

Effectiveness of Technical Civil RHL Structure Distribution in the Lake Catchment Area Period 2021-2025 to Support The Ecosystem Resilience of Lake Limboto

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ABSTRACT

Lake Limboto is one of Indonesia's national priority lakes subject to severe ecological pressure resulting from sedimentation and land-cover change within its catchment area (DTA). In response, the Watershed and Protected Forest Management Center of Bone Bolango (BPDAS Bone Bolango) implemented a Technical Civil Forest and Land Rehabilitation (RHL) program over the 2021–2025 period, constructing a total of 172 structures comprising Gully Plugs (GP), Sediment Retention Dams (DPN), Rainwater Harvesting Installations (IPAH), Infiltration Wells (SRA), and Ecohydraulic structures. This study analyzes the annual trends, proportional distribution, and functional relevance of each structure type in supporting the ecosystem resilience of Lake Limboto. Data were obtained from the BPDAS Bone Bolango Database (2026) and analyzed through annual trend tabulation, proportional analysis, and qualitative literature-based assessment. Results indicate that GPs dominated the total output at 79 units (45.93%), followed by IPAH and SRA at 34 units each (19.77%), DPN at 19 units (11.05%), and Ecohydraulic at 6 units (3.49%). Annual implementation fluctuated, peaking in 2022 (64 units) and 2024 (54 units), with complete stagnation in 2025. The combined deployment of erosion-control and water-conservation structures reflects an integrated conservation approach aimed at strengthening the hydrological and ecological resilience of the DTA. Recommendations include increasing the proportion of ecohydrological structures, integrating geospatial-based site prioritization, and ensuring program continuity beyond 2025.

Keywords: Technical Civil Structures, Lake Limboto, Rainwater Harvesting, Infiltration Well, Ecosystem Resilience

1. INTRODUCTION

A watershed (Daerah Aliran Sungai/DAS) constitutes an integrated ecosystem encompassing biophysical components from headwaters to outlet, functioning as a natural system that supports complex hydrological processes and the socioeconomic activities of surrounding communities [1]. Land-cover change from forested to non-forested conditions diminishes watershed carrying capacity and triggers erosion, flooding, drought, riverbed aggradation, and siltation of reservoirs and irrigation channels [2]. The reduction of vegetative cover decreases rainfall infiltration and increases surface runoff, facilitating the detachment and transport of soil particles that ultimately elevate erosion and sedimentation rates [1], [3].

Lake Limboto, situated in Gorontalo Province, is a national priority lake facing severe ecological pressure in the form of surface area reduction and bed shallowing caused by sedimentation originating from its catchment (DTA). This condition is analogous to numerous lakes and ponds across Indonesia that have experienced similar pressures; several have been converted to settlement areas due to weak riparian governance and low community participation [4]. The preservation of lake ecosystems necessitates synergy among government agencies, academic institutions, and local communities [4].

Forest and Land Rehabilitation (RHL) is implemented to restore, maintain, and improve the functional capacity of forests and land in response to rising rates of natural resource degradation,

evidenced by the expanding area of critical land [5]. Soil and water conservation efforts must be intensified to mitigate the effects of climate change, particularly in controlling flooding, erosion, and landslides [3]. The expansion of settlement areas without adequate infiltration space increases surface runoff that flows into rivers and ultimately into the lake, exacerbating its shallowing and creating conditions conducive to eutrophication [6].

Sediment-retention structures prevent siltation and erosion at both upstream and downstream reaches of river systems while also protecting hydraulic structures along watercourses [7]. Ex-situ rainwater harvesting technology represents an environmentally friendly approach that improves water availability through collection and storage of rainwater for use during dry seasons [8]. The optimal placement of rainwater harvesting structures can be effectively identified using geospatial technology integrating remote sensing and GIS [9].

Understanding ecohydrological processes within a watershed constitutes the scientific foundation for sustainable water resource management [10]. An evidence-based approach is essential to ensure that watershed restoration programs generate not only physical outputs but also measurable ecological outcomes [11]. Recent studies on the integrated drivers of tropical lake catchment degradation in Indonesia identify agricultural expansion, deforestation, and urbanization as primary drivers of erosion, nutrient loading, and declining aquatic biodiversity [12]. The recovery of critical watersheds in Indonesia began in 2009, yet institutional and coordination constraints continue to impede achievement of sustainable watershed management [13], [14].

Despite the ongoing implementation of the Technical Civil RHL program in the DTA of Lake Limboto, systematic academic analyses examining the distribution trends, proportional composition, and functional relevance of these structures to ecosystem resilience remain limited. This study therefore aims to: (1) analyze the annual construction trends of Technical Civil RHL structures during the 2021–2025 period; (2) determine the proportional contribution of each structure type to the total program output; and (3) assess the functional relevance of each structure type to the ecosystem resilience of Lake Limboto through a literature-based synthesis.

2. LITERATURE REVIEW

2.1 *Forest and Land Rehabilitation (RHL) in the Context of Watershed Management*

Forest and Land Rehabilitation (RHL) is a strategic government program in the forestry sector aimed at restoring, maintaining, and improving forest and land functions to counteract the escalating rate of natural resource degradation [5]. Forest degradation and the expansion of critical land generate adverse effects, including flooding, landslides, and droughts, with one of the primary causes being the deterioration of ecosystems in watershed headwater areas that serve as catchment zones [5]. The Strategic Plan of the Directorate General of Watershed Management and Protected Forests of the Ministry of Environment and Forestry (2020–2024) designated 108 priority watersheds for restoration, among which DAS Limboto is classified as a national priority [2]. RHL is implemented through two primary approaches: vegetative activities involving tree planting, and civil engineering activities involving the construction of physical soil and water conservation structures. Evaluation of RHL programs has generally been limited to administrative assessments of planting realization and first-year survival rates, without comprehensive evaluation of RHL impacts on watershed conditions [5].

The sustainability of watershed management in Indonesia is constrained by several institutional challenges, including hierarchical confusion and regulatory discrepancy, weak participation, synchronization, and coordination among watershed management stakeholders, and insufficient integration of watershed planning into regional spatial planning [13]. A sustainable watershed begins with management institutions established through bottom-up approaches, starting from the local community and working toward the national level [13]. Improvement of integrated watershed management (IWM) requires strengthening institutional synergies between agencies responsible for watershed governance and those addressing climate change mitigation and adaptation [15]. The implementation of the Micro Watershed Model (MWM), supported by local culture, indigenous wisdom, and traditional community knowledge, offers a promising avenue to improve current IWM effectiveness [15].

2.2 *Soil Erosion, Sedimentation, and Threats to Lake Ecosystems*

Soil erosion is a process involving the detachment and transport of soil particles from their original aggregates by erosive agents, primarily water and wind. The reduction of land cover or vegetation decreases rainfall infiltration and amplifies surface runoff, rendering soils susceptible to transport by surface flow and resulting in elevated erosion and sedimentation rates [1]. Erosion intensity varies across Indonesia's watersheds, ranging from slight to extreme, depending on the combined influence of rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), crop management (C), and conservation practices (P), as formulated by the Universal Soil Loss Equation (USLE): $A = R.K.LS.C.P$ [1]. In sloped-gully systems, erosion proceeds in succession from splash erosion and sheet erosion at the upper slopes to rill erosion, ephemeral erosion, and ultimately severe gully erosion in the inner-gully incised zones [16].

Sedimentation refers to the processes of soil material transport and deposition resulting from land quality deterioration. It causes the shallowing of rivers, irrigation channels, and river mouths; reduces the effective lifespan of reservoirs; and damages hydraulic structures along watercourses [7]. In the context of lake ecosystems, high sedimentation rates from catchment areas directly reduce the volume and surface area of lakes. Specifically, spatial analysis of DAS Limboto using the USLE method estimated approximately 8.54 million tons/year of sediment entering Lake Limboto, with the largest contributions from sub-watersheds Alo, Molamahu, and Pulubala at approximately 3.8 million tons/year, while the watershed is dominated by the very severe erosion class (29.28%) with rates exceeding 480 tons/ha/year [17]. Declining water quality in freshwater lake systems driven by elevated nutrient inflows, sedimentation, and land-use changes has well-documented negative impacts on aquatic biodiversity, contributing to eutrophication, habitat loss, and reduced species richness [12]. Changes in land use without adequate infiltration space increase surface runoff that contributes to lake sedimentation and the potential for eutrophication [6].

2.3 *Technical Civil Conservation Structures: Functions and Mechanisms*

Technical Civil RHL structures are physical constructions designed to control erosion and sedimentation while conserving water resources within watersheds. The program in the DTA of Lake Limboto encompasses five structure types, each with

specific functions and operational mechanisms. A Gully Plug (GP) is a gully erosion control structure placed within an active gully channel to impede water flow and trap transported sediment. Among all forms of water erosion, gully erosion is the most destructive and cannot be controlled without permanent civil engineering structures [18]. Field research in the Lisu watershed demonstrated that more than half the capacity of retaining dams and gully plugs was filled with sediment within a single year of construction, underscoring the high erosion intensity in active catchment areas and the importance of complementary SWC measures on surrounding agricultural lands [18]. The effectiveness of gully control dams is also influenced by the morphological development of gullies, as studies in Ethiopian highlands confirmed that without adequate catchment-level management, gully dimensions continue to expand even in the presence of check dams [19].

A Sediment Retention Dam (DPN, check dam) is a structure that impedes sedimentation and erosion, preventing upstream degradation and downstream aggradation (Gunawan et al., 2019) [7]. DPN design incorporates flood discharge projections and sediment particle-size distributions specific to watershed characteristics, with structural stability analyzed against overturning, sliding, bearing capacity, and seepage forces [7].

A Rainwater Harvesting Installation (IPAH, ex-situ RWH) is a system that collects and stores rainwater from catchment surfaces such as building rooftops for use during dry seasons [8]. Meta-analysis across 25 agricultural watersheds in semi-arid tropics demonstrated that RWH interventions effectively enhanced groundwater availability by 2.6–6.9 m, crop intensification by 40–100%, and farmers' incomes by 50–200%, while reducing annual soil loss by up to 70% [20]. Identification of optimal RWH sites can be effectively conducted using geospatial technology based on the SCS-CN method and weighted overlay analysis, with results showing approximately 8.9% of watershed area suitable for gully plugs and 5.74% for check dams [9].

An Infiltration Well (SRA) is a well structure designed to collect and percolate rainwater into the soil, functioning as artificial infiltration to reduce surface runoff volume and recharge groundwater reserves [21]. Benefits include reducing surface ponding, minimizing flood risk, reducing coastal saltwater intrusion, and increasing groundwater availability. Construction typically involves a cylindrical excavation filled with crushed stone, bricks, or perforated concrete pipes, with a concrete lid and roof drainage connection [21].

Ecohydraulic structures represent a conservation approach integrating hydrological and ecological principles to maximize ecosystem services while regulating surface flow. Ecohydrology as a discipline examines the interactions and feedbacks between hydrological flows and ecosystem processes, and how these interconnections manifest and provide regulatory control at different scales [10]. Watershed ecohydrological processes are complex and influenced by interacting factors including topography, precipitation, temperature, soil type, vegetation, land use, and land cover, with climate change and land-use change identified as the two most critical drivers [10]. Implementation of ecohydrology in Indonesia has been demonstrated through the development of an Ecohydrology Demonstration Site (EDS) in the Cibitung River

catchment of the Saguling Reservoir, Citarum watershed, where phytoremediation ponds achieved turbidity reduction of up to 92% [22].

3. METHODS

3.1 Study Area

This study focuses on the Catchment Area (DTA) of Lake Limboto, which administratively encompasses Gorontalo Regency and Gorontalo City in Gorontalo Province, Indonesia. Lake Limboto is a national priority lake receiving considerable attention under the watershed restoration and ecosystem management programs of the Ministry of Environment and Forestry. The spatial distribution of Technical Civil RHL structures in the DTA of Lake Limboto is presented in Figure 1.

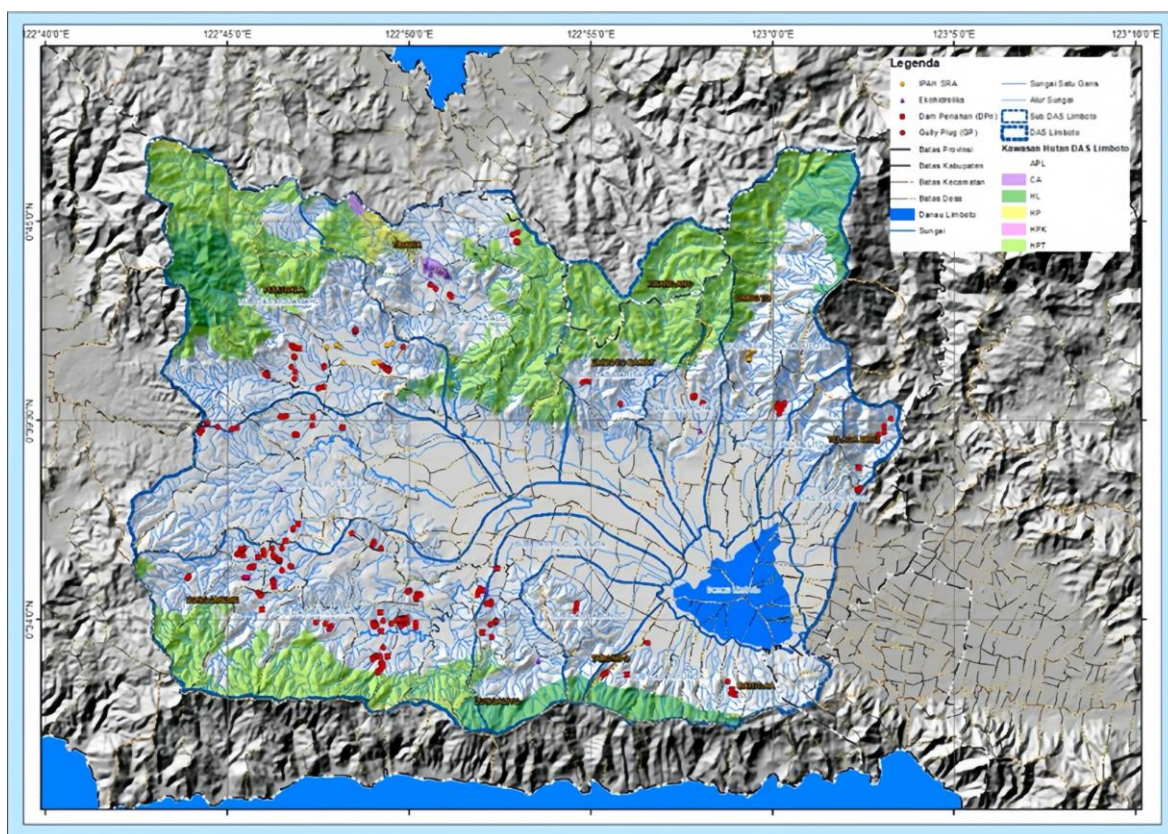


Figure 1. Spatial Distribution Map of Technical Civil RHL Structures in the DTA of Lake Limboto, 2021–2025
(Source: BPDAS Bone Bolango, 2026)

Figure 1 illustrates that Gully Plugs (GP), denoted by red dots, dominate the spatial distribution and are dispersed across nearly the entire watershed, particularly in zones with high gully and stream channel density. IPAH and SRA, indicated by orange dots, are clustered in several concentrations, while Sediment Retention Dams (DPN), shown as red squares, are positioned along major river channels. Ecohdraulic structures, marked by purple triangles, appear in limited numbers at specific locations within the watershed. The overall spatial pattern indicates that structures are more concentrated in the western and southern portions of the DTA, which correspond to zones with higher critical land density compared to the eastern portions that retain relatively better forest cover.

3.1 Data Type and Sources

Secondary data used in this study consist of annual unit-count summaries for each Technical Civil RHL structure type constructed during the 2021–2025 period, encompassing: (1) Gully Plugs (GP), (2) Sediment Retention Dams (DPN), (3) Rainwater Harvesting Installations (IPAH), (4) Infiltration Wells (SRA), and (5) Ecohydraulic structures. Data were obtained from the BPDAS Bone Bolango Database (2026) as the primary authoritative source. Literature review drew on peer-reviewed sources in soil and water conservation, watershed hydrology, ecohydrology, lake ecosystem management, and rainwater harvesting.

3.2 Methods of Analysis

Analysis was conducted in three sequential stages. The first stage involved tabulation of annual data to identify construction trends across the 2021–2025 period. The second stage comprised proportional analysis of each structure type against the total program output (172 units), reflecting the strategic conservation focus of the period. The third stage involved a qualitative literature-based assessment of the functional relevance of each structure type to the ecosystem resilience of Lake Limboto, drawing on current scientific literature in soil and water conservation [1], [3], watershed hydrology and RHL [2], [5], sediment-control structures [7], [18], [19], rainwater harvesting [8], [9], [20], infiltration wells [21], watershed ecohydrology [10], [11], [22], and lake and pond ecosystem management [4], [6], [12].

4. RESULTS AND DISCUSSION

4.1 Annual Construction Trends of Technical Civil RHL Structures (2021–2025)

Based on the BPDAS Bone Bolango Database (2026), a total of 172 Technical Civil RHL structures were constructed in the DTA of Lake Limboto over the 2021–2025 period. The annual distribution by structure type is presented in Table 1.

Table 1. Annual Technical Civil RHL Structure Construction in the DTA of Lake Limboto (2021–2025)

Structure	2021	2022	2023	2024	2025	Total
GP	18	34	–	27	–	79
DPN	4	12	–	3	–	19
IPAH	–	8	14	12	–	34
SRA	–	8	14	12	–	34
Ecohydraulic	–	2	4	–	–	6
Total	22	64	32	54	0	172

Source: BPDAS Bone Bolango Database, 2026

Table 1 reveals significant inter-annual fluctuation in construction output. In 2021, the program commenced with 22 units composed entirely of erosion-control structures: GP (18 units) and DPN (4 units). The year 2022 recorded the highest output across the study period (64 units), marking the first simultaneous deployment of all structure types, including IPAH, SRA, and Ecohydraulic structures. The elevated 2022 output indicates programmatic acceleration, likely facilitated by adequate budget availability and technical field capacity. The year 2023 showed a strategic shift toward water-conservation structures (32 units: IPAH 14, SRA 14, Ecohydraulic 4) without any GP or DPN construction. The year 2024 returned to high output (54 units) with GP again dominant (27 units). The most critical observation is the complete stagnation in 2025 (0 units), a condition warranting thorough evaluation given the ongoing degradation pressures on the DTA of Lake Limboto. Assessment of RHL impacts on watershed hydrological functions requires programmatic consistency, as the ecological effects of technical civil structures are typically measurable only after several years of implementation [2], [5].

The spatial distribution illustrated in Figure 1 shows that GPs are concentrated in zones with high gully density, while DPNs are positioned along major river channels constituting the primary sediment transport pathways toward Lake Limboto. This hierarchical positioning GPs intercepting sediment at source, DPNs capturing residual loads in main channels is consistent with the prescribed cascade approach to sediment control [7]. These trends are also consistent with broader national evaluations indicating that RHL program effectiveness is highly sensitive to budget availability, institutional capacity, land readiness, and on-site implementer commitment [5]. Government-led RHL programs have demonstrated significant potential to improve forest cover, ecosystem functionality, and biodiversity in priority watersheds across Indonesia [12].

4.2 Proportional Analysis of Structure Types

The proportional contribution of each structure type to the total program output of 172 units is presented in Table 2.

Table 2. Proportional Distribution of Technical Civil RHL Structure Types Against Total Program Output

Structure Type	Units	Proportion (%)	Primary Function
Gully Plug (GP)	79	45.93	Gully erosion control and sediment interception
Sediment Retention Dam (DPN)	19	11.05	Sediment retention and slope stabilization
IPAH	34	19.77	Ex-situ rainwater collection and storage
Infiltration Well (SRA)	34	19.77	Groundwater recharge and runoff reduction
Ecohydraulic	6	3.49	Hydrology-ecology integration (nature-based)
Total	172	100.00	

Source: Authors' analysis of BPDAS Bone Bolango Database, 2026

Table 2 demonstrates that GPs dominated the total program output at 79 units (45.93%), reflecting prioritization of gully erosion control among all forms of water erosion, the most destructive and the one least controllable without permanent civil engineering structures [18]. GPs function by intercepting flow within active gullies, enabling sediment deposition before material reaches watercourses feeding Lake Limboto. Geospatial analysis indicates that approximately 8.9% of a watershed area is typically suitable for gully plugs based on multi-criteria suitability analysis [9], suggesting that the optimal placement of the 79 constructed GPs should be evaluated against spatially derived suitability maps to ensure maximum hydrological impact.

IPAH and SRA each contributed 34 units (19.77%), collectively representing 39.54% (68 units) of total program output. Infiltration wells intercept rainwater and percolate it into the soil, reducing surface runoff while recharging groundwater [21]. This dual function runoff reduction and groundwater replenishment is particularly critical for communities in the DTA who rely on groundwater for daily needs. The IPAH system collects roof runoff into storage tanks for dry-season use, a technology that has demonstrated significant improvements in water use efficiency and agricultural productivity [8], [20]. Together, IPAH and SRA address the water-conservation dimension of resilience, complementing the erosion-control function of GPs and DPNs.

DPNs, at 19 units (11.05%), are designed for larger-scale slope stabilization and sediment retention relative to GPs. Structural design follows standards for planned flood discharge and sediment particle distribution, with stability analyses encompassing resistance to overturning, sliding, bearing capacity, and seepage [7]. Within the DTA of Lake Limboto, DPNs function as the second tier of defense in the hierarchical cascade sediment-control network from headwater to outlet, intercepting sediment loads that bypass the upstream GP network. The combined 98 units of GP and DPN (57.56% of total) constitute the backbone of the program's erosion-control strategy.

Ecohydraulic structures, at 6 units (3.49%), represent the smallest proportional component but carry the highest strategic value, as they integrate hydrological functions with ecological principles aligned with the global ecohydrology paradigm emphasizing the coupling of hydrological and ecological processes as the basis for sustainable watershed management [10]. The low proportion of Ecohydraulic structures constitutes an important observation for future program planning.

4.3 Functional Relevance of Structures to the Ecosystem Resilience of Lake Limboto

From the perspective of erosion and sedimentation control, 98 units of GP and DPN (57.56% of total) form a hierarchical sediment-control network from headwater to outlet, as visualized in Figure 1. Low sedimentation rates are recognized as an indicator of successful watershed management [2]. RHL programs in Indonesia's micro-watersheds have documented erosion reductions of 33–62% through changes in the crop management factor (C) in the USLE framework [2]. Predictive modeling using USLE confirms that changes in vegetative cover and conservation practice factors resulting from RHL activities significantly reduce erosion and sediment yields in treated watersheds [1]. Empirical evidence from DAS Limboto itself demonstrates that the land area requiring restoration reaches 55.82% (49,892 ha), and that the implementation of vegetative rehabilitation through reforestation, revegetation, and agroforestry can reduce erosion rates by up to 89.56% [17]. This evidence positions the 172 Technical Civil RHL structures as essential mechanical complements that intercept sediment directly at active erosion points before vegetative cover achieves functional maturity.

From the perspective of water conservation, 74 units of IPA, SRA, and Ecohydraulic structures (43.02% of total) contribute to increasing water storage within the DTA. Land-cover change without adequate infiltration space increases surface runoff that flows into rivers and accumulates in the lake, accelerating shallowing and creating conditions conducive to eutrophication [6]. Infiltration wells reduce surface ponding, minimize flood risk, and replenish groundwater reserves [21]. Rainwater harvesting contributes to dry-season water availability and climate change impact mitigation at the DTA level [8]. RWH interventions across semi-arid watersheds have demonstrated an average of 40 mm of annual harvestable runoff with soil-loss reductions of up to 70% [20].

Geospatial technology based on remote sensing has proven effective in identifying optimal locations for rainwater harvesting structures and conservation infrastructure [9]. Application of this approach in the DTA of Lake Limboto where the spatial distribution of existing structures is already documented in Figure 1 would improve the precision of structure placement in locations with the greatest hydrological impact potential. The 6 Ecohydraulic units reflect an effort to integrate ecosystem-based approaches into water management, consistent with the contemporary global paradigm emphasizing evidence-based restoration that generates measurable ecological outcomes [11]. The implementation of ecohydrology in Indonesia through the Saguling EDS has demonstrated that online monitoring, ecohydrological modeling, and phytotechnology can be combined to address water quality and sedimentation challenges in priority watershed catchments [22].

Overall, the combination of structures constructed reflects a conservation approach addressing two critical dimensions of lake ecosystem resilience: (1) resilience to erosion and sedimentation, supported by the dominance of GP and DPN; and (2) resilience to water deficit or drought, supported by IPA, SRA, and Ecohydraulic structures. The spatial distribution in Figure 1 indicates that both dimensions are addressed geographically across the DTA, although the intensity and proportion of ecohydrological structures warrant strengthening.

4.4 Integration of Civil Engineering and Vegetative Approaches as an Integrated Conservation Strategy for the DTA of Lake Limboto

The achievements of the 2021–2025 Technical Civil RHL program must be contextualized within the broader rehabilitation requirements of the DTA of Lake Limboto. Spatial analysis

indicates that 55.82% of DAS Limboto's land area totaling 49,892 ha requires restoration, comprising 16,362 ha (18.30%) for reforestation and revegetation and 33,530 ha (37.51%) for agroforestry [17]. This scale contextualizes the 172 constructed technical civil structures as one component of a substantially larger and more complex effort, the success of which will be determined by the degree to which physical structures synergize with concurrently implemented vegetative programs.

Theoretically, effective DAS conservation requires the integration of mechanical (civil engineering) and vegetative techniques. Mechanical techniques provide immediate and measurable sediment interception and flow retardation, while vegetative techniques provide long-term protection through improved land cover, enhanced soil infiltration capacity, and reduced rainfall erosivity [3]. Community farmers acknowledge that the combination of mechanical and vegetative methods is the most effective approach to minimizing land erosion impacts [3]. The Integrated Natural Resource Management Program (UPSA) previously implemented in DAS Limboto integrated both vegetative and civil engineering techniques with explicit consideration of land suitability and capability, providing a model that should guide future RHL program planning [17].

The dominance of GP at 45.93% indicates a program orientation toward curative erosion control addressing damage that has already occurred while preventive approaches through vegetative cover enhancement still require acceleration. National evaluations of RHL programs across Indonesia have shown that implementation does not necessarily translate into land-use transitions to secondary forest, and that annual runoff coefficients (KAT) do not always respond significantly to RHL activities in the short term [5]. This underscores the strategic role of technical civil structures as a hydrological function bridge during the transitional period before vegetative programs achieve ecological maturity.

In the context of Lake Limboto's sediment burden of approximately 8.54 million tons/year [17], the 172 constructed technical civil structures represent a meaningful but insufficient contribution requiring multilayered reinforcement. An optimal integrated approach for subsequent program periods should encompass three intervention layers: (1) technical civil structures (GP, DPN, Ecohydraulic) for direct sediment interception at source points; (2) water-conservation structures (IPAH and SRA) for increasing water storage within the DTA; and (3) vegetative programs (reforestation, revegetation, agroforestry) for restoring land cover and long-term hydrological function. The vegetative mitigation effectiveness of 89.56% in controlling sedimentation in DAS Limboto [17] indicates that layer three, when implemented synergistically with layers one and two, would yield substantially greater ecological outcomes than implementation in isolation.

The policy implication of this analysis is the need for a paradigm shift in RHL program planning—from a sectoral approach to an integrated landscape-based approach that considers the spatial distribution of structures, current land-cover conditions, the degree of land criticality by sub-watershed, and the socioeconomic dynamics of DTA communities. Long-term monitoring and evaluation of the performance of constructed conservation structures including measurement of sedimentation rate changes and annual runoff coefficients in rivers feeding Lake Limboto constitute an urgent need to ensure that DTA rehabilitation programs achieve measurable and sustainable ecological outcomes [5], [11].

4.5 Linkage of the Technical Civil RHL Program to Biodiversity and Sustainable Watershed Management

The degradation of tropical lake catchment areas in Indonesia extends beyond hydrological and sedimentation processes to encompass the biodiversity of aquatic ecosystems. Increased nutrient inflows from agricultural runoff accelerate eutrophication, leading to substantial declines in water quality and aquatic biodiversity, while land-use changes driven by agricultural expansion and urbanization are closely associated with declining habitat quality and species richness [12]. In this context, the 172 Technical Civil RHL structures in the DTA of Lake Limboto may be interpreted as physical interventions that contribute to sediment control while simultaneously supporting lake water quality as aquatic habitat. Government-led RHL programs in Indonesia have documented

significant improvements in forest cover, ecosystem functionality, and biodiversity outcomes in priority watersheds [12].

Studies on slope-gully erosion systems demonstrate that gully erosion is among the most severe environmental problems in sloped landscapes globally, with erosion patterns and rates strongly influenced by slope gradient, slope length, vegetative cover, and rainfall intensity [16]. In slope-gully systems, erosion processes progress successively from splash and sheet erosion at upper slopes to rill erosion, ephemeral erosion, and ultimately severe gravitational gully erosion in the incised inner-gully zone [16]. The concentration of GP structures in active gully zones as depicted in Figure 1 is consistent with the principles of permanent civil engineering-based gully erosion control.

From a water-conservation perspective, a meta-analysis across 25 agricultural watersheds in semi-arid tropics demonstrated that RWH interventions enhance groundwater availability by 2.6–6.9 m, crop intensification by 40–100%, and farmer incomes by 50–200%, while reducing annual soil loss by 70% through harvesting an average of 40 mm of surface runoff annually [20]. Over 70% of semi-arid tropical areas exhibit high to medium RWH intervention potential [20]. These findings reinforce the scientific rationale for the 34 IPA units constructed in the DTA of Lake Limboto and provide quantitative justification for increasing the proportion of rainwater harvesting structures in subsequent program periods.

Conservation experiences at other national priority lakes in Indonesia, notably Lake Toba in North Sumatra, demonstrate that integrated deployment of vegetative and civil engineering conservation methods yields significantly larger impacts on erosion reduction and DTA water balance improvement [24]. Regional conservation modeling using SWAT in the Lake Toba DTA showed that combinations of infiltration wells, terracing, agroforestry, and Multi-Purpose Tree Species (MPTS) measurably improved baseflow and reduced surface runoff [24]. Similar modeling approaches could be applied in the DTA of Lake Limboto to evaluate and optimize structure placement for subsequent program periods. A sustainable watershed management framework requires robust data-driven monitoring, cross-sectoral collaboration, and adaptive strategies responsive to climate change and land-use dynamics [13], [15]. Furthermore, [25] emphasize that successful integrated watershed management in Indonesia requires community involvement, appropriate management action tailored to specific site conditions, technological support, regulatory alignment, and multi-stakeholder collaboration preconditions that are equally applicable to the sustained effectiveness of the Technical Civil RHL program in the DTA of Lake Limboto.

CONCLUSION

The Technical Civil RHL program in the DTA of Lake Limboto for the 2021–2025 period produced 172 conservation structures comprising GP (79 units/45.93%), IPA (34 units/19.77%), SRA (34 units/19.77%), DPN (19 units/11.05%), and Ecohydraulic (6 units/3.49%). Annual implementation trends exhibited significant fluctuation, peaking in 2022 (64 units) and 2024 (54 units), with complete stagnation recorded in 2025 a critical finding that requires urgent programmatic response. The spatial distribution map confirms that structures are dispersed across the DTA, with higher concentrations in steep-slope zones characterized by dense gully networks. Erosion-control structures (GP and DPN) account for 57.56% of total output, while water-conservation structures (IPA, SRA, and Ecohydraulic) contribute 43.02%. Functionally, the combined deployment of both structural groups reflects an integrated conservation strategy relevant to supporting two critical dimensions of Lake Limboto's ecosystem resilience: sedimentation control and water resource conservation. The integration of technical civil structures with vegetative rehabilitation programs represents the most effective pathway to addressing the 55.82% of DAS Limboto land area that still requires restoration, given that vegetative mitigation effectiveness reaches 89.56% in controlling sedimentation when implemented synergistically with mechanical interventions [17].

Based on the findings of this study, several research and policy directions are recommended for subsequent program periods. Future studies should apply hydrological modeling approaches such as SWAT to quantitatively evaluate changes in sedimentation rates and annual runoff coefficients attributable to the constructed structures, providing measurable performance indicators [5], [24]. Geospatial suitability analysis integrating remote sensing, terrain data, and land-cover classification should be conducted to identify priority zones for future structure placement, particularly for GP, IPA, and Ecohydraulic structures [9]. The proportion of Ecohydraulic structures should be increased in subsequent planning cycles, given their alignment with ecohydrological principles proven effective in improving water quality and ecological resilience at watershed scale [10], [11], [22]. Program continuity beyond 2025 must be institutionally guaranteed to prevent stagnation that would diminish cumulative ecological gains, and community empowerment through participatory soil and water conservation education should be strengthened as a complementary strategy to sustain long-term program outcomes [3], [13], [25].

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