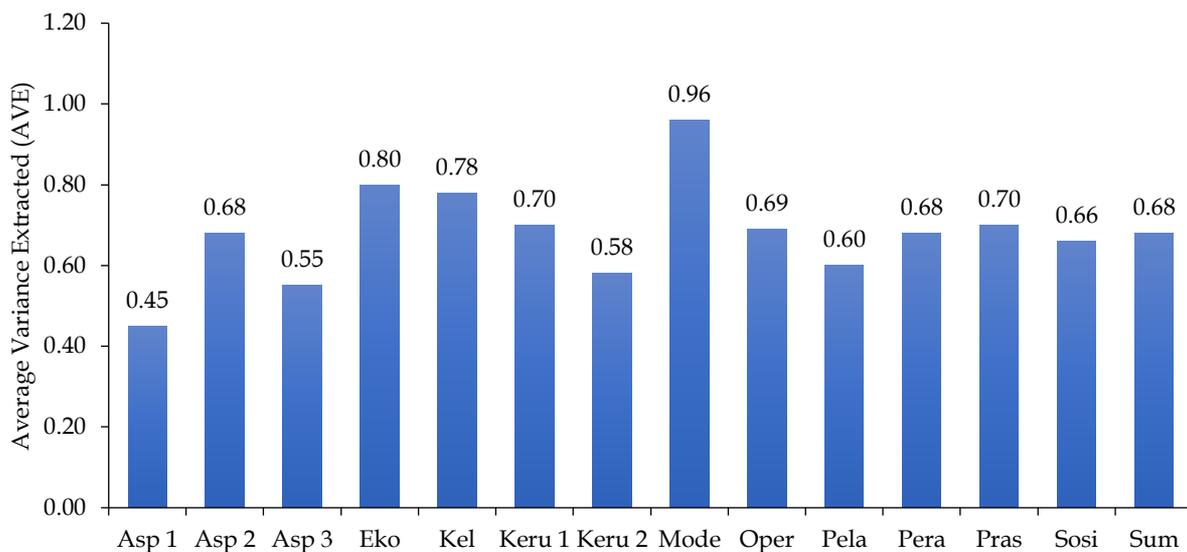

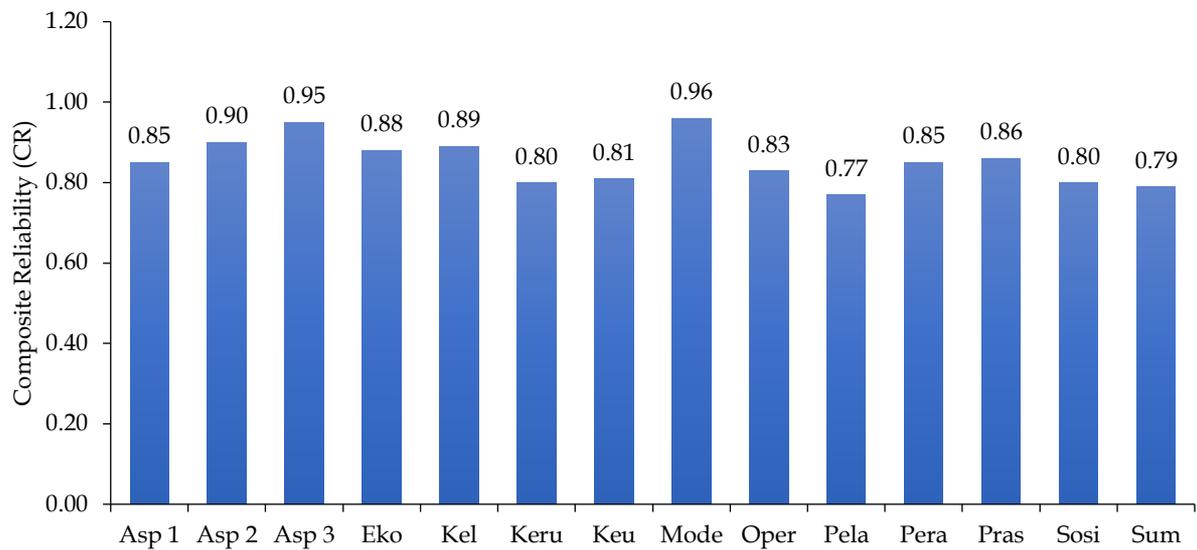**Figure 3.** Diagram of Average Variance Extracted (AVE)

Figure 4. Diagram of Composite Reliability (CR)

Path Coefficients and Structural Relationships

The SEM-PLS analysis revealed that technical factors had the most dominant effect on SiPAS performance, accounting for 72.10% of the variance. These factors particularly infrastructure reliability, water source adequacy, and the condition of treatment facilities form the backbone of reliable water supply services in decentralized systems. This finding aligns with previous studies emphasizing the central role of infrastructure quality in ensuring long-term system functionality (Goharian et al., 2018; Melo et al., 2024). This finding is also consistent with research that advocates clustered and decentralized water supply systems as a means to improve sustainability and operational resilience (Tsegaye et al., 2020). Key drivers of performance included infrastructure reliability, water source availability, and the condition of water treatment facilities.

Social factors, while contributing a smaller share (15.10%), also exhibited statistically significant relationships with performance. Community participation, user satisfaction, and social capital emerged as essential determinants of success. Although their direct numerical contribution is modest, these factors foster local ownership, improve system transparency, and strengthen collaboration between users and managing institutions, consistent with findings that highlight the role of community involvement in enhancing resilience and sustainability of decentralized water systems (Tesfay et al., 2024).

Managerial factors explained 26.70% of the variance, demonstrating that governance quality, financial planning, and institutional capacity substantially influence system performance. Strong managerial capacity ensures that infrastructure investments are maintained, funds are allocated efficiently, and institutional responsibilities are well-defined. These aspects contribute to system resilience by preventing operational failures and enabling adaptive management practices. The role of institutional capacity and governance aligns with frameworks assessing institutional performance in water supply systems (Mishra, 2019).

Using SEM-PLS with bootstrapping, the statistical significance of these relationships was confirmed. Technical factors exerted the largest and most significant influence (T-value = 11.63, $p < 0.00$), followed by managerial (T-value = 4.67, $p < 0.00$) and social dimensions (T-value = 3.02, $p < 0.01$) (Table 1). These results validate the integrated framework used in this study for assessing multidimensional system performance.

Table 1. Path coefficients and statistical analysis of the performance index model for simple water supply systems

Path Coefficient	Original Sample	Sample Average	T Stat	p Values
Technical Aspects	0.72	0.72	11.63	0.00
Social Aspects	0.15	0.14	3.02	0.00
Management Aspects	0.27	0.27	4.67	0.00

The model exhibits excellent explanatory power ($R^2=0.95$), confirming its ability to capture the multidimensional nature of SiPAS performance. The path diagram (Figure 5) provides a visual representation of these relationships, illustrating the proportional contributions of each dimension to the integrated performance index.
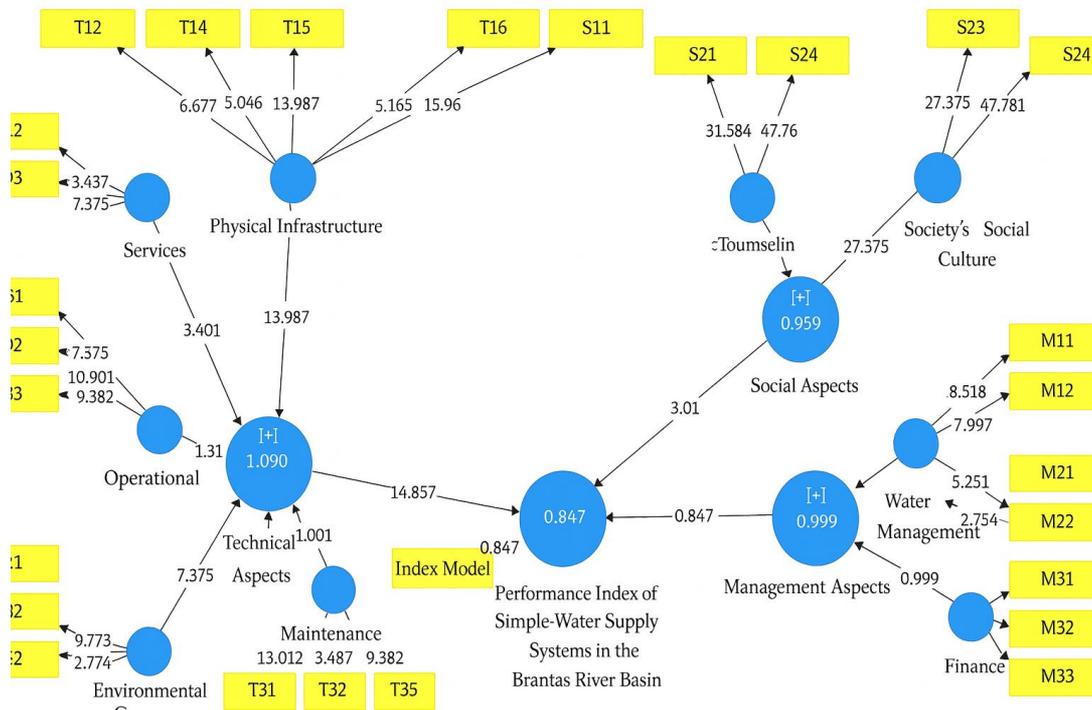
Figure 5. Path diagram of the performance index model for simple water supply systems in the Brantas River Basin

Non-Linear Generalized Reduced Gradient (GRG) Method for Performance Evaluation

To refine the performance index and address potential non-linear interactions among dimensions, the study employed a Generalized Reduced Gradient (GRG) optimization method. This technique enables the model to achieve an optimal allocation of weights for the technical, social, and managerial dimensions in a non-linear framework. Such an approach has been widely used in multi-objective optimization of infrastructure systems (Lasdon et al., 1978), as it provides a more realistic representation of interdependencies between variables than linear models.

The GRG process confirmed that the technical dimension encompassing infrastructure reliability, water supply efficiency, and system condition is the most influential component, with an optimized weight of 0.7833. This is an indicator of the central role played by infrastructure in ensuring the optimal functioning of decentralized water systems (Li et al., 2023). Sensitivity analysis revealed that improvements in technical scores produced the most significant gains in the overall performance index, underscoring the need for investments in infrastructure renewal, preventive maintenance, and technology upgrades. Systems with newer, well-maintained infrastructure consistently outperformed those relying on outdated facilities, confirming the central role of asset quality in determining service reliability.

The social dimension including community participation, social capital, and user satisfaction received an optimized weight of 0.1011. While this contribution is quantitatively smaller, its qualitative importance is substantial. SiPAS systems located in rural regions with strong community involvement scored significantly higher on this dimension, demonstrating that active local participation enhances system resilience and ensures higher user satisfaction. This result supports (Tesfay et al., 2024), who found that community engagement in decentralized water projects fosters accountability, encourages cost sharing, and strengthens overall system governance.

The managerial dimension covering operational management, financial planning, and regulatory compliance was assigned a weight of 0.1156. This reflects the considerable but secondary influence of managerial capacity on performance. Systems with robust institutional frameworks, transparent financial mechanisms, and trained personnel displayed superior outcomes. That governance quality is indispensable for ensuring sustainability, especially in community based water management models (Mishra, 2019). These results suggest that managerial interventions, such as capacity building for local committees and enhanced financial oversight, can substantially improve system reliability and user trust. The optimal coefficients were obtained through the GRG optimization process were α = 0.7833, β = 0.1011, and γ = 0.1156. The final performance model integrated these weighted coefficients, offering a

comprehensive performance index for each SiPAS system, formulated as:

$$IK_{SiPAS} = 0.7833 \times IK_{Technical} + 0.1011 \times IK_{Social} + 0.1156 \times IK_{Management} \qquad (4)$$

The final performance scores ranged from 0.45 to 0.95, highlighting significant disparities across the 31 SiPAS systems. Some high-performing systems combined modern infrastructure with engaged communities and strong governance, whereas low-performing systems were typically characterized by aging infrastructure, limited participation, and weak institutional support.

Validation of the Performance Model

The findings highlight that technological infrastructure reliability and maintenance exert a moderate yet significant influence on the effectiveness of decentralized water supply systems (Bahri et al., 2023; Supardiono et al., 2023). While the adoption of advanced technologies can optimize operations, these benefits are limited when the underlying infrastructure is poorly maintained. Thus, technology alone cannot ensure sustainability; it must be complemented by robust maintenance regimes and integrated management practices to achieve consistent and reliable service delivery (Kong & Simonović, 2018).

Furthermore, financial resources, operational efficiency, and management practices interact synergistically to underpin the sustainability and quality of water supply services. Adequate funding enables infrastructure upkeep and technology upgrades, while effective management ensures optimal resource allocation and operational resilience. This interdependence reinforces the need for holistic strategies that integrate economic, managerial, and technical domains to achieve long term service sustainability (Aigbavboa et al., 2023).

Improvements in technical capacity directly enhance water supply reliability and efficiency by reducing water losses, improving treatment processes, and streamlining distribution systems. However, these gains require integration with effective management and active community participation to fully realize their potential. Without such integration, technological enhancements risk underperformance and may fail to translate into sustainable outcomes (Bai et al., 2021).

To validate the robustness of the Integrated Performance Index Model (IPIM), this study compared the computed performance index with the field-based measurement index across multiple SiPAS locations using a Student's t-test. The hypothesis posited that there would be no statistically significant difference between the two indices, which would indicate that the model accurately reflects field conditions. The statistical

test confirmed this hypothesis, yielding a very small mean difference of 0.0581 with a t-value of 0.0418 and a p-value of 0.4835. Since the p-value exceeds the 0.05 threshold, these findings indicate that the model's predictions are statistically consistent with actual field measurements (Kępa, 2021). This result demonstrates the resilience and reliability of the model for evaluating real-world decentralized water systems and underscores its utility for guiding operational and policy decisions, as further detailed in Table 2.

Table 2. Findings from the student's t-Test on the Brantas River Basin's simple water supply systems performance index

Aspects	Calculated Performance Index	Field Performance Index
Average	64.01	63.95
Observations	25	25
Hypothesized Mean Difference	0.06	
Degree of Freedom	24	
t Stat	0.04	
t Critical	2.06	

Conclusion

This study developed and validated an Integrated Performance Index Model (IPIM) for SiPAS in the Brantas River Basin, integrating technical, managerial, and social dimensions with SEM–PLS and GRG-based weighting. The model showed strong explanatory power ($R^2 = 0.95$) and predictive reliability. Technical factors especially infrastructure condition and operational continuity dominated performance (72.1%), followed by managerial (26.7%) and social (15.1%) dimensions. The IPIM distinguished low- and high-performing sites and aligned with field-audit observations; a companion mobile app enables real-time monitoring and community feedback. Because the constructs are common to community-based decentralized supply, the IPIM is transferable to other contexts with minor localization of indicators and weights. The index supports prioritizing technical rehabilitation and continuity, strengthening Operation and Maintenance, financial planning, setting performance targets and budgets for local governments, and embedding transparent, continuous monitoring via the app. Findings reflect one watershed and exclude explicit environmental metrics. Future work should expand to multiple basins, integrate climate and water-quality resilience indicators, and use longitudinal data to refine weights and thresholds.

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