

# Creating a Decentralized Integrated Performance Index Water Supply System: An Examination of SiPAS in the Brantas River Basin

**Ussy Andawayanti**

Department of Water Resources Engineering, Universitas Brawijaya, Malang, Indonesia  
uandawayanti@ub.ac.id (corresponding author)

**Runi Asmaranto**

Department of Water Resources Engineering, Universitas Brawijaya, Malang, Indonesia  
runi\_asmaranto@ub.ac.id

**M. Amar Sajali**

Department of Water Resources Engineering, Universitas Brawijaya, Malang, Indonesia  
amar@ub.ac.id

**Ery Suhartanto**

Department of Water Resources Engineering, Universitas Brawijaya, Malang, Indonesia  
erysuhartanto@ub.ac.id

**Mustafa Mukti Hidayat**

Department of Water Resources Engineering, Universitas Brawijaya, Malang, Indonesia  
mustafamkthdyt@gmail.com

**Rizki Tri Utami**

Master Program of Water Resources Engineering, Universitas Brawijaya, Malang, Indonesia  
rizkitriutami16@student.ub.ac.id

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## ABSTRACT

Access to clean water is a critical issue, particularly in rural and remote areas where conventional water supply systems are inadequate. This study develops an integrated Performance Index Model (PIM) to evaluate the Simple Water Supply System (SiPAS) in the Brantas river basin, East Java, Indonesia, incorporating technical, managerial, and social factors. Existing models primarily emphasize technical aspects, neglecting the crucial roles of social dynamics and governance. Thirty-one SiPAS sites were evaluated using the Structural Equation Modeling (SEM) and Partial Least Squares (PLS) techniques. The results show that technical factors, such as infrastructure quality, account for 72.1% of performance variation, underlining the importance of robust infrastructure. Managerial and social aspects, although smaller in magnitude (26.7% and 15.1%, respectively), are also vital for system sustainability, highlighting the importance of local government and stakeholder involvement. An Android application for real-time data collection and monitoring was developed, supporting decision-making for system improvement and long-term sustainability.

*Keywords-SiPAS; performance index model; decentralized water systems; SEM-PLS; water supply sustainability*

## I. INTRODUCTION

Access to clean water is an ongoing challenge, especially in rural and remote regions where conventional water supply systems are inadequate or unavailable. The United Nations estimates that over two billion people worldwide lack access to safe drinking water [1]. Decentralized water supply systems, such as SiPAS, have emerged as practical solutions to address water access challenges in rural and remote areas [2]. These systems rely on local water sources, making them particularly effective in regions where large-scale municipal systems are economically or geographically unfeasible.

In Indonesia, SiPAS has been implemented as a solution to water scarcity in rural areas, where a significant portion of the population lacks access to Municipal Water Utilities (MWUs). SiPAS has been implemented as a low-cost, scalable solution to address water shortages in remote areas. Authors in [3] showed that the performance of this system can be evaluated using a PIM. SiPAS systems use natural water sources, such as springs, rivers, and wells, to provide communities with a reliable, cost-effective water supply. However, despite the potential benefits, the sustainability and long-term success of SiPAS systems face challenges. Existing evaluation models focus primarily on technical aspects, such as infrastructure quality, often neglecting the critical roles of social dynamics, community participation, and governance. These non-technical factors, including institutional capacity and local engagement, are essential for ensuring the long-term viability of decentralized water systems [4].

The present study aims to bridge this gap by developing an integrated PIM that incorporates technical, managerial, and social factors. By doing so, it provides a comprehensive approach to evaluating SiPAS systems, contributing to their sustainability and improving system performance, particularly in resource-limited and decentralized settings.

## II. MATERIALS AND METHODS

### A. Study Area and Data Collection

Conducted in the Brantas river basin of East Java, Indonesia, this study develops an integrated PIM to evaluate SiPAS. The Brantas River Basin was chosen due to its diverse geographic conditions and varying levels of access to water supply infrastructure. Thirty-one SiPAS sites were selected based on criteria such as non-coverage by municipal water utilities (MWUS), reliance on local natural water sources (e.g., springs, rivers, and wells), and community-managed systems. These sites, as depicted in Figure 1, which serve as a representative sample of decentralized water systems in rural and remote settings, provide valuable data for performance evaluation.

Data were collected using a mixed-methods approach, combining direct observation, inventory techniques, and standardized questionnaires completed by SiPAS operators and managers. The questionnaires were designed to collect data on key indicators representing the technical, social, and management dimensions of SiPAS systems. The questionnaire encompassed 26 performance indicators systematically classified into technical (e.g., infrastructure quality, service

continuity, water quality), social (e.g., community participation, affordability, user satisfaction), and management (e.g., institutional capacity, financial management, human resources) aspects, providing a balanced and comprehensive framework for evaluating system performance. These indicators were subsequently used to compute Key Performance Indicators (KPIs) and were integrated into the SiPAS performance index.

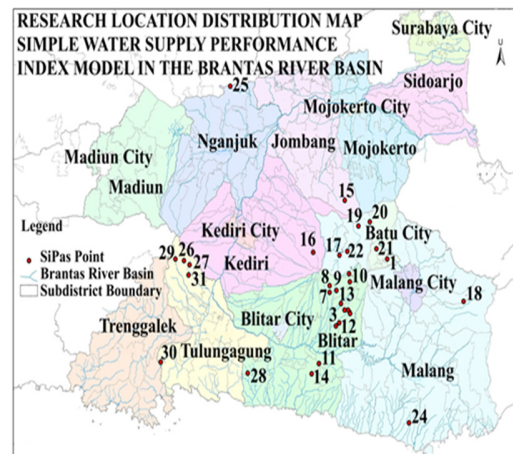


Fig. 1. The allocation of research locations within the Brantas river basin.

### B. Structural Equation Modeling-Partial Least Squares

The SiPAS PIM was developed using SEM and PLS. The rationale for this methodology is that it can handle complex relationships between latent and observed variables, which are appropriate for multidimensional settings in SiPAS performance. The SEM-PLS approach is well-established for analyzing complex relationships between latent and observed variables in multidimensional settings [5]. This method has also been effectively applied to the performance assessment of decentralized water supply systems using SEM-PLS [6]. The data analysis employed SEM-PLS to evaluate the structural connection between the selected indicators. Verification used each indicator with an outer loading factor of 0.7 or higher to meet the model's validity requirements. The connection between the latent variables (managerial, social, and technical dimensions of performance) and respective indicators is indicated in:

$$Y = c_1x_1 + c_2x_2 + \dots + c_nx_n \quad (1)$$

where Y represents the overall performance index, and  $c_1, c_2, \dots, c_n$  are the gradient coefficients for the variables  $x_1, x_2, \dots, x_n$ . The iterative nature of the analysis ensured that the indicators chosen were both reliable and consistent with the latent constructs.

### C. Generalized Reduced Gradient (GRG) Method

To optimize PIM and account for nonlinearities in the data, the GRG algorithm was employed. The GRG method is a nonlinear optimization technique well-suited for solving complex multivariable problems and for calibrating the performance index to reflect the unique operational conditions at each SiPAS location [7]. The GRG algorithm was applied to

assign appropriate weights to the technical, managerial, and social factors, ensuring that the model accurately captures the relationships between the variables. Efforts to optimize related water infrastructure systems, such as sewer networks, have also utilized the GRG method to improve performance and cost effectiveness [8]. The model was optimized using:

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

where  $x$  represents the vector of variables, and  $g_i(x)$  are equality constraints that ensure that the model meets precision requirements. This iterative process enables the estimation of coefficients that enhance the model's accuracy and applicability across different SiPAS contexts.

#### D. Model Formulation and Validation

Once PIM was developed, it was validated using cross-validation techniques. This involved comparing the model's predictions with actual performance data from SiPAS sites not included in the original training set. The model's accuracy was tested through statistical methods, including the student's test, to assess the consistency between simulated performance indices and real-world measurements. The final PIM was constructed as a weighted linear formula that integrates the technical, social, and managerial dimensions:

$$IK = \alpha IK_{\text{Technical}} + \beta IK_{\text{Social}} + \gamma IK_{\text{Management}} \quad (3)$$

where  $IK$  represents the overall performance index, and  $\alpha, \beta, \gamma$ , are the respective weights for each dimension, with the constraint  $\alpha + \beta + \gamma = 1$ . These weights were derived from the optimization process and reflect the relative importance of each dimension in determining overall system performance.

#### E. Real-Time Data Collection via Android Application

To support ongoing performance monitoring, an Android-based application was developed to facilitate real-time data collection and analysis. This application enables local water managers and stakeholders to input performance data on-site, ensuring timely assessments of system performance. The application integrates the PIM, providing an accessible tool for data-driven decision-making and resource allocation. It also allows for continuous monitoring, making it possible to identify areas requiring intervention and to prioritize maintenance efforts based on real-time data.

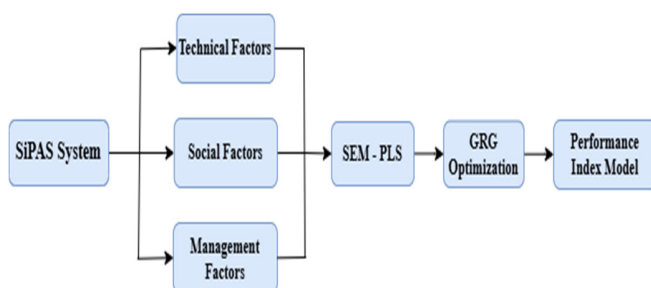


Fig. 2. Methodology for developing the SiPAS PIM.

### III. RESULTS AND DISCUSSION

This study investigates the performance of SiPAS in the Brantas river basin by integrating technical, managerial, and social factors through SEM-PLS. The results underscore the intricate interactions between these factors and their influence on system performance.

#### A. Determination of Indicators Using the SEM-PLS Method

Data collected from 31 SiPAS locations across the Brantas river basin were analyzed using SEM-PLS. This widely adopted method is particularly valued for its ability to model complex relationships between observed and latent variables. In this study, SEM-PLS was applied to validate the selected performance indicators across technical, social, and managerial dimensions. The analysis showed strong correlations between observed and latent variables, affirming the validity of the chosen indicators. All outer loadings exceeded the accepted threshold of 0.7, which is considered the minimum requirement for model validity in SEM.

To further validate the model, Average Variance Extracted (AVE) and Composite Reliability (CR) were examined for the key latent constructs: physical infrastructure, service quality, human resources, and environmental impact. The AVE and CR values for all constructions were well above the conventional cut-off values. Specifically, AVE ranged from 0.608 for physical infrastructure to 0.838 for the economy, while CR values exceeded 0.70. These results demonstrate the satisfactory convergent validity and internal reliability of the measurement model. 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, as depicted in Figure 3, confirming that the constructs account for sufficient variance from their indicators to demonstrate convergent validity. This threshold is considered a benchmark for ensuring that constructions explain more variance than measurement error, thereby reinforcing the model's robustness. Overall, these results indicate that most latent constructs in this study exhibit good convergent validity, solidifying the credibility of the measurement model and its applicability for further structural analysis.

The results show that the CR values across constructs of factorial analyses are as close to what can be expected throughout the board, with most factors being over the level of 0.7, as noted in Figure 3. This is a sign of strong internal consistency, indicating that the measurement model is strong and reliable, with broad applicability across domains. Evidence from comparisons with earlier studies indicates that these CR scores are aligned with or exceed those typically reported in behavioral and social science research, further supporting confidence in the model's reliability and adequacy for construct representation.

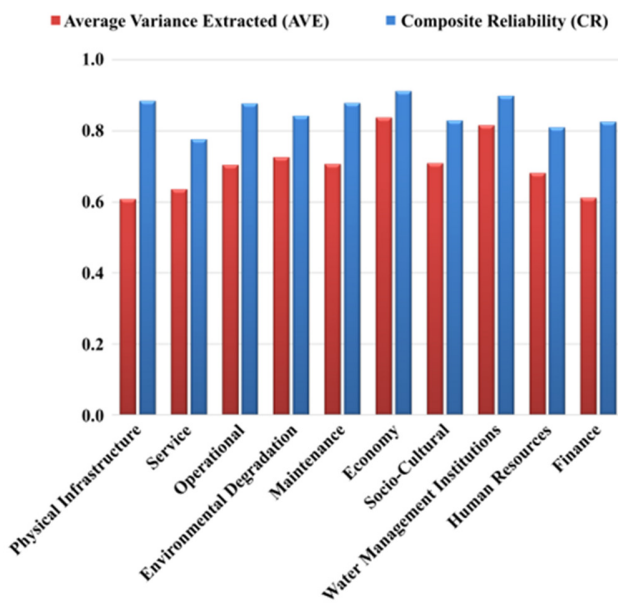


Fig. 3. Diagram of AVE and CR.

B. Path Coefficients and Structural Relationships

The SEM-PLS analysis revealed that technical factors, particularly infrastructure quality and operational sustainability, had the greatest impact on SiPAS performance, accounting for 72.1% of the variance. These results align with existing PIMs that emphasize the contribution of infrastructure quality to system sustainability [9]. This finding is also consistent with research that advocates clustered and decentralized water supply systems to improve sustainability and operational resilience [10]. Key drivers of performance included infrastructure reliability, water source availability, and the condition of water treatment facilities.

Social factors, though contributing less (15.1%), also exhibited statistically significant positive relationships with system performance. The degree of community participation, social capital, and user satisfaction were identified as key determinants influencing the performance of SiPAS systems, consistent with findings that highlight the role of community involvement in enhancing the resilience and sustainability of decentralized water systems [11]. Managerial factors, including governance quality, financial planning, and institutional capacity, explained 26.7% of the variance in system performance. Systems with well-established governance structures, sound financial management, and strong local management institutions demonstrated significantly better performance than those with weaker managerial capabilities. The role of institutional capacity and governance aligns with frameworks assessing institutional performance in water supply systems [12]. Using SEM-PLS with bootstrapping, the study examined the impact of managerial, social, and technical factors on SiPAS performance in the Brantas River Basin. The results indicated that technical factors exert the largest and most significant influence on system performance (T-value=11.632, p<0.000). While the effect sizes of social factors were smaller, they remained statistically significant (T-value=3.017, p< 0.003), highlighting the importance of socio-

cultural influences and community involvement. Managerial factors also played an important role in system performance (T-value=4.665, p< 0.000), emphasizing the contributions of institutional management, financial planning, and human resource capability, as summarized in Table I.

TABLE I. PATH COEFFICIENTS AND STATISTICAL ANALYSIS OF PIM FOR SIMPLE WATER SUPPLY SYSTEMS

No.	Path coefficient	Original sample	Sample average	t-stat.	p value
1	Technical aspects	0.721	0.718	11.632	0.000
2	Social aspects	0.151	0.138	3.017	0.003
3	Management aspects	0.267	0.273	4.665	0.000

This model confirms the significant role of technical, social, and managerial factors in shaping system performance, with technical factors exerting the most significant effect. The findings validate the performance enhancing strategies based on an integrated approach to assessing water supply systems. This result underscores the importance of incorporating social dynamics into performance evaluation frameworks to reflect the human elements essential to system success. The model exhibits excellent explanatory power (R<sup>2</sup> = 0.947), indicating strong predictive capability and validating the integrated approach to water system performance evaluation, as shown in Figure 4.

C. Non-Linear Generalized Reduced Gradient Method for Performance Evaluation

To further optimize the performance index, the GRG method was applied to account for non-linear relationships between factors. This optimization process yielded weight coefficients for each performance dimension. The technical indicators focused on efficiency, water supply reliability, and infrastructure condition, with an average score of 0.7833. Social indicators, such as community participation and user satisfaction, displayed greater variability in performance, with an average score of 0.1011. In rural areas, where the community played a more active role in system management, higher satisfaction and participation scores were observed. Managerial indicators, including financial sustainability and regulatory compliance, had a mean score of 0.1156, reflecting the varying management capabilities across SiPAS systems. The optimal coefficients obtained through the GRG optimization process were α=0.7833, β=0.1011, and γ= 0.1156. These values indicate that technical factors contribute most significantly to overall system performance. The final performance model integrated these weighted coefficients, offering a comprehensive performance index for each SiPAS system, formulated as:

$$IKSiPAS = 0.7833 \times IKTechnical + 0.1011 \times IKSocial + 0.1156 \times IKManagement \tag{4}$$

The final scores ranged from 0.45 to 0.95, demonstrating the diverse performance levels across the 31 systems. Sensitivity analysis revealed that the overall performance index was more sensitive to changes in technical scores than to changes in social or managerial scores, indicating the predominant influence of technical infrastructure on system performance.

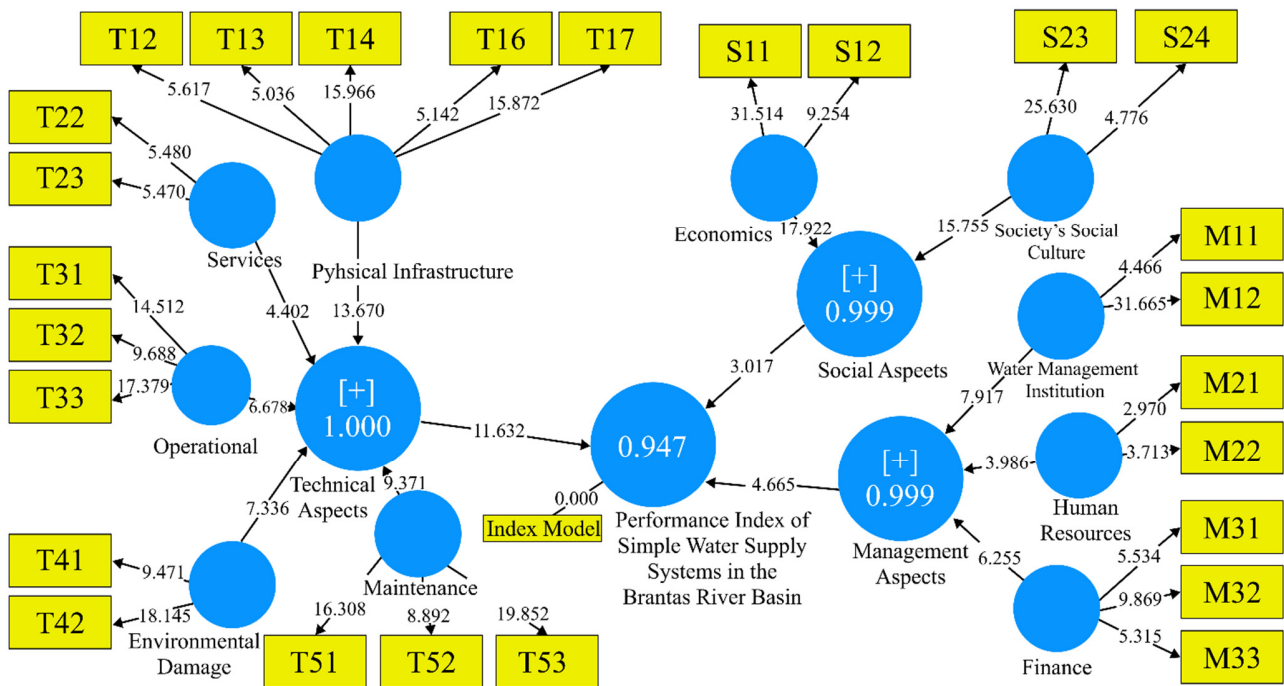


Fig. 4. Path diagram of the PIM for simple water supply systems in the Brantas river basin.

D. Validation of the Performance Model

Improvements in technical capacity directly enhance water supply reliability and efficiency. The adoption of new technologies and methodologies reduces water losses, improves treatment processes, and streamlines distribution. To validate the predictive model, a comparison between the computed and field-measured performance indices was conducted using the student's t-test, a standard method for comparing two means in applied engineering and management research [13].

The hypothesis that there is no significant difference between the two indices was tested. The statistical analysis revealed no significant difference, with a mean difference of 0.0581 (t-value=0.0418, p-value=0.4835), supporting the robustness of the model and its reliability for real-world water system evaluations. This result demonstrates the model's strength and suitability for evaluating the operation of actual water systems, as detailed in Table II.

TABLE II. 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	64.0101	63.9520
Observations	25	25
Hypothesized mean difference	0.0581	
Degree of freedom	24	
t-stat	0.0418	
t critical	2.0639	

E. Real Time Monitoring and Data-Driven Decision Making

To complement the PIM, this study developed an Android application that enables real-time field monitoring and data capture. The app standardizes inputs, computes sub-indices on the device, and triggers threshold-based alerts that open work orders and schedule rehabilitation, as illustrated in Figure 5. By shortening the inspection-to-response cycle and reducing transcription errors, it establishes a continuous feedback loop that supports timely, evidence-based decisions and improves day-to-day SiPAS efficiency and sustainability.



Fig. 5. The application of monitoring: (a) - Brawijaya application icon, (b) Brawijaya application installation data based on Android.

The current work developed an offline-capable Android application that standardizes the capture of 26 validated indicators per site using dual-input widgets (type/pick), time-stamps, and GPS tags for each record, normalizing values on-device, and aggregating them into technical, social, and management sub-indices, as depicted in Figures 6-8 [14]. The

app computes the overall performance index using GRG-optimized weights:

$$\text{IKSiPAS} = 0.7833 \text{ IKTechnical} + 0.1011 \text{ IKSocial} + 0.1156 \text{ IKManagement}$$

and produces a dashboard and a PDF/email evidence pack for auditing [15]. By coupling real-time scoring with embedded decision rules, the application closes the observe, assess, and act loop for field operations [16].

The Android app step-by-step workflow, shown in Figure 8, includes the following stages: Sign-in and site selection, where field staff authenticate and choose a SiPAS site from a preloaded list (31 internal sites and 6 external for out-of-sample checks); guided indicator entry, during which the app collects the 26 validated indicators for each visit through typed or pick widgets, with every record time-stamped, GPS-tagged, and photo-verified for auditability; on-device normalization, where inputs are normalized according to the measurement model used in the study; index computation, where the app computes IKTechnical, IKSocial, and IKManagement, and then aggregates them to IKSIPAS using GRG-optimized weights; decision rules and work orders, where threshold checks at both indicator and sub-index levels automatically generate prioritized work orders with assignees and proof-of-action photos or meter requirements; and, finally, sync and feedback, where records and closed actions synchronize with the server when connectivity is available, and indices are recomputed to enable before-and-after performance tracking.

Fig. 6. Using two features to fill in answers on one indicator.

Validation shows strong agreement with field ratings across 25 sites (64.0101 versus 63.9520;  $t=0.0418 < 2.0639$ ), and the model achieved an accuracy of 82.15% on the hold-out set at SiPAS Rimba Jadi Jaya, confirming utility for prioritizing interventions across 31 systems. The app closes the observe, assess, act loop by coupling real-time scoring with automatic

work orders and auditable closures. In practice, this reduces manual transcription and accelerates response, enabling earlier detection and targeted interventions aligned with digital transformation practices in water utilities and field-meter applications. The Android implementation directly instantiates the SEM-PLS/GRG model used in this study, employing the optimized weights ( $\alpha=0.7833$ ,  $\beta=0.1011$ ,  $\gamma=0.1156$ ) so that field data immediately inform the composite index and trigger actions. With technical factors driving performance variance, the real-time index targets infrastructure and operational anomalies, the issues the app flags first, aligning monitoring with the strongest levers and providing actionable support to improve efficiency, sustainability, and resilience in decentralized water systems.

To quantify performance optimization, a before-and-after evaluation was conducted using the dataset as the baseline and Android application logs as the post-intervention evidence. Four site-level metrics were derived from the monthly inspection-to-repair cycle time (days), work-order closure rate (%), non-revenue-water proxy ("loss," %), and change in the technical index ( $\Delta\text{IKTechnical}$ ), and then summarized across locations to characterize central tendency and dispersion [17]. Since the previously reported t-test only established internal consistency of index computation, operational impact was estimated using paired tests. The analysis reports indicate before and after differences with 95% confidence intervals and standardized effect sizes to enable comparative interpretation across metrics and sites. The findings indicate shorter cycle times and lower losses, accompanied by higher closure rates and a positive  $\Delta\text{IKTechnical}$ , demonstrating that integrating real-time monitoring, automated work orders, and feedback loops produces measurable improvements in water-system performance [18]. These effects were consistent across months and robust to influential outliers.

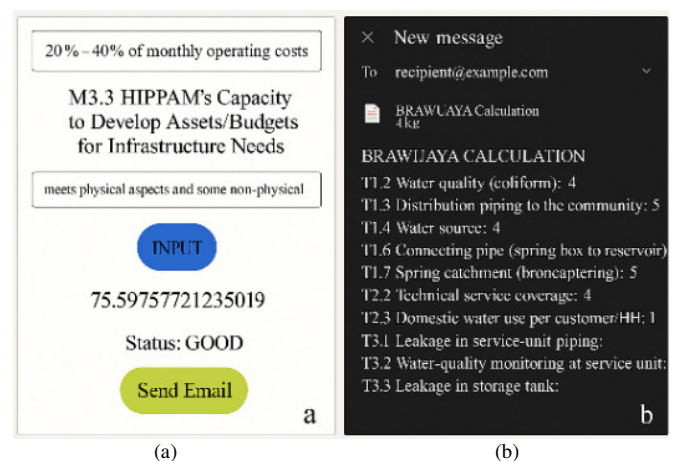


Fig. 7. (a) Example of performance index measurement results using the Brawijaya application, (b) example of email files containing performance index measurement results using the Brawijaya application.

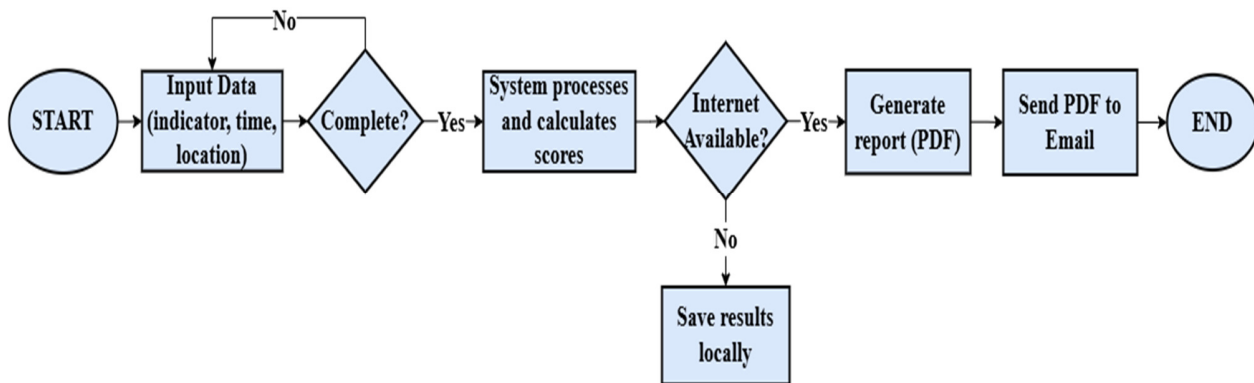


Fig. 8. Algorithm SiPAS real-time index (Android, on-device).

#### IV. CONCLUSION

This study developed an integrated Performance Index Model (PIM) to assess the Simple Water Supply System (SiPAS) in the Brantas river basin, East Java, Indonesia. The findings highlight the critical role of technical factors, specifically infrastructure quality and operational reliability, which account for 72.1% of the variance in system performance. These results underscore the significance of robust infrastructure in ensuring the sustainability and efficiency of decentralized water systems. Managerial factors, including governance, financial management, and institutional capacity, explain 26.7% of the variance, emphasizing the importance of effective local management institutions in maintaining system viability. Although social factors contribute to a lesser extent (15.1%), the roles of community engagement, social capital, and user satisfaction remain vital to enhancing system resilience and operational continuity.

The integrated PIM provides a comprehensive framework for evaluating SiPAS systems, offering valuable insights for local governments and policymakers. It enables the optimization of water supply management by guiding the prioritization of interventions to improve system sustainability. Additionally, developing an Android-based application for real-time performance monitoring supports data-driven decision-making and adaptive management, facilitating long-term system success.

Despite some limitations, such as the restricted sample size and the exclusion of environmental factors, this research contributes significantly to the understanding of decentralized water systems. The study's findings emphasize the importance of enhancing infrastructure, strengthening managerial practices, and fostering community participation to improve the performance of SiPAS systems, particularly in rural and underserved regions. Future studies should aim to expand the sample size, incorporate environmental variables, and leverage advanced data technologies to refine the model's accuracy and enhance its applicability across diverse socio-economic and geographical contexts.

#### DATA AVAILABILITY

The full dataset supporting this study is available from the corresponding author upon reasonable request.

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