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Diagnostic Assessment of Small Dam Performance Using a Hierarchical Composite Index: Limiting Indicators and Robustness Analysis in Semi-Arid Area

Sessito Vincentius Sapay[1]*, Pitojo Tri Juwono[1], M. Amar Sajali[1]

[1] Department of Water Resources Engineering, Universitas Brawijaya, Malang, Indonesia.

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Corresponding Author:
Sessito Vincentius Sapay
sessitosapay@gmail.com

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Abstract: Small dams are strategic infrastructure in semi-arid areas such as Kupang, where performance sustainability is shaped by technical and institutional dimensions. This study analyzes the performance of three small dams, namely Oelanisa, Bisiti, and Oekolo, using a hierarchical composite index to identify limiting indicators and examine weighting robustness within the Performance Index Model of Small Dams (IKEK). A total of 37 indicators across physical, O&M, institutional, and service aspects were evaluated through weighted linear aggregation and six weighting scenarios. Using an inverse scoring convention (lower = better), IKEK values were 2.44 for Oelanisa (Moderate-2), 2.86 for Bisiti (Moderate-4), and 2.97 for Oekolo (Poor), indicating systemic deficiencies despite water availability reliability. The O&M aspect contributed 63.51–66.43% to the total index, a consequence of its structural weight (0.53) combined with poor O&M performance, reflecting governance weaknesses rather than model imbalance. Staff competence held the highest effective weight (β = 0.1549) and greatest marginal impact (ΔIKEK = 0.465), the maximum index gain achievable at optimal condition. Robustness testing confirmed ranking stability, demonstrating performance differences are structurally determined by actual score distributions. These findings affirm that strengthening O&M capacity and institutional governance is the primary rehabilitation priority in semi-arid small dam systems.

Keywords: Effective weight; Hierarchical composite index; Robustness analysis; Semi-arid area; Small dams

Introduction

Small dams in Indonesia are technically classified as embung kecil, defined as water storage structures built in natural depressions, typically outside river channels, with a maximum storage capacity of 100,000 m^3 and a catchment area of no more than 100 hectares, primarily designed to collect rainfall runoff for domestic, livestock, and agricultural use during the dry season (Ibnu Kasiro et al., 1994; Kementerian PUPR, 2018). This classification distinguishes embung kecil from bendungan (large dams) based on structural scale and hydrological function. As off-channel rain-fed structures, small dams operate independently of river networks and are not capable of influencing broader watershed hydrology; their value lies entirely in sustaining micro-scale water availability for local communities. In semi-arid areas such as East Nusa Tenggara Province (NTT), which has a long dry season and uneven rainfall distribution, small dams are critical infrastructure for meeting domestic, irrigation, and livestock needs. As of 2020, there were 3,658 small dams spread across NTT (Pentewati et al., 2023a), indicating the significant public investment in local-scale water infrastructure. Small dams have been constructed massively in Timor Island since the early 1980s as a proven rainwater harvesting technology to support water supply in semi-arid areas (Suni et al., 2023).

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Globally, small dams play an important role in water resource management in arid and semi-arid areas and support the sustainability of agricultural landscapes (Casadei et al., 2019; Owusu et al., 2022). However, various studies point to challenges such as rapid sedimentation, structural degradation, seepage through embankment bodies and foundations, and water loss due to high evaporation (Mady et al., 2020; Umukiza et al., 2023). These challenges are well-documented across NTT, where functional degradation of small dams — particularly in Kupang — is marked by sedimentation, erosion, seepage, and reduced storage capacity (Bunganaen, 2013; Fallo et al., 2022; Semiun, 2019). Beyond physical deterioration, sustainability is further constrained by managerial and institutional dimensions, with weaknesses in institutional role sharing, limited human resource capacity, and suboptimal management mechanisms identified as factors limiting service delivery — including suboptimal utilization of community-based management due to limited distribution infrastructure and weak management — across the province (Punuf et al., 2025; Wadu et al., 2023). Prior evaluations of small dams across NTT consistently identify O&M and institutional aspects as the primary limiting dimensions, even when physical conditions remain relatively moderate to good (Dethan et al., 2015; Melani et al., 2024; Pentewati et al., 2023a). These findings confirm that evaluations based on physical conditions alone are not sufficient to comprehensively describe system performance.

A performance evaluation model has been developed through the Performance Index Model of Small Dams (IKEK) based on four aspects — physical, O&M, institutional, and service — using the SEM-PLS approach (Pentewati et al., 2024), representing part of a broader family of performance index models for water infrastructure systems in Indonesia (Kurniawan et al., 2022; Limantara et al., 2023; Limantara et al., 2024). The model produced an index structure with 40 initial indicators representing technical and non-technical dimensions, of which 37 were retained as valid following loading factor testing with a threshold of 0.5 (Pentewati et al., 2023b). Although the index structure and dominant parameters have been validated, the sensitivity of results to methodological assumptions such as weighting and normalization schemes has not been explicitly analyzed. In international literature, composite index construction requires conceptualization, indicator selection, normalization, weighting, aggregation, and robustness testing (Nardo et al., 2008). Transparency and consistency in each stage are prerequisites for scientific accountability (Greco et al., 2019). Sensitivity and uncertainty analysis studies show that variations in weighting schemes can trigger changes in index values and rank reversals, making robustness testing an important component in ensuring the stability of policy interpretations (Becker et al., 2017; Saisana et al., 2005). Based on this review, there is still a gap in the integration of hierarchical index structures, the identification of limiting indicators based on actual effective weight contributions, and the testing of weighting robustness within a single integrated analytical framework. Previous studies have focused on validating the index structure and identifying dominant parameters (Pentewati et al., 2023b), but have not developed a prescriptive approach based on systemic leverage that links global effective weights, marginal indicator contributions (ΔIKEK), and ranking stability to support rehabilitation prioritization.

This gap is significant for three interconnected reasons. First, current rehabilitation practices for small dams in semi-arid areas are predominantly guided by visible physical damage, a criterion that may systematically underweight managerial and institutional deficiencies that have greater aggregate impact on index performance. Second, in an additive hierarchical composite index, the indicator with the worst score is not necessarily the highest rehabilitation priority; what determines priority is the interaction between actual score and global effective weight (Greco et al., 2019; Nardo et al., 2008). Third, the marginal contribution metric (ΔIKEK) provides a quantitative basis for distinguishing between indicators with high damage severity and those with high systemic leverage, enabling rehabilitation prioritization grounded in aggregate index impact rather than visible physical damage severity alone.

The novelty of this study lies in the integration of three analytical elements within a single defensible quantitative framework: the application of hierarchical effective weight propagation to identify limiting indicators based on their actual contribution to the composite index; the operationalization of marginal contribution analysis (ΔIKEK) as a prescriptive diagnostic instrument for systemic rehabilitation prioritization; and robustness testing through six alternative weighting scenarios to evaluate the comparative stability of evaluation results against normative assumption variations. This integration transforms the IKEK model from a descriptive classification instrument into a prescriptive decision-support tool grounded in structural leverage. This study aims to apply this integrated framework to analyze small dam performance in the semi-arid area of Kupang across physical, O&M, institutional, and service aspects. The expected output is a transparent, methodologically defensible evaluation framework capable of guiding evidence-based rehabilitation prioritization in semi-arid small dam systems.

Method

Research Design

This study is a quantitative evaluative study that uses a hierarchical composite index approach to analyze the performance of small dams in the semi-arid area of Kupang. The methodological framework refers to the principles of composite index construction in the OECD Handbook (Nardo et al., 2008), including conceptualization of structure, indicator selection, scoring, weighting, aggregation, and robustness evaluation.

The principles of transparency and explicit normative assumptions also follow the methodological approach in the composite indicator literature (Becker et al., 2017; Greco et al., 2019). A hierarchical approach is used because the IKEK model has a tiered structure (indicators, components, aspects, and total index), so that aggregation is carried out propagatively from the indicator level to the composite index (Nardo et al., 2008). The research flow is presented in Figure 1.

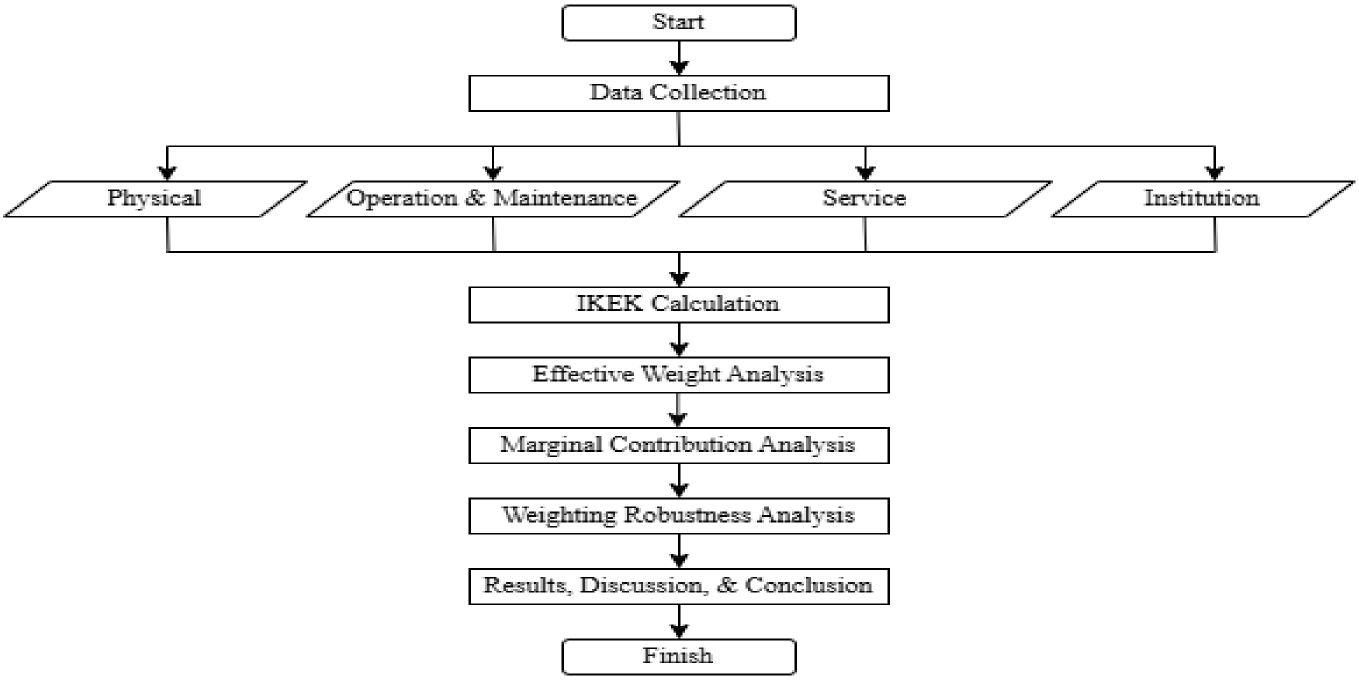

Figure 1. Flowchart of the study

Study Area and Data Collection

The research locations included three small dams in the semi-arid areas of Kupang City and Kupang Regency: Oelanisa Dam (built 2019, operational age 6 years), Bisiti Dam (built 2013, operational age 12 years), and Oekolo Dam (built 2007, operational age 18 years), with operational ages ranging from six to eighteen years at the time of data collection in 2025. This variation in operational age enabled comparative analysis of technical degradation trajectories and institutional capacity across different lifecycle phases.

Data were obtained through three complementary sources. First, direct field observation of physical conditions was conducted across all structural components using the standardized IKEK scoring instrument (Pentewati et al., 2024), which provides explicit condition descriptors for each score level from 1.0 to 4.0, enabling systematic and replicable field-based scoring without requiring instrumental measurement. Second, technical documents were reviewed, including O&M records, operational logbooks, construction implementation documents, and As-Built Drawings held by dam managers, which informed institutional and O&M indicator scoring. Third, structured interviews were conducted with dam managers and water user groups to assess institutional governance, staff competence, and service delivery aspects. This multi-source approach ensures that all indicator scores are grounded in both observable field evidence and verifiable documentary records, strengthening the replicability and credibility of the assessment.

Calculation of IKEK Value

The evaluation model uses the Performance Index Model of Small Dams (IKEK) developed for semi-arid areas (Pentewati et al., 2024). The structure and weighting of aspects were adopted without modification to maintain methodological comparability. The model consists of four aspects — physical, O&M, institutional, and service — with 37 valid indicators retained from an initial pool of 40 following loading factor testing at a threshold of 0.5, excluding KBP5 (lighting condition), PA1 (social condition in water regulation), and DOP1 (small dam design document) (Pentewati et al., 2023b).

Each indicator is assessed using an ordinal scale of 1 to 4, where 1 = Good (best condition) and 4 = Very Poor (worst condition). This inverse scoring convention, in which lower values indicate better performance, is consistent with the original IKEK model design (Pentewati et al., 2024) and produces a composite index in which lower IKEK values represent better overall performance and higher values represent poorer performance. Following OECD composite index standards (Nardo et al., 2008), the IKEK value is calculated using weighted linear aggregation expressed in general form as:

$$IKEK = \sum_{j=1}^{n} w_j . A_j \tag{1a}$$

where w_j is the weight assigned to aspect j and A_j is the computed index value of aspect j, with the constraint that $\sum w_j = 1$. Applied to the four-aspect IKEK structure, this yields:

$$IKEK = 0.15\, IK_{Physic} + 0.12\, IK_{Institution} + 0.20\, IK_{Service} + 0.53\, IK_{O\&M} \tag{1b}$$

The aspect weights (0.15, 0.53, 0.12, 0.20) were determined through Structural Equation Modeling–Partial Least Squares (SEM-PLS) analysis on empirical data from 85 small dams across NTT, followed by optimization using the Generalized Reduced Gradient (GRG) method (Pentewati et al., 2024). These weights are therefore statistically derived from field data rather than assigned subjectively through expert judgment, which constitutes the objective basis of the baseline weighting scenario.

Each aspect index value (IK_{Physic}, $IK_{O\&M}$, $IK_{Institution}$, $IK_{Service}$) is itself computed from a per-aspect weighted formula in which component weights sum to 1.0 within each aspect, with each component value being a weighted aggregate of its constituent indicator scores — the complete hierarchical weight structure is presented in Pentewati et al. (2024). Because of this nested weighted aggregation, aspect index values are not bounded by the indicator scoring scale of 1 to 4; they may fall below 1.0 or exceed 4.0 depending on the distribution of indicator scores across components with unequal internal weights.

Effective Weight and Limiting Indicator Analysis

In an additive hierarchical structure, the global weight of indicators is obtained through weight propagation between levels (Nardo et al., 2008). The effective weight (βi) represents the actual structural contribution of indicator i to the total composite index, and is calculated as:

$$\beta_i = W_{indicator}\ x\ W_{component}\ x\ W_{aspect} \tag{2}$$

Limiting indicators are identified through simulation of score improvement to the best condition (score = 1). Because the model is linearly additive, the marginal contribution of each indicator to index improvement is directly proportional to its effective weight (Greco et al., 2019). The marginal contribution metric ΔIKEKi is defined as the maximum achievable improvement in the total composite index if indicator i is brought to optimal condition, calculated as:

$$\Delta IKEK_i = (S_i - 1.0)\ \beta_i \tag{3}$$

where S_i is the actual score of indicator i and (S_i - 1.0) represents the maximum achievable score improvement. Because $S_i \geq 1.0$ by definition of the scoring scale, $\Delta IKEK_i \geq 0$ in all cases. A larger value indicates higher priority for interventions with greater systemic aggregate impact on overall performance. This approach fundamentally distinguishes between indicators with high damage severity and those with high systemic leverage, enabling impact-based rehabilitation prioritization rather than severity-based prioritization alone.

Weighting Robustness Analysis

Robustness analysis was conducted through scenario-based weighting to evaluate the robustness of evaluation results against variations in normative weighting assumptions at the aspect level (Becker et al., 2017; Saisana et al., 2005). Six weighting scenarios were developed as shown in Table 1. The use of a scenario-based deterministic approach is justified by the uniform ordinal scale of all 37 indicators (1 to 4), which renders them inherently commensurable without additional normalization, making weighting schemes the primary source of normative variation appropriate to evaluate at the aspect aggregation level. The evaluation focused on two dimensions of robustness: ranking stability across all six weighting scenarios, and variations in absolute index values to assess whether categorical performance classifications remain consistent under alternative weight configurations.

Table 1. Weighting Scenarios in the IKEK Robustness Analysis

Scenario	W_{Physic}	$W_{O\&M}$	$W_{Institution}$	$W_{Service}$
Baseline	0.15	0.53	0.12	0.20
Equal Weighting	0.25	0.25	0.25	0.25
Physical Priority	0.40	0.30	0.10	0.20
Reduced O&M	0.20	0.40	0.15	0.25
Service Priority	0.15	0.35	0.10	0.40
Institutional Priority	0.15	0.35	0.30	0.20

Result and Discussion

Performance Assessment Results for Three Small Dams

Table 2 presents the assessment scores for 37 performance indicators across the three small dams, using the inverse scoring convention of the IKEK model (1 = Good; 4 = Very Poor) as described in the Method section.

Table 2. Results of the IKEK Indicator Assessment

Aspect	Component	Indicator	Oelanisa	Bisiti	Oekolo
Physic	Condition of embankment (KT)	Condition of embankment body subsidence (KT1)	2.0	2.0	2.2
		Condition of slope damage (KT2)	2.0	2.0	2.0
	Condition of small dam storage (KTE)	Condition of seepage (KTE1)	1.0	1.0	1.0
		Condition of sediment (KTE2)	2.6	2.0	2.2
	Condition of spillway structure (KBS)	Drempel (KBS1)	2.0	2.2	4.0
		Approach channel (KBS2)	1.4	1.2	2.2
		Spillway channel (KBS3)	1.6	2.4	3.2
		Stilling basin (KBS4)	4.0	2.4	4.0
	Intake structure (BPL)	Inlet pipe (BPL1)	1.2	1.4	4.0
	Distribution network (JD)	Condition of distribution pipe (JD1)	1.2	1.8	4.0
		Availability of distribution pipe (JD2)	1.2	1.8	4.0
	Condition of service tub (KBLY)	Human tub condition (KBLY1)	1.4	4.0	4.0
		Animal tub condition (KBLY2)	1.4	4.0	4.0
		Garden tub condition (KBLY3)	1.4	1.4	4.0
	Condition of completion structure (KBP)	Safety fence (KBP1)	3.8	1.8	3.8
		Peil Scale (KBP2)	2.0	4.0	4.0
		Information board (KBP3)	2.2	1.6	4.0
		BM pole (KBP4)	3.0	4.0	4.0
Operation & Maintenance (O&M)	Implementation of O&M activity (PKOP)	Suitability of O&M activity (PKOP1)	2.2	3.8	3.8
		Application of O&M implementation (PKOP2)	2.2	3.8	3.8
	Small dam guardian staff (PPE)	Adequacy of small dam staff (PPE1)	4.0	4.0	4.0
		Condition of staff competence (PPE2)	4.0	4.0	4.0
	Availability of O&M facility (KSOP)	Manual document of O&M (KSOP1)	3.4	4.0	4.0
		Maintenance tool of O&M (KSOP2)	2.8	2.8	2.8
Institution	Documentation of O&M (DOP)	Document of O&M history (DOP2)	4.0	4.0	4.0
		Document of implementation (DOP3)	3.0	4.0	4.0
	Member meeting (RA)	Structure of organization (RA1)	4.0	4.0	4.0
		Member competence (RA2)	3.2	3.2	3.4
		Routine schedule of meeting (RA3)	2.0	2.4	2.2
Service	Availability of service tub (KBL)	Human tub availability (KBL1)	1.4	3.0	3.0
		Animal tub availability (KBL2)	1.4	3.2	3.2
		Garden tub availability (KBL3)	1.4	1.4	3.0
	Inflow (AM)	Condition of flow and water source (AM1)	2.0	2.0	2.0
	Volume of inundation (VG)	Condition of inundation volume change (VG1)	1.8	1.8	1.8
	Availability of time (WK)	Availability of water along year (WK1)	1.0	1.0	1.0
	Water allocation (PA)	Society water utilization (PA2)	1.6	2.0	2.0
		Number of water utilization (PA3)	3.0	3.0	3.0

IKEK Values and Performance by Aspect

Table 3 presents the computed aspect index values for each small dam; as described in the Method section, these values may fall below 1.0 or exceed 4.0 as valid outcomes of the nested weighted aggregation structure of the IKEK model (Pentewati et al., 2024).

The total IKEK values are 2.44 for Oelanisa (Moderate-2), 2.86 for Bisiti (Moderate-4), and 2.97 for Oekolo (Poor), indicating systemic performance deficiencies across all three small dams. Performance categories follow the classification scheme of the IKEK model (Pentewati et al., 2024), in which scores closer to 1.0 reflect better performance and scores approaching 4.0 reflect the worst condition.

Table 3. Total IKEK Values and Performance Index by Aspect of Three Small Dams

Aspect	Oelanisa	Bisiti	Oekolo
$\text{IK}_{\text{Physic}}$	0.88	1.02	1.47
$\text{IK}_{\text{O\&M}}$	3.06	3.56	3.56
$\text{IK}_{\text{Institution}}$	4.34	4.53	4.56
$\text{IK}_{\text{Service}}$	0.83	1.37	1.59
IKEK	2.44 (Moderate-2)	2.86 (Moderate-4)	2.97 (Poor)

At the aspect level, the most significant differences were found in the O&M and institutional aspects. The O&M index value ranged from 3.06 to 3.56, while the institutional index ranged from 4.34 to 4.56, indicating consistently poor conditions. In contrast, the physical and service aspects performed relatively better, with physical index values of 0.88 to 1.47 and service index values of 0.83 to 1.59. This pattern reveals a clear gap between structural and hydrological stability on one hand and managerial capacity on the other. These findings are consistent with previous evaluations in NTT (Melani et al., 2024; Pentewati et al., 2023a). Studies on dam governance in semi-arid areas further confirm that limitations in institutional capacity and management effectiveness contribute to a decline in service functions even when physical infrastructure remains available (Punuf et al., 2025; Wadu et al., 2023). Institutional capacity frameworks identify organizational structure, resource adequacy, and stakeholder accountability as the key determinants of sustained water infrastructure performance (Raja Ariffin et al., 2024), while empirical evidence from rural water management in developing countries shows that institutional failures persist as cross-contextual barriers regardless of physical infrastructure condition (Angmor et al., 2024). Thus, the managerial dimension emerges as a key determinant in shaping the aggregate performance of small dams.

Decomposition of Aspect Contributions to IKEK Values

The O&M aspect contributes 63.51 to 66.43% to the total index across the three small dams (Table 4), reflecting the combined effect of its highest structural weight (0.53) and the consistently poor O&M indicator scores across all three dams ($IK_{O\&M}$ = 3.06 to 3.56). The contribution of the institutional aspect ranges from 18 to 21%, while the physical and service aspects each contribute less than 11%.

Table 4. Decomposition of Aspect Contributions to the Total IKEK Values

Aspect	Oelanisa (Index; %)	Bisiti (Index; %)	Oekolo (Index; %)
IK_{Physic}	0.13 (5.42)	0.15 (5.37)	0.22 (7.43)
$IK_{O\&M}$	1.62 (66.43)	1.89 (66.04)	1.89 (63.51)
$IK_{Institution}$	0.52 (21.33)	0.54 (19.01)	0.55 (18.39)
$IK_{Service}$	0.17 (6.82)	0.27 (9.57)	0.32 (10.67)
IKEK	2.44 (100.00)	2.86 (100.00)	2.97 (100.00)

Cross-Dam Performance Patterns and the Structural-Managerial Performance Paradox

Cross-indicator analysis identifies three main patterns: structural indicators, shared strength indicators, and differential indicators. These patterns collectively reveal a phenomenon termed here as the structural-managerial performance paradox — a condition in which the structural integrity, geotechnical stability, and hydrological availability of small dams remain relatively adequate, while governance and operational deficiencies systematically suppress aggregate performance values. The term "structural-managerial" reflects the precise nature of the contrast: indicators showing consistently good performance are predominantly structural and geotechnical in character, while those showing consistently poor performance are exclusively managerial and institutional in character, as detailed in the following sub-sections.

Structural Indicators

Structural indicators are those showing consistently poor scores of 3.0 or above across all three small dams (Table 5). The indicators of staff adequacy (PPE1), staff competence (PPE2), O&M history documentation (DOP2), organizational structure (RA1), and member competence (RA2) all fall within the poor to very poor category, with PPE1 and PPE2 scoring 4.0 at all three locations, indicating the complete absence of an adequate operational management system. The consistency of these poor scores across small dams of different ages and locations confirms that the weaknesses are systemic in nature rather than site-specific (Pentewati et al., 2024; Wadu et al., 2023). The international literature indicates that failures in routine maintenance systems accelerate the degradation of service capacity even when initial physical conditions remain adequate (Owusu et al., 2022; Umukiza et al., 2023).

Table 5. Structural Indicators - Consistently Poor Conditions Across All Three Small Dams (Score ≥ 3.0)

Indicator	Oelanisa	Bisiti	Oekolo
Adequacy of small dam staff (PPE1)	4.0	4.0	4.0
Condition of staff competence (PPE2)	4.0	4.0	4.0
Document of O&M history (DOP2)	4.0	4.0	4.0
Structure of organization (RA1)	4.0	4.0	4.0
Member competence (RA2)	3.2	3.2	3.4
Manual document of O&M (KSOP1)	3.4	4.0	4.0
Document of implementation (DOP3)	3.0	4.0	4.0
BM pole (KBP4)	3.0	4.0	4.0
Number of water utilization (PA3)	3.0	3.0	3.0

Shared Strength Indicators

Shared strength indicators (Table 6) include seepage condition (KTE1), slope damage (KT2), inundation volume stability (VG1), year-round water availability (WK1), condition of flow and water source (AM1), and society water utilization (PA2), all of which are in good condition (score of 2.0 or below) across all three small dams. This condition reinforces the structural-managerial performance paradox, whereby structural and hydrological performance is relatively stable, yet governance weaknesses suppress the aggregate index value. In water resource systems, physically functional infrastructure without adequate governance support does not guarantee long-term sustainability (Loucks & van Beek, 2017). This paradox indicates that the managerial dimension functions as a leverage point for the sustainability of technical functions, and composite index-based evaluation enables the identification of imbalances between aspects that are not visible through physical assessment alone.

Table 6. Shared Strength Indicators - Consistently Good Conditions Across All Three Small Dams (Score ≤ 2.0)

Indicator	Oelanisa	Bisiti	Oekolo
Condition of seepage (KTE1)	1.0	1.0	1.0
Condition of slope damage (KT2)	2.0	2.0	2.0
Condition of flow and water source (AM1)	2.0	2.0	2.0
Condition of inundation volume change (VG1)	1.8	1.8	1.8
Availability of water along year (WK1)	1.0	1.0	1.0
Society water utilization (PA2)	1.6	2.0	2.0

Differential Indicators

Differential indicators (Table 7) show that Oekolo, the oldest small dam at 18 years of operation, experienced more pronounced degradation in spillway structures, inlet pipes, distribution networks, and condition of service tubs (KBLY), indicating the contribution of operational age as a factor in physical degradation risk.

Table 7. Differential Indicators - Score Range Across Small Dams ≥ 2.0

Indicator	Oelanisa	Bisiti	Oekolo
Drempel (KBS1)	2.0	2.2	4.0
Inlet pipe (BPL1)	1.2	1.4	4.0
Condition of distribution pipe (JD1)	1.2	1.8	4.0
Availability of distribution pipe (JD2)	1.2	1.8	4.0
Human tub condition (KBLY1)	1.4	4.0	4.0
Animal tub condition (KBLY2)	1.4	4.0	4.0
Garden tub condition (KBLY3)	1.4	1.4	4.0
Safety fence (KBP1)	3.8	1.8	3.8
Peil Scale (KBP2)	2.0	4.0	4.0
Information board (KBP3)	2.2	1.6	4.0

However, age alone is not the primary determinant. Performance variation in younger small dams indicates that the interaction between operational age and maintenance quality is the primary determining factor — physical degradation is accelerative when not offset by an adequate O&M system, particularly in distribution components and service tub conditions (Owusu et al., 2022; Umukiza et al., 2023).

Effective Weight and Performance Limiting Indicators

The analysis of global effective weights (βi), calculated as the product of indicator, component, and aspect weights following Equation (2), shows that the ten indicators with the greatest structural contribution to the index value are dominated by O&M and institutional aspects (Table 8). The two indicators with the highest effective weights are staff competence (PPE2, β = 0.1549) and staff adequacy (PPE1, β = 0.1236), together representing nearly 28% of the total model influence. In addition, the O&M implementation indicators (PKOP1 and PKOP2) and institutional documentation indicators (DOP2 and RA1) are also among the group with the highest contributions, indicating that human resource capacity is the primary determinant in shaping the total index value.

Table 8. Global Effective Weights (β_i) of the Top Ten Indicators

Indicator	Oelanisa	Bisiti	Oekolo	β_i
Condition of staff competence (PPE2)	4.0	4.0	4.0	0.1549
Adequacy of small dam staff (PPE1)	4.0	4.0	4.0	0.1236
Application of O&M implementation (PKOP2)	2.2	4.0	4.0	0.0747
Suitability of O&M activity (PKOP1)	2.2	3.8	3.8	0.0694
Document of O&M history (DOP2)	4.0	4.0	4.0	0.0550
Human tub availability (KBL1)	1.4	3.0	3.0	0.0358
Member competence (RA2)	3.2	3.2	3.4	0.0323
Manual document of O&M (KSOP1)	3.4	4.0	4.0	0.0322
Structure of organization (RA1)	4.0	4.0	4.0	0.0297
Maintenance tool of O&M (KSOP2)	2.8	2.8	2.8	0.0296

An effective weight of β = 0.1549 for PPE2 reflects the hierarchical weight propagation of the IKEK model: PPE2 carries the highest indicator-level weight within the PPE component (0.515), which belongs to the O&M aspect carrying the highest aspect-level weight (0.53). This concentration of weights on operational staff capacity is empirically grounded, reflecting the demonstrated primacy of human resource capacity in determining small dam performance in semi-arid areas (Owusu et al., 2022; Wadu et al., 2023).

Marginal contribution analysis (ΔIKEK*i*), following Equation (3), quantifies the maximum achievable improvement in the total composite index if a given indicator is brought from its actual score to the optimal condition (score = 1.0). For PPE2, with an actual score of 4.0 at all three small dams, ΔIKEK*i* = (4.0 − 1.0) × 0.1549 = 0.465 — the highest value in the dataset, as PPE2 combines both the worst possible score and the highest effective weight. In this context, improving staff competence and adequacy has a greater aggregate impact than rehabilitating physical components with low effective weights, and interventions in the human resource dimension have the potential to produce multiplicative effects through improvements in O&M implementation quality and institutional documentation (Fallo et al., 2022; Loucks & van Beek, 2017).

Weighting Robustness Analysis

Robustness testing through six weighting scenarios (Table 9) shows that no rank reversal occurred between small dams across all weight configurations, indicating that the IKEK model has high comparative stability.

Table 9. IKEK Values Across Six Weighting Scenarios: Model Robustness Test Results

Scenario	Oelanisa	Bisiti	Oekolo	Status
Baseline	2.44	2.86	2.97	Stable
Equal Weighting	2.28	2.62	2.80	Stable
Physical Priority	1.87	2.21	2.43	Stable
Reduced O&M	2.26	2.65	2.80	Stable
Service Priority	1.97	2.13	2.24	Stable
Institutional Priority	2.67	3.03	3.15	Stable

Notably, even under Scenario 2 (Equal Weighting, $W_{O\&M}$ = 0.25, less than half the baseline value) and Scenario 3 (Physical Priority, $W_{O\&M}$ = 0.30), the ranking Oelanisa < Bisiti < Oekolo is preserved. This stability provides evidence that the actual score differences between small dams are sufficiently pronounced that even substantial shifts in aspect weights cannot alter their relative ranking, confirming that the conclusion of O&M dominance reflects empirical reality rather than a mathematical artifact of the baseline weight structure.

However, variations in absolute index values between scenarios indicate that numerical interpretations must still be made with caution. Although the ranking structure does not change, changes in absolute values have the potential to affect category classifications — such as Moderate or Poor — if categorical thresholds are applied strictly. The composite indicator literature emphasizes that index values are relative to the normative assumptions used and cannot be treated as context-free absolute measures (Greco et al., 2019). Sensitivity analyses of composite indicators demonstrate that even seemingly minor modifications to normalization thresholds — not only weight changes — can produce remarkable shifts in ranking outcomes (Kelemen et al., 2024). Thus, ranking stability provides a strong basis for relative comparisons between small dams, but policy implications based on categorical thresholds must still be considered contextually.

Impact-Based Rehabilitation Intervention Priorities

Building on the effective weight analysis above, marginal contribution analysis (ΔIKEK*i*) was applied to each small dam to rank intervention priorities by their potential aggregate impact on the total composite index. Indicators with larger ΔIKEK*i* values represent higher-leverage intervention points regardless of their visible physical damage severity.

Oelanisa Dam

As presented in Table 10, intervention priorities are dominated by indicators related to human resource capacity and operational governance. Staff competence (PPE2) has the potential to increase the index by 0.46470 points, followed by staff adequacy (PPE1) by 0.37094 points.

Table 10. Rehabilitation Intervention Priorities Based on Marginal Contribution ($\Delta IKEK_i$) - Oelanisa Dam

Indicator	Δ_{Oelanisa}
Condition of staff competence (PPE2)	0.46470
Adequacy of small dam staff (PPE1)	0.37094
Document of O&M history (DOP2)	0.16495
Application of O&M implementation (PKOP2)	0.08966
Structure of organization (RA1)	0.08921
Suitability of O&M activity (PKOP1)	0.08332
Manual document of O&M (KSOP1)	0.07721
Member competence (RA2)	0.07096
Maintenance tool of O&M (KSOP2)	0.05330
Document of implementation (DOP3)	0.03202

Cumulatively, these two indicators contribute to more than 34% of the total potential performance improvement. The indicators of O&M history documentation (DOP2), application of O&M implementation (PKOP2), and organizational structure (RA1) are also among the top five priorities. These findings are consistent with governance analyses of small dams in NTT and Kupang, which identified management capacity and operational documentation as the primary limiting factors for service sustainability (Pentewati et al., 2023a; Wadu et al., 2023).

Bisiti Dam

As shown in Table 11, the top two indicators remain staff competence (PPE2) and staff adequacy (PPE1) with identical ΔIKEK*i* values. However, the contribution of application of O&M implementation (PKOP2) and suitability of O&M activity (PKOP1) increased significantly compared to Oelanisa Dam, indicating that in small dams with a medium operational age, the effectiveness of O&M implementation becomes an additional limiting factor alongside staff capacity.

Table 11. Rehabilitation Intervention Priorities Based on Marginal Contribution ($\Delta IKEK_i$) - Bisiti Dam

Indicator	Δ_{Bisiti}
Condition of staff competence (PPE2)	0.46470
Adequacy of small dam staff (PPE1)	0.37094
Application of O&M implementation (PKOP2)	0.22415
Suitability of O&M activity (PKOP1)	0.19441
Document of O&M history (DOP2)	0.16495
Manual document of O&M (KSOP1)	0.09651
Structure of organization (RA1)	0.08921
Human tub availability (KBL1)	0.07155
Member competence (RA2)	0.07096
Animal tub availability (KBL2)	0.05729

Oekolo Dam

At Oekolo Dam (Table 12), the priority pattern is again dominated by O&M and institutional indicators. The top four indicators are identical to those of Bisiti Dam, reinforcing the finding that the primary limiting factors are systemic and cross-cutting across infrastructure ages.

Table 12. Rehabilitation Intervention Priorities Based on Marginal Contribution ($\Delta IKEK_i$) - Oekolo Dam

Indicator	Δ_{Oekolo}
Condition of staff competence (PPE2)	0.46470
Adequacy of small dam staff (PPE1)	0.37094
Application of O&M implementation (PKOP2)	0.22415
Suitability of O&M activity (PKOP1)	0.19441
Document of O&M history (DOP2)	0.16495
Manual document of O&M (KSOP1)	0.09651
Structure of organization (RA1)	0.08921
Member competence (RA2)	0.07741
Human tub availability (KBL1)	0.07155
Animal tub availability (KBL2)	0.05729

The emergence of service indicators such as human tub availability (KBL1) and animal tub availability (KBL2) in the top ten indicates that the long-term accumulation of managerial weaknesses has begun to manifest in the degradation of downstream service components.

Cross-Location Synthesis

Across small dams, staff competence (PPE2) and staff adequacy (PPE1) are consistently the intervention points with the highest leverage. This consistency indicates that human resource capacity and supervision issues are not local problems, but rather structural weaknesses in the small dam management system within the study area. If interventions are focused on these two indicators, the potential for aggregate performance improvement can approach one performance category. Conversely, physical rehabilitation with low effective weights only produces a marginal impact on the total index, even though it may appear more visually urgent. The integration of effective weight analysis and marginal contribution in this study thus provides a prescriptive diagnostic framework grounded in systemic aggregate impact — enabling rehabilitation prioritization that goes beyond visible physical damage severity to target the structural leverage points of small dam performance.

Conclusion

This study demonstrates that the performance of small dams in the semi-arid area of Kupang is predominantly determined by O&M and institutional aspects, with IKEK values of 2.44 (Oelanisa, Moderate-2), 2.86 (Bisiti, Moderate-4), and 2.97 (Oekolo, Poor) indicating a consistent pattern of moderate to poor performance. Despite good water availability reliability — with year-round water availability (WK1) scoring 1.0 at all three locations — governance weaknesses systematically suppress aggregate performance, confirming the structural-managerial performance paradox. The decomposition of aspect contributions shows that O&M contributes 63.51 to 66.43% to the total index value, reflecting the combination of the highest structural weight (0.53) with the worst indicator scores across all three dams ($IK_{O\&M}$ = 3.06 to 3.56). At the indicator level, staff competence (PPE2, β = 0.1549) and staff adequacy (PPE1, β = 0.1236) hold the highest effective weights and produce the greatest marginal contributions (ΔIKEK*i* = 0.465 and 0.371 respectively), identifying both as the primary systemic leverage points for improving small dam performance. Robustness testing through six weighting scenarios produced no rank reversals between small dams. This stability provides evidence that the actual score differences between small dams are sufficiently pronounced that even substantial shifts in aspect weights, including reducing the O&M weight to 0.25 under equal weighting, cannot alter their relative ranking. This confirms that performance differences are structurally determined by the distribution of actual indicator scores rather than by normative weight configurations. The policy implication is strategic: rehabilitation of small dams in semi-arid areas should not focus solely on physical structure improvement, but must prioritize strengthening human resource capacity, O&M documentation systems, and institutional governance structures. A marginal contribution-based approach enables more rational resource allocation grounded in systemic aggregate impact rather than visible physical damage severity alone, providing a replicable decision-support framework for rehabilitation prioritization in resource-constrained contexts, consistent with the principles of evidence-based composite index application (Greco et al., 2019; Nardo et al., 2008). Conceptually, this study contributes to the development of performance evaluation models for small-scale water infrastructure by integrating three analytical elements within a single defensible quantitative framework: a hierarchical index structure based on a validated empirical model; identification of limiting indicators through effective weight propagation and marginal contribution analysis; and robustness testing through alternative weighting scenarios. This integration has demonstrated that the IKEK model can function beyond descriptive classification — as a prescriptive diagnostic tool for prioritizing interventions based on structural leverage in resource-constrained semi-arid contexts. Future research should address several directions that extend beyond the scope of this study. Expanding the coverage to a larger and more geographically distributed sample of small dams across NTT would allow testing of whether the leverage patterns identified here, particularly the dominance of O&M and institutional indicators, hold consistently at a regional scale or vary by island, watershed, or operational age cohort. Longitudinal application of the IKEK framework at the same small dams over multiple assessment periods would enable tracking of performance trajectories following targeted rehabilitation interventions, providing empirical validation of the marginal contribution predictions generated by the ΔIKEKi analysis. Integrating the IKEK evaluation framework with spatial watershed analysis approaches has the potential to deepen understanding of the interactions between managerial capacity, physical degradation risk, and water availability reliability at the catchment level in semi-arid small dam systems.

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Author Contributions

Conceptualization, S.V.S., P.T.J., and M.A.S.; methodology, S.V.S.; validation, S.V.S., P.T.J., and M.A.S.; formal analysis, S.V.S.; investigation, S.V.S.; resources, S.V.S.; data curation, S.V.S.; writing—original draft preparation, S.V.S.; writing—review and editing, P.T.J. and M.A.S.; visualization, S.V.S.; supervision, P.T.J. and M.A.S.; project administration, S.V.S.; funding acquisition, S.V.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

References

Angmor, E., Frimpong, L. K., Mensah, S. L., & Okyere, S. A. (2024). Exploring the institutional barriers to rural water management in Ghana. *Water Policy, 26*(9), 921–940. https://doi.org/10.2166/wp.2024.130

Becker, W., Saisana, M., Paruolo, P., & Vandecasteele, I. (2017). Weights and importance in composite indicators: Closing the gap. *Ecological Indicators, 80,* 12–22. https://doi.org/10.1016/j.ecolind.2017.03.056

Bunganaen, W. (2013). Analisis kinerja embung Oelomin. *Jurnal Teknik Sipil, 2*(1), 23–36. https://doi.org/10.35508/jts.2.1.23-36

Casadei, S., Di Francesco, S., Giannone, F., & Pierleoni, A. (2019). Small reservoirs for a sustainable water resources management. *Advances in Geosciences, 49,* 165–174. https://doi.org/10.5194/adgeo-49-165-2019

Dethan, Y., Bunganaen, W., & Messah, Y. A. (2015). Evaluasi kinerja embung Oeltua. *Jurnal Teknik Sipil, 4*(1), 105–118. https://doi.org/10.35508/jts.4.1.105-118

Fallo, S. D. A., Udiana, I. M., & Utomo, S. (2022). Evaluasi kinerja embung kecil di Kabupaten Kupang. *Jurnal Forum Teknik Sipil, 2*(1), 44–55. Retrieved from https://ejurnal.undana.ac.id/index.php/ForTekS/article/view/4260/3739

Greco, S., Ishizaka, A., Tasiou, M., & Torrisi, G. (2019). On the methodological framework of composite indices: A review of the issues of weighting, aggregation, and robustness. *Social Indicators Research, 141*(1), 61–94. https://doi.org/10.1007/s11205-017-1832-9

Ibnu Kasiro, I., Asidharma, W., Rusli, B. S., Nugroho, C. L., & Sunarto. (1994). *Pedoman kriteria desain embung kecil untuk daerah semi kering di Indonesia*. Puslitbang

Pengairan, Departemen Pekerjaan Umum.

Kelemen, A., Szabó, Z. K., Bozóki, S., Szádoczki, Z., & Hartvig, Á. D. (2024). A sensitivity analysis of composite indicators: Min/max thresholds. *Environmental and Sustainability Indicators, 23,* 100453. https://doi.org/10.1016/j.indic.2024.100453

Kementerian Pekerjaan Umum dan Perumahan Rakyat. (2018). *Pedoman pembangunan embung kecil dan bangunan penampung air lainnya di desa* (Surat Edaran No. 07/SE/M/2018). Kementerian Pekerjaan Umum dan Perumahan Rakyat. Retrieved from https://jdih.pu.go.id/detail-dokumen/2302/1

Kurniawan, T., Bisri, M., Juwono, P. T., Suhartanto, E., Tohari, A., & Riandasenya, S. A. R. (2022). Performance index model of river and infrastructure. *Journal of Hunan University Natural Sciences, 49*(2), 111–122. https://doi.org/10.55463/issn.1674-2974.49.2.11

Limantara, L. M., Tawakal, F. I., Bisri, M., & Andawayanti, U. (2024). Performance index model for water allocation in watershed. *Journal of Law and Sustainable Development, 12*(3), e3216. https://doi.org/10.55908/sdgs.v12i3.3216

Limantara, L. M., Juwono, P. T., Dermawan, V., Wijatmiko, I., & Tohari, A. (2023). Performance index model of main structure (case study in IPDMIP). *Journal of Law and Sustainable Development, 11*(12), e1991. https://doi.org/10.55908/sdgs.v11i12.1991

Loucks, D. P., & van Beek, E. (2017). *Water resource systems planning and management: An introduction to methods, models, and applications*. Springer. https://doi.org/10.1007/978-3-319-44234-1

Mady, B., Lehmann, P., Gorelick, S. M., & Or, D. (2020). Distribution of small seasonal reservoirs in semi-arid regions and associated evaporative losses. *Environmental Research Communications, 2*(6), 061003. https://doi.org/10.1088/2515-7620/ab92af

Melani, M. A. H., Udiana, I. M., & Sina, D. A. T. (2024). Evaluasi kinerja embung kecil di Kabupaten Ende. *JUTEKS: Jurnal Teknik Sipil, 9*(1), 88–97. https://doi.org/10.32511/juteks.v9i1.1157

Nardo, M., Saisana, M., Saltelli, A., Tarantola, S., Hoffmann, A., & Giovannini, E. (2008). *Handbook on constructing composite indicators: Methodology and user guide*. OECD Publishing. https://doi.org/10.1787/9789264043466-en

Owusu, S., Cofie, O., Mul, M., & Barron, J. (2022). The significance of small reservoirs in sustaining agricultural landscapes in dry areas of West Africa: A review. *Water, 14*(9), 1440. https://doi.org/10.3390/w14091440

Pentewati, P., Juwono, P. T., Limantara, L. M., & Sholichin, M. (2023a). Assessment of the small dam performance for its support in the semi-arid area. *Journal of Hunan University Natural Sciences, 50*(3), 76–83. https://doi.org/10.55463/issn.1674-2974.50.3.8

Pentewati, P., Juwono, P. T., Limantara, L. M., & Sholichin, M. (2023b). The limiting parameter for supporting the performance assessment of small dams in the semi-arid area. *Journal of Law and Sustainable Development, 11*(12), e2060. https://doi.org/10.55908/sdgs.v11i12.2060

Pentewati, P., Juwono, P. T., Limantara, L. M., & Sholichin, M. (2024). Performance index model of small dam in semi-arid area. *Civil Engineering Journal, 10*(8), 2645–2660. https://doi.org/10.28991/CEJ-2024-010-08-014

Punuf, D. A., Sartohadi, J., & Setiawan, M. A. (2025). Community-based management of small reservoirs in an erosion-landslide-drought area in the dry tropical region of Kupang Regency. *Journal of Degraded and Mining Lands Management, 12*(2), 7337–7351. https://doi.org/10.15243/jdmlm.2025.122.7337

Raja Ariffin, R. N., Sawon, S., Abd Rahman, N. H., Hanafi, H., & Zahari, R. K. (2024). Contextualizing institutional capacity in water governance framework: A literature review. *Water Policy, 26*(1), 18–36. https://doi.org/10.2166/wp.2023.074

Saisana, M., Saltelli, A., & Tarantola, S. (2005). Uncertainty and sensitivity analysis techniques as tools for the quality assessment of composite indicators. *Journal of the Royal Statistical Society: Series A (Statistics in Society), 168*(2), 307–323. https://doi.org/10.1111/j.1467-985X.2005.00350.x

Semiun, O. E. (2019). Identifikasi kerusakan dan rekomendasi perbaikan embung kecil di Kota Kupang, Provinsi Nusa Tenggara Timur. *Jurnal Pengabdian Pada Masyarakat, 4*(3), 341–352. https://doi.org/10.30653/002.201943.172

Suni, Y. P. K., Sujono, J., & Istiarto. (2023). Identifying potential sites for rainwater harvesting ponds (embung) in Indonesia's semi-arid region using GIS-based MCA techniques and satellite rainfall data. *PLoS ONE, 18*(6), e0286061. https://doi.org/10.1371/journal.pone.0286061

Umukiza, E., Abagale, F. K., & Adongo, T. A. (2023). A review on significance and failure causes of small-scale irrigation dams in arid and semi-arid lands. *Journal of Infrastructure Planning and Engineering, 2*(2), 1–9. https://doi.org/10.22225/jipe.2.2.2023.1-9

Wadu, J., Raga Lay, M., Toda, H., Rihi, D. W., & Nifu, Y. I. (2023). Water governance analysis in the development of embung for water supply security for agriculture (Study in Sabu Raijua District, NTT Province). *Journal of Social Research, 2*(10), 3613–3627. https://doi.org/10.55324/josr.v2i10.1437