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Original Research

Effect of Sustainable Groundwater Resource Management on Groundwater Sustainability Performance: A PLS-SEM Study in Probolinggo Regency

Faradlillah Saves[1,4], Mohammad Bisri[2], Hari Siswoyo[2] and Muhammad Sasmito Djati[3]

[1] Postgraduate Study of Environmental Science, Brawijaya University, East Java, Indonesia

[2] Department of Water Resources Engineering, Brawijaya University, East Java, Indonesia

[3] Department of Biology, Brawijaya University, East Java, Indonesia

[4] Department of Civil Engineering, University of 17 Agustus 1945 Surabaya, East Java, Indonesia

† Corresponding author: Faradlillah Saves; farasaves@student.ub.ac.id

ORCID IDs Authors: 0000-0002-8969-842X; 0000-0002-9296-3626; 0000-0001-9460-5649; 0000-0002-1245-2528

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Abstract: Groundwater, as a vital resource, is facing a crisis in Probolinggo Regency due to rapid industrialization and land conversion, both of which threaten the groundwater sustainability performance. This study aims to quantitatively identify the dominant factors among six aspects of sustainable groundwater resource management and to quantify their causal influence, both positive and negative, on the groundwater sustainability performance. A quantitative approach with an explanatory survey design was used, and analysis was conducted through Partial Least Squares-Structural Equation Modeling (PLS-SEM) involving data from key stakeholders. The results show that the model possesses very high predictive power ($R^2 = 0.925$), revealing two contrasting dominant factors. Utilization (X6) has the strongest and statistically significant positive effect ($\beta = 0.57$; $P = 0.004$), driven by technological innovation, while Implementation (X2) exhibits a significant negative effect ($\beta = -0.54$; $P = 0.049$). This negative coefficient provides empirical confirmation of a critical "policy-practice gap," suggesting that weaknesses in human resource capacity and inconsistent budgetary support during the execution phase significantly hinder overall sustainability performance. Consequently, this study concludes that the greatest challenge to achieving sustainable groundwater management lies in policy execution failure rather than in the planning stages. The policy implications call upon the local government to prioritize investment in technological innovation for utilization (X6) and to immediately undertake structural reforms and budget auditing within the implementation phase (X2) to bridge the gap between policy intent and actual sustainability outcomes.

INTRODUCTION

Groundwater, as a vital resource supporting human life and environmental sustainability, is now facing a global crisis due to increasing depletion and pollution (Aloui et al. 2023, Bierkens & Wada 2019). Groundwater is generally stored in specific types of aquifers, including unconfined and confined aquifers (Darsono, 2016). Indonesia possesses significant groundwater potential that varies according to local hydrogeological conditions, and many people, especially local communities, rely on it to meet their daily needs (Kusumaningrum et al. 2024). In addition, groundwater plays a critical role in both agriculture and industry, which represent the largest portions of total water requirements, with agriculture alone often accounting for approximately 70% of total usage. Globally, according to FAO (2018), groundwater extraction has increased drastically by more than 300% in the last 50 years (1960–2010) (Barati et al. 2019).

Probolinggo Regency is experiencing rapid industrial development, which directly causes land conversion. The consequence of this conversion is a threat to Groundwater Sustainability Performanceand a reduction in the water absorption capacity, which directly challenges the sustainability performance of the local groundwater resource management. Data from the Central Bureau of Statistics (BPS) indicate that residential land (built-up area) currently accounts for only 2.24% of the total land area. However, the accelerating pace of industrialization suggests that land conversion from water catchment zones will continue to increase. This change in land use causes rainwater that should infiltrate the soil to instead flow as surface runoff (Aryanto & Hardiman 2017), making groundwater recharge zones within aquifers highly vulnerable. When this recharge function is disrupted, the balance of local groundwater becomes threatened, ultimately exacerbating the groundwater crisis.

Previous studies on water resources in this region generally focused on macro-level analyses of water availability or mapping land use as a physical factor influencing infiltration (Widodo 2013). A study by Khalimi and Kusuma (2018) identified a significant gap in assessing groundwater resource sustainability from management and regulatory perspectives. The sustainability of groundwater performance depends strongly on multidimensional interactions among management aspects; however, existing literature has not adequately quantified the structural relationships among management variables such as planning, implementation, monitoring and evaluation, conservation, damage control, and utilization.

The core problem addressed by this study is the critical difficulty local governments face in prioritizing effective interventions for sustainable groundwater management. This difficulty stems from the absence of a clear, structural model that quantitatively identifies which specific managerial, institutional, and technical factors (among the six established dimensions) are the dominant drivers of performance. Using the PLS-SEM model, this study aims to quantitatively analyze these causal relationships and determine the effect of the management variables on the Groundwater Sustainability Performance. This causal analysis is urgent for providing local governments with the necessary evidence to prioritize appropriate interventions and achieve long-term sustainability.

Therefore, the novelty of this research lies in its comprehensive structural interaction analysis between six aspects of sustainable groundwater resource management and the groundwater sustainability performance. The study seeks to quantify the causal relationships among the dominant influencing factors. This includes identifying both the positive and potential negative effects of management variables on Groundwater Sustainability Performance in Probolinggo Regency. These findings are significant because they provide precise empirical evidence of the driving and inhibiting factors. This evidence, in turn, forms a sound basis for developing measurable and effective local policy recommendations.

MATERIALS AND METHODS

Study Area and Duration

This study was conducted within the administrative boundaries of Probolinggo Regency, which serves as the primary unit of analysis for evaluating Groundwater Sustainability Performance. The regency covers a total area of 1,639 km^2. The groundwater resources utilized in this region consist of unconfined aquifers (Q1) producing approximately 711 million m^3 per year and confined aquifers (Q2) yielding about 124 million m^3 per year. The choice of the administrative boundary is essential for this study, as it aligns with the jurisdictional scope of policy implementation and resource management. The study area is shown in Fig. 1.

The research was carried out over a one-year period (September 2024 - September 2025). The study comprised several stages, including field surveys, literature review, on-site observations and semi-structured interviews, assessment of groundwater management practices, and quantitative analysis of the influence of sustainable groundwater management on groundwater sustainability performance.

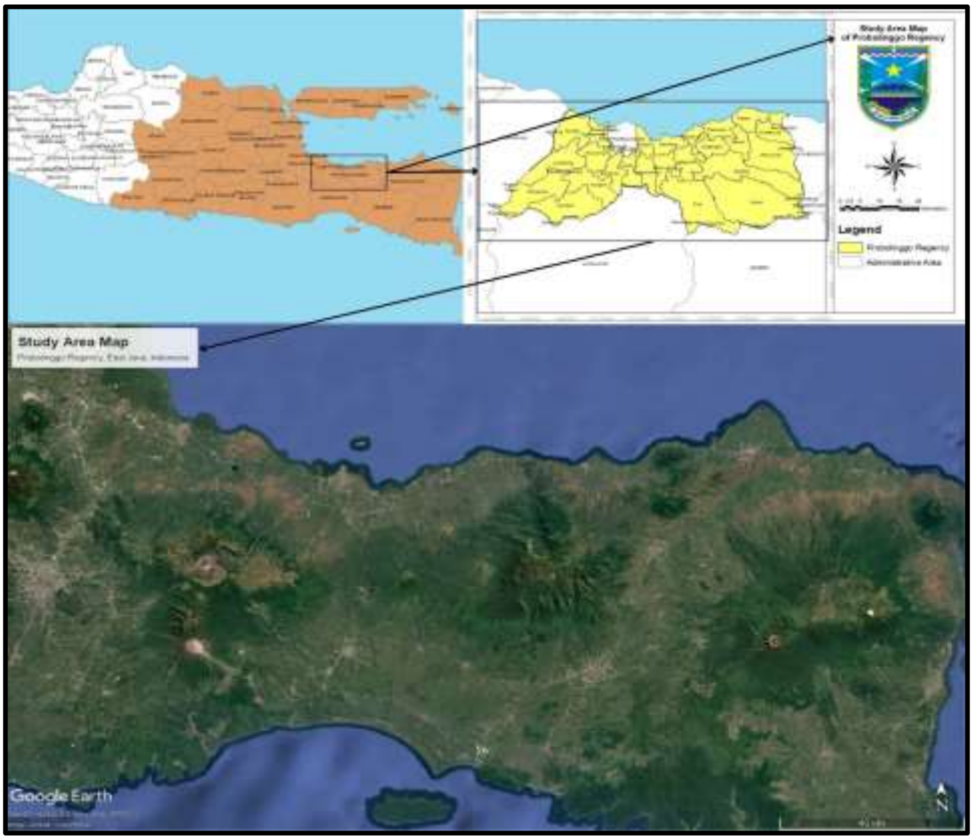

Fig. 1. Study area.

Source: Decree of the Minister of Energy and Mineral Resources No. 1451K/10/MEM/2000

Research Design and Methodology

This study employs a quantitative research design with an explanatory survey approach to analyze causal mechanisms in groundwater management. To align with the study's focus on policy effectiveness, Groundwater Sustainability Performance (GSP) is operationalized as a latent construct measured through perception-based indicators from key stakeholders rather than physical hydrogeological observations. The primary analytical tool is Partial Least Squares Structural Equation Modeling (PLS-SEM), selected for its robustness in handling non-normal data distributions and exploratory causal models (Sofyani 2025).

The analysis follows a two-stage evaluation: the measurement model to ensure construct integrity and the structural model to test hypothesized relationships. The measurement model is evaluated through construct reliability (Cronbach's Alpha and Composite Reliability) and construct validity, comprising convergent validity (AVE) and discriminant validity. Detailed procedures for sampling and the specific thresholds for these tests are elaborated in the subsequent subsections.

Population and Sample

The study population comprised stakeholders directly involved in the planning, utilization, conservation, and supervision of sustainable groundwater resource management in Probolinggo Regency. These included:

1. Heads of Provincial and Regency/Municipal Offices of Energy and Mineral Resources (ESDM)
2. Heads of Groundwater Development and Management Projects in East Java
3. City-level technical policymakers from BAPPEDA, Public Works Department, Tourism Department, PDAM, and the Environmental and Forestry Department

Sampling was conducted using a non-probability purposive sampling approach. The minimum sample size was determined based on power analysis criteria and general PLS-SEM rules of thumb to ensure adequate statistical representation of key stakeholder groups.

Sampling Technique

Primary data were collected using a structured questionnaire designed to measure all research variables on a five-point Likert scale ranging from Strongly Disagree (1) to Strongly Agree (5) (Koo & Yang 2025). The questionnaires were distributed directly to selected respondents through official coordination channels and in-person meetings.

Research Variables

The independent variables represent six key aspects of sustainable groundwater resource management, each measured using specific indicators:

1. Planning (X1),
2. Implementation (X2),
3. Monitoring and Evaluation (X3),
4. Conservation (X4),
5. Damage Control (X5), and
6. Utilization (X6)

The dependent variable (Y) is the Groundwater Sustainability Performance, representing the overall outcome of sustainable groundwater resource management. To validate the theoretical constructs of the latent variables (X and Y) with empirical data collected through the questionnaire, Table 1 presents their operational definitions.

Table 1. Operational definitions of variables.

Variable	Operational Definition
X1: Planning	Planning is the process of setting policies and plans for the allocation of sustainable groundwater resources. Its effectiveness is measured based on the level of involvement of key stakeholders, including government, private sector, and civil society, in developing plans to achieve groundwater basin sustainability (Bryła et al. 2025).
X2: Implementation	Implementation is the effectiveness of enforcing policies, programs, and regulations in the field. This effectiveness is measured by the conformity of actions with policy targets. It can be improved through integration of ISO 14000-based Environmental Management Systems (EMS) as a decision-making tool, which critically includes impact identification, pollution control schemes, and Environmental Action Plans (EAP) (Farouk et al. 2024).
X3: Monitoring and Evaluation	Monitoring and evaluation is the systematic process of measuring the performance of sustainable groundwater management and comparing it with targets. This includes field mapping and recording coordinates of hydrogeological points of interest (Putranto et al. 2020). Success is measured by transparency of reporting results and use of evaluations as adaptive input for policy regulation adjustments.
X4: Conservation	Conservation involves the application of structural (physical) and non-structural (policy) measures to maintain and restore the quality, quantity, and environmental carrying capacity that define Groundwater Sustainability Performance (GSP). The intensity of these efforts is measured through conservation programs, the adoption of water-saving (efficiency) technologies, and strategic initiatives to restore infiltration areas. Regarding quality aspects, GSP is further supported by the capacity to monitor a wider range of water-quality parameters, which can be optimized through increasing the number of spectral bands and refining analytical algorithms (Ma et al. 2023).
X5: Damage Control	Damage control refers to mitigation and adaptation efforts focused on safeguarding Groundwater Sustainability Performance and infrastructure from water-related damage risks, such as floods, saltwater intrusion, and drought. It encompasses practical preventive measures and sustainable mitigation strategies, including early warning systems and groundwater flow protection zoning, to enhance resilience against the impacts of irregular weather patterns caused by climate change (Abbass et al. 2022).
X6: Utilization	Utilization refers to the management practices governing groundwater use to ensure efficient and equitable resource allocation. Guided by the relevant Ministerial Regulations of Energy and Mineral Resources, these practices are a primary driver in achieving Groundwater Sustainability Performance. The objective is to guarantee long-term groundwater availability and provide optimal socio-economic benefits in a sustainable manner (Rifai 2022).
Y: Groundwater Sustainability Performance	Groundwater Sustainability Performance reflects the achievement of sustainable ecological and hydrogeological functions, indicated by the absence of undesirable results such as water level instability, seawater intrusion, or land subsidence. Conceptually, this performance can be verified using a physics-based groundwater model-grounded in Darcy's Law and the Continuity Equation-combined with a management model to assist in sustainable groundwater resource planning and decision-making (Yeh 2015).

Instrument Validity and Reliability Tests

Instrument validity was tested using Confirmatory Factor Analysis (CFA) to assess convergent validity (Average Variance Extracted, AVE ≥ 0.50) and discriminant validity (by comparing the square root of the AVE with inter-variable correlations).

Instrument reliability was evaluated through Composite Reliability (CR ≥ 0.70) and Cronbach's Alpha (Amalia et al. 2023), ensuring internal consistency among indicators for each latent construct.

Hypothesis Formulation

The significance of relationships between latent variables was examined through the following hypotheses:

- $H_0 : \beta_1 = 0$ - Planning (X1) does not significantly influence the Groundwater Sustainability Performance (Y)
  $H_1 : \beta_1 \neq 0$ - Planning (X1) significantly influences the Groundwater Sustainability Performance (Y)

- $H_0 : \beta_2 = 0$ - Implementation (X2) does not significantly influence the Groundwater Sustainability Performance (Y)
  $H_1 : \beta_2 \neq 0$ - Implementation (X2) significantly influences the Groundwater Basin Function (Y)

- $H_0 : \beta_3 = 0$ - Monitoring and Evaluation (X3) do not significantly influence the Groundwater Sustainability Performance (Y)
  $H_1 : \beta_3 \neq 0$ - Monitoring and Evaluation (X3) significantly influence the Groundwater Sustainability Performance (Y)

- $H_0 : \beta_4 = 0$ - Conservation (X4) does not significantly influence the Groundwater Sustainability Performance (Y)
  $H_1 : \beta_4 \neq 0$ - Conservation (X4) significantly influences the Groundwater Sustainability Performance (Y)

- $H_0 : \beta_5 = 0$ - Damage Control (X5) does not significantly influence the Groundwater Basin Function (Y)
  $H_1 : \beta_5 \neq 0$ - Damage Control (X5) significantly influences the Groundwater Sustainability Performance (Y)

- $H_0 : \beta_6 = 0$ - Utilization (X6) does not significantly influence the Groundwater Sustainability Performance (Y)
  $H_1 : \beta_6 \neq 0$ - Utilization (X6) significantly influences the Groundwater Sustainability Performance (Y)

RESULTS

Validity and Reliability Tests

Validity and reliability tests of the research instrument were conducted using RStudio. The study involved seven latent variables (X1–X6 and Y) comprising a total of 129 questionnaire items.

Table 2 presents the results of the validity test, showing that the Pearson correlation coefficients for all 129 items ranged from 0.30 to 0.97. All items were declared valid, as each correlation coefficient exceeded the minimum threshold of 0.30.

Table 2: Validity test results.

No.	Pearson correlation coefficient	Validity status	No.	Pearson correlation co-efficient	Validity status	No.	Pearson correlation coefficient	Validity status
1	0.751	Valid	44	0.930	Valid	87	0.886	Valid
2	0.671	Valid	45	0.833	Valid	88	0.900	Valid
3	0.797	Valid	46	0.778	Valid	89	0.741	Valid
4	0.903	Valid	47	0.970	Valid	90	0.824	Valid
5	0.865	Valid	48	0.826	Valid	91	0.921	Valid
6	0.830	Valid	49	0.721	Valid	92	0.844	Valid
7	0.367	Valid	50	0.832	Valid	93	0.885	Valid
8	0.747	Valid	51	0.842	Valid	94	0.799	Valid
9	0.854	Valid	52	0.825	Valid	95	0.765	Valid
10	0.634	Valid	53	0.557	Valid	96	0.830	Valid
11	0.330	Valid	54	0.507	Valid	97	0.755	Valid
12	0.795	Valid	55	0.755	Valid	98	0.918	Valid
13	0.887	Valid	56	0.868	Valid	99	0.887	Valid
14	0.850	Valid	57	0.838	Valid	100	0.567	Valid
15	0.814	Valid	58	0.812	Valid	101	0.884	Valid
16	0.766	Valid	59	0.851	Valid	102	0.692	Valid
17	0.906	Valid	60	0.883	Valid	103	0.916	Valid
18	0.879	Valid	61	0.816	Valid	104	0.713	Valid
19	0.884	Valid	62	0.878	Valid	105	0.946	Valid
20	0.791	Valid	63	0.692	Valid	106	0.871	Valid
21	0.723	Valid	64	0.852	Valid	107	0.871	Valid
22	0.844	Valid	65	0.826	Valid	108	0.881	Valid
23	0.850	Valid	66	0.860	Valid	109	0.936	Valid
24	0.814	Valid	67	0.798	Valid	110	0.884	Valid
25	0.686	Valid	68	0.871	Valid	111	0.869	Valid
26	0.316	Valid	69	0.910	Valid	112	0.892	Valid
27	0.880	Valid	70	0.882	Valid	113	0.958	Valid
28	0.852	Valid	71	0.828	Valid	114	0.582	Valid
29	0.919	Valid	72	0.866	Valid	115	0.698	Valid
30	0.868	Valid	73	0.883	Valid	116	0.643	Valid
31	0.720	Valid	74	0.899	Valid	117	0.600	Valid
32	0.908	Valid	75	0.894	Valid	118	0.644	Valid
33	0.826	Valid	76	0.942	Valid	119	0.834	Valid
34	0.795	Valid	77	0.879	Valid	120	0.787	Valid
35	0.764	Valid	78	0.860	Valid	121	0.853	Valid
36	0.849	Valid	79	0.834	Valid	122	0.928	Valid
37	0.876	Valid	80	0.897	Valid	123	0.911	Valid
38	0.770	Valid	81	0.887	Valid	124	0.895	Valid
39	0.901	Valid	82	0.897	Valid	125	0.798	Valid
40	0.955	Valid	83	0.899	Valid	126	0.868	Valid
41	0.726	Valid	84	0.923	Valid	127	0.843	Valid
42	0.944	Valid	85	0.920	Valid	128	0.944	Valid
43	0.860	Valid	86	0.909	Valid	129	0.903	Valid

PLS-SEM Modeling Results

PLS-SEM analysis was employed to examine the influence of the Sustainable Groundwater Resource Management variables (X1–X6) on the Groundwater Sustainability Performance (Y). The Outer (Measurement)

Model was reflective, evaluated based on Cronbach's Alpha, factor loadings, and Average Variance Extracted (AVE) values.

Reliability and Convergent Validity of the Outer Model

For the reflective PLS-SEM model, the first step involved assessing the internal consistency reliability of the questionnaire for each latent variable (X1–X6 and Y). Reliability was assessed using Cronbach's Alpha. If the value exceeded 0.70, the construct was considered reliable and suitable for further analysis within the reflective model.

Table 3. Cronbach's alpha values.

Latent variable	Cronbach's Alpha
X1	0.940
X2	0.946
X3	0.907
X4	0.947
X5	0.969
X6	0.971
Y	0.963

All Cronbach's Alpha values are greater than 0.70, confirming the reliability of the constructs in the outer model.

Parameter Estimation Results (PLS-SEM)

Parameter estimation in the PLS-SEM model was conducted using the Ordinary Least Squares (OLS) method. The complete estimation results are illustrated in Fig. 2.

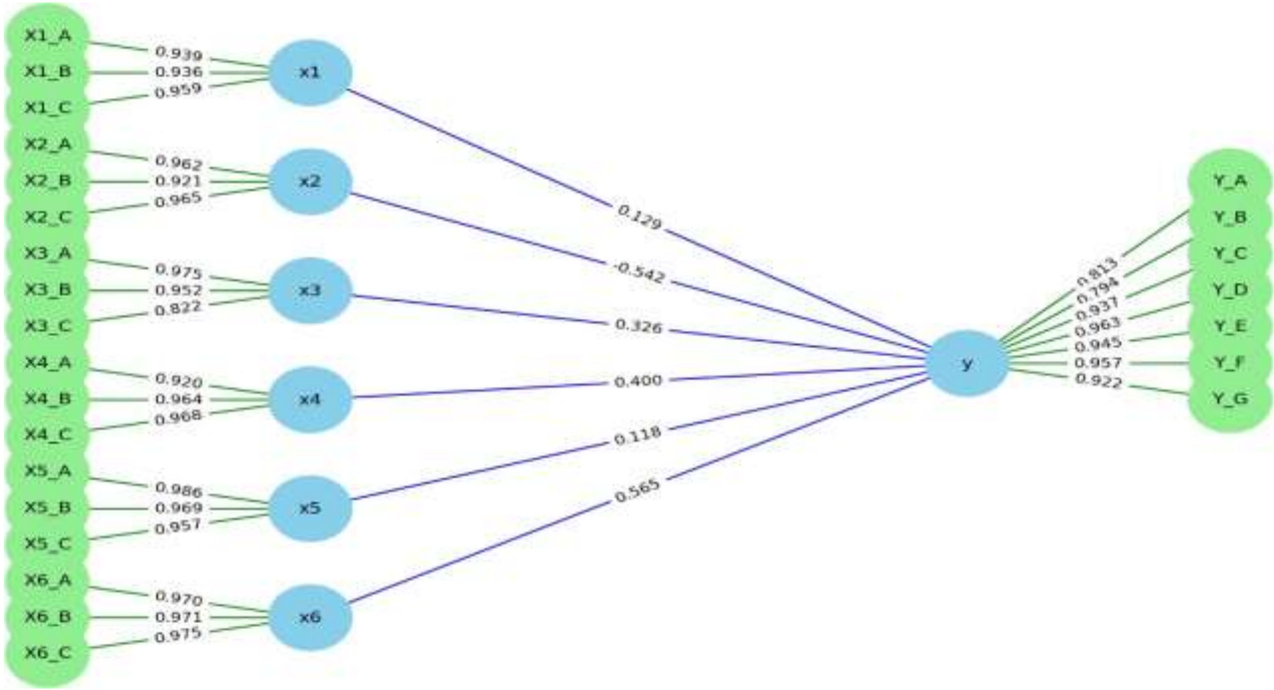

Fig. 2. PLS-SEM model parameter estimation.

In Fig. 2, the SEM diagram consists of two components:

(1) the outer (measurement) model, and

(2) the inner (structural) model, each with its respective coefficients.

In the outer model, the coefficient (loading) values represent the contribution of each indicator to its respective latent variable. The outer model coefficients for each latent variable are presented in Table 4.

Table 4. Outer model coefficients.

No.	Indicator	Latent Variable	Loading Value
1	X1.A (Data and information)	X1 (Planning)	0.939
2	X1.B (Institutional)		0.936
3	X1.C (Disaster integration)		0.959
4	X2.A (Human resources)	X2 (Implementation)	0.962
5	X2.B (Budgetary support)		0.921
6	X2.C (Program implementation)		0.965
7	X3.A (Monitoring system)	X3 (Monitoring and evaluation)	0.975
8	X3.B (Performance evaluation)		0.952
9	X3.C (Data transparency)		0.822
10	X4.A (Protection of recharge areas)	X4 (Conservation)	0.920
11	X4.B (Water-use efficiency)		0.964
12	X4.C (Education and outreach)		0.968
13	X5.A (Planning control)	X5 (Damage control)	0.986

No.	Indicator	Latent Variable	Loading Value
14	X5.B (Exploitation regulation)		0.969
15	X5.C (Law enforcement)		0.957
16	X6.A (Fair access)	X6 (Utilization)	0.970
17	X6.B (Economic value)		0.971
18	X6.C (Technological innovation)		0.975
19	Y.A (Ecological and environmental)	Y (Groundwater Sustainability Performance)	0.813
20	Y.B (Social)		0.794
21	Y.C (Economic)		0.937
22	Y.D (Institutional)		0.963
23	Y.E (Technology and information)		0.945
24	Y.F (Risk and resilience)		0.957
25	Y.G (Legal)		0.922

The results in Table 4 indicate that all indicators across the seven latent variables exhibit high loading values, all exceeding the minimum threshold of 0.70, thereby meeting the criteria for convergent validity.

- The most dominant indicators representing each construct are as follows:
- Disaster Integration under Planning (X1) – 0.959
- Program Implementation under Implementation (X2) – 0.965
- Monitoring System under Monitoring and Evaluation (X3) – 0.975
- Education and Outreach under Conservation (X4) – 0.968
- Planning Control under Damage Control (X5) – 0.986
- Technological Innovation under Utilization (X6) – 0.975
- Institutional under Groundwater Sustainability Performance (Y) – 0.963

Since all loading values exceed the required threshold, the reflective measurement model is confirmed to be valid and appropriate for subsequent hypothesis testing within the structural model.

Hypothesis Testing Results

Hypothesis testing was conducted by analyzing the coefficients in the Inner (Structural) Model at a significance level of 0.05. The rejection criterion was: if $p < 0.05$, then H_0 is rejected, indicating a statistically significant effect between the latent variables.

Table 5: Significance test of parameters.

Parameter	Estimate	Std. Error	t-statistic	p-value
Intercept (β_0)	0.00	0.057	0.00	1
X1 (β_1)	0.13	0.209	0.61	0.554
X2 (β_2)	-0.54	0.238	-2.28	0.049
X3 (β_3)	0.33	0.191	1.71	0.122
X4 (β_4)	0.40	0.241	1.66	0.131

X5 (β_5)	0.12	0.180	0.66	0.529
X6 (β_6)	0.57	0.214	3.92	0.004

The results indicate that only Utilization (X6) and Implementation (X2) have statistically significant effects on the Groundwater Sustainability Performance (Y):

- Utilization (X6) exhibits the strongest positive and significant effect (β = 0.57; p = 0.004).
- Implementation (X2) demonstrates a negative and significant effect (β = −0.54; p = 0.049).
- The remaining variables - Planning (X1), Monitoring and Evaluation (X3), Conservation (X4), and Damage Control (X5), are statistically insignificant ($p > 0.05$).

Overall, the model shows very high predictive power, with a Coefficient of Determination ($R^2 = 0.925$). This means that 92.5% of the variability in the Groundwater Sustainability Performance can be explained by the six predictor variables in the model.

Model Evaluation Results

At the final stage of the PLS-SEM analysis, the model was evaluated using the Average Variance Extracted (AVE) values for each latent variable. The results are presented in Table 6.

Table 6. PLS-SEM model evaluation (AVE values).

Latent Variable	AVE Value
X1	0.893
X2	0.901
X3	0.844
X4	0.905
X5	0.943
X6	0.945
Y	0.822

All AVE values exceed the minimum threshold of 0.50, confirming that the reflective measurement model demonstrates satisfactory convergent validity and is suitable for the objectives of this study.

DISCUSSION

Dominance of the Influence of Utilization (X6) and Implementation (X2)

The structural analysis revealed a crucial and contrasting finding in predicting Groundwater Sus-tainability Performance (Y) in Probolinggo Regency. The overall model demonstrates exceptionally high predictive power, with a Coefficient of Determination (R^2) of 0.925, indicating that 92.5% of the varia-bility in Groundwater Sustainability Performance is explained by the six predictor variables. Further-more, the robustness of these findings is supported by strong convergent validity, with Average Vari-ance Extracted (AVE) values for all latent variables exceeding the 0.50 threshold (ranging from 0.822 to 0.945), ensuring that the constructs effec-tively represent their intended measures.

Within this robust framework, Utilization (X6) exhibited the strongest significant positive effect (β = 0.57; p = 0.004). This result indicates that the optimization of Groundwater Sustainability Performance is fundamentally driven by the utilization aspect, particularly through its most influential indicator, Technological Innovation (loading = 0.975). This reflects a global shift in water resource management moving away from passive conservation toward active demand management focused on efficiency and technology-based resilience. Consistent with the perspectives of global environmental governance (Burchard-Levine et al. 2025), technological optimization directly enhances both the economic and environmental value of groundwater resources.

Conversely, Implementation (X2) demonstrated a negative and significant effect (β = −0.54; p = 0.049). This striking finding suggests an "implementation gap." Although the conceptual program implementation is strong (loading = 0.965), its execution in the field is likely hindered by the constraints identified in the Performance Report of the Ministry of Energy and Mineral Resources (2024), such as inadequate human resource capacity and financial limitations. In the context of Probolinggo Regency, these execution failures have direct physical consequences; the inability to effectively enforce extraction quotas and conservation programs has been linked to declining water levels in several monitoring wells and an increased risk of seawater intrusion along the coastal aquifers. In a model with such high predictive accuracy (R^2= 92.5%), this negative coefficient serves as a stark warning that administrative failures at the execution stage directly translate into the degradation of Groundwater Sustainability Performance, manifesting as tangible hydrogeological instability.

Comparison with Previous Studies and Novelty of the Research

These findings provide both confirmation and correction to existing theoretical frameworks on groundwater resource management. Historically, studies have emphasized the dominant role of Planning (X1) (Abdurrohim 2024) and Conservation (X4) (Jenahu et al. 2023) as predictors of effective man-agement outcomes. However, in this study, Planning (X1), Monitoring and Evaluation (X3), Conserva-tion (X4), and Damage Control (X5) were found to have no direct significant effects on the Groundwa-ter Sustainability Performance (Y). The statistical non-significance of these variables is likely a manifes-tation of a ''policy-practice gap" or institutional decoupling. Within this context, while management frameworks are well-documented administratively, they appear to lack the operational capacity and budgetary consistency required to exert a tangible influence on sustainability outcomes. For instance, planning and conservation efforts in Probolinggo Regency tend to be normative and administrative in nature, failing to translate into concrete, measurable field actions.

Furthermore, monitoring and evaluation functions fail to provide a direct impact because their out-puts are not integrated into a responsive feedback loop capable of adjusting actual groundwater extrac-tion behavior. These findings suggest that such variables serve as latent preconditions or enabling fac-tors that establish a formal managerial foundation. However, their actual impact on Groundwater Sus-tainability Performance is fully mediated through the quality of Implementation (X2) and the efficiency of Utilization (X6), rather than exerting a direct, independent influence.

The novel contribution of this study lies in highlighting the Implementation (X2) variable as a critical yet underexplored determinant in sustainable groundwater management. While previous research has predominantly focused on improving planning frameworks and regulatory mechanisms, this study demonstrates that the core weakness lies in policy execution, not formulation.

The strong negative coefficient for Implementation (X2) challenges the optimism inherent in conventional planning models and highlights the importance of enhancing institutional capacity, effective budget allocation, and human resource development as the key to reversing current negative trends at the implementation level.

Policy Implications and Future Research Directions

The findings of this study have important policy implications for improving environmental management and the Groundwater Sustainability Performanc in Probolinggo Regency. Given the strong positive influence of Utilization (X6) and the negative influence of Implementation (X2), policy measures should focus on two strategic pillars:

(1) promoting technological efficiency, and

(2) addressing institutional and capacity-related barriers.

First, local governments should prioritize investment in technological innovation for groundwater utilization to improve water-use efficiency and enhance Groundwater Sustainability Performance. This may include providing subsidies for water-saving irrigation technologies in the agricultural sector and implementing smart metering systems in industries to monitor and control groundwater extraction in real time. Policies should also link the economic value of groundwater with ecological sustainability, introducing incentives for efficient use and penalties for wasteful practices, thereby maintaining both groundwater levels and quality as key indicators of performance.

Second, a comprehensive evaluation of the Implementation (X2) stage is necessary to identify and eliminate structural barriers responsible for the negative effect observed in this study. This involves bureaucratic reforms in groundwater management agencies, enhanced technical training programs for staff, and rigorous budget audits to ensure that funds allocated for conservation programs, such as reforestation of recharge zones, are implemented efficiently. Improving these processes is vital to reversing the negative impact on the overall Groundwater Sustainability Performance.

For future research, attention should be given to exploring the mediating mechanisms among variables to produce more refined policy recommendations. Methodologically, future work should explicitly test mediation effects using PLS-SEM, for instance, to examine whether the influence of Planning (X1) and Conservation (X4) on Groundwater Sustainability Performance operates through Implementation (X2) and Utilization (X6).

Additionally, qualitative investigations are recommended to identify specific causal factors behind the negative coefficient of Implementation (X2), focusing on issues such as budget allocation inefficiencies, institutional incentive gaps, and governance fragmentation within local environmental management systems.

CONCLUSIONS

This PLS-SEM study demonstrates that 92.5% of the variability in Groundwater Sustainability Performance is explained by the six latent variables within the model. These findings reflect managerial performance based on stakeholder perceptions and institutional indicators.

The most critical and contrasting results are dominated by two key factors:

1. Utilization (X6) has the strongest and statistically significant positive influence ($\beta = 0.57$), primarily driven by Technological Innovation. This confirms that the performance of the groundwater basin is increasingly determined by efficient demand management and technological adaptation.
2. Implementation (X2) exhibits a negative and significant influence ($\beta = -0.54$), indicating the presence of a critical implementation gap. This suggests that weaknesses in human resource capacity and budgetary constraints during the execution phase hinder the overall sustainability performance.

The main contribution of this research is the empirical confirmation that the greatest challenge in groundwater management lies in execution failure rather than policy planning. The study emphasizes that local governments must prioritize investment in technological innovation while undertaking structural reforms to overcome implementation barriers.

Future research should focus on testing the mediating roles of Implementation (X2) and Utilization (X6) using longitudinal data. Additionally, in-depth qualitative studies are needed to identify the specific institutional and financial constraints behind the negative coefficient of Implementation. Finally, future work could integrate these perception-based findings with physical hydrogeological modeling to provide a more holistic view of groundwater sustainability.

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