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A Hierarchical Function-Based Soil Quality Index Integrating Water Balance and Erosion Dynamics in a Sloping Tropical Watershed

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ABSTRACT

A hierarchical function-based soil quality framework was developed to evaluate soil system performance in a sloping tropical watershed in Central Sulawesi, Indonesia. The framework integrates three functional domains—water regulation, structural stability, and chemical buffering—within a multi-level aggregation structure that captures soil–landscape interactions. The framework was applied to 13 land units representing cocoa monoculture and agroforestry systems. The Composite Soil Quality Index (CSQI) reached 0.74, indicating high overall soil functional performance. Among the functional domains, water regulation exhibited the highest index value (0.78) and contributed the largest share to CSQI (0.27), followed by chemical buffering (0.73) and structural stability (0.72). Statistical analysis revealed strong and significant positive relationships between functional domains and CSQI, with water regulation showing the highest correlation ($r = 0.82$, $p < 0.01$), followed by structural stability ($r = 0.76$) and chemical buffering ($r = 0.74$). Regression analysis further demonstrated that water regulation explained a substantial proportion of CSQI variability ($R^2 = 0.67$), highlighting its role as a primary driver of soil system performance. Moderate interdependencies among functional domains were also observed, with no evidence of trade-offs under the studied conditions. Sensitivity analysis using ±10% variation in domain weights resulted in CSQI values ranging from 0.71 to 0.77, indicating low sensitivity and high robustness of the framework. These findings demonstrate that integrating hydrological processes within a hierarchical structure improves both interpretability and reliability of soil quality assessment. From an applied perspective, the proposed framework provides a transparent decision-support tool for soil conservation prioritization and sustainable land-use planning in tropical watershed systems.

1. INTRODUCTION

Soil quality is increasingly recognized as a key determinant of ecosystem stability, agricultural productivity, and environmental sustainability. Soils underpin more than 95% of global food production, yet approximately one-third of the world's soils are moderately to highly degraded due to interacting pressures such as erosion, organic matter decline, and unsustainable land use [1]. This global trend highlights the urgency of developing reliable approaches to evaluate soil system performance under changing environmental conditions.

In response to these challenges, Soil quality assessment has progressively evolved from reductionist evaluations based on isolated parameters toward integrative, function-oriented frameworks that better represent the complexity of soil system processes [2-4]. Contemporary concepts extend beyond isolated physical and chemical attributes to represent the soil's ability to regulate water, maintain structural stability, retain nutrients, and buffer environmental disturbances. This functional perspective links measurable soil properties to ecosystem services, providing a more meaningful basis for evaluating soil performance in dynamic landscapes.

Such an approach is particularly critical in sloping tropical agroecosystems, where intense rainfall, complex topography, and fragile soil structures generate strong interactions among hydrological fluxes, erosion dynamics, and biogeochemical processes. Empirical evidence indicates that soil water storage, infiltration capacity, and aggregate stability strongly influence the balance between runoff generation and subsurface water retention [5, 6]. In these environments, soil degradation rarely results from a single factor but emerges from coupled hydrological and geomorphological processes that progressively reduce soil structural integrity and nutrient retention capacity [7].

Recent studies have emphasized the importance of integrating soil processes within broader agro-ecosystem frameworks to better represent system complexity and improve environmental assessments. The incorporation of soil and agro-ecosystem models into sustainability evaluation has enabled more site-specific and process-explicit analyses by capturing interactions among climate, soil properties, and management practices [8]. However, increasing model complexity does not always translate into improved interpretability, highlighting the need for balanced frameworks that remain both robust and operational.

Despite these advances, many soil quality assessments in tropical upland systems remain largely parameter-based and reductionist. Composite soil quality indices (CSQI) derived from statistical reduction approaches such as Principal Component Analysis (PCA) and Minimum Data Set (MDS) optimization are effective for dimensional simplification; however, they frequently reduce ecological interpretability by compressing complex soil processes into statistically optimized variables.

In heterogeneous watershed environments, such reductionist approaches often obscure complex hydrological feedbacks, functional interdependencies, and degradation pathways that regulate long-term ecosystem resilience [9, 10]. At finer spatial scales, these methods further tend to overlook slope-induced hydrological interactions and the topographically driven feedbacks that control localized degradation trajectories [11].

Moreover, soil erosion has been shown to alter key physical properties—including bulk density (BD), soil structure, and water retention—thereby affecting soil functionality beyond simple mass [12, 13]. These limitations are particularly evident in the upper Gumbasa watershed, Central Sulawesi, Indonesia, where agricultural land has experienced increasing degradation over the past two decades. Accelerated soil erosion on sloping land has reduced productivity and contributed to watershed instability. Land degradation has long been recognized as a major environmental issue in Indonesia, prompting the development of soil and water conservation policies and research initiatives, although their effectiveness varies across regions [14]. These conditions highlight the need for scientifically robust soil evaluation frameworks that can support sustainable land management in tropical agricultural systems.

Although function-based frameworks provide a promising alternative by organizing indicators into ecological domains, their structured application remains limited, particularly in tropical agroecosystems. Previous studies have emphasized the importance of integrating hydrological balance, erosion dynamics, and biogeochemical indicators within transparent evaluation systems [3, 4]. However, few studies have operationalized hierarchical function-based indices while simultaneously testing their robustness under varying weighting assumptions. Sensitivity analysis is increasingly recognized as essential for evaluating the reliability of composite environmental indices and reducing subjectivity in index construction [15]. The absence of such rigor limits the development of reliable and transferable soil quality assessment tools for watershed-scale applications.

Hierarchical functional frameworks offer an important conceptual advantage because they explicitly separate parameter measurement, ecological interpretation, and system-level integration, thereby reducing conceptual ambiguity and improving analytical transparency.

To address this gap, the present study develops and applies a hierarchical function-based soil quality index in the upper Gumbasa watershed by integrating three functional domains: (i) water regulation and storage, (ii) structural stability and degradation control, and (iii) chemical retention and buffering capacity. The framework adopts a multi-level aggregation structure (parameter–indicator–functional index–composite index) to preserve spatial-process relationships. A sensitivity analysis was conducted using ±10% variation in domain weights to evaluate the robustness of the composite index.

We hypothesize that integrating seasonal water balance and erosion dynamics within a hierarchical functional framework improves both the sensitivity and stability of soil quality assessment compared with conventional parameter-based approaches. By combining process representation with methodological transparency, this study contributes to the development of a more robust, interpretable, and transferable framework for soil quality evaluation in tropical watershed systems.

2. METHODOLOGY

2.1 Study area and data source

This study was conducted in the upper Gumbasa watershed, Central Sulawesi, Indonesia, a humid tropical landscape characterized by undulating to steep topography and cocoa-based agroecosystems. A quantitative index-development approach was employed to construct and apply a hierarchical function-based soil quality framework in sloping tropical environments.

The dataset used in this study was derived from field investigations conducted during 2004-2005, encompassing cocoa monoculture and cocoa agroforestry systems distributed across 13 delineated land units. Although the dataset was collected during 2004-2005, the study primarily aims to develop and evaluate a hierarchical soil quality assessment framework rather than to analyze temporal soil change. The selected variables largely represent slow-changing soil properties and process-based relationships that remain suitable for functional integration analysis in perennial tropical agroecosystems.

The study area is located within the buffer zone of the Lore-Lindu National Park, where land-use practices are subject to environmental regulations and relatively controlled management. As a result, large-scale land-use conversion and intensive agricultural expansion have been relatively limited compared to many other tropical regions. This context suggests that the general structure of cocoa-based agroecosystems has remained broadly consistent over time, although localized variations due to management practices and climate variability may still occur.

The validity of using this dataset is further supported by the relatively stable nature of several key soil properties over decadal timescales. Soil attributes such as texture, BD, cation exchange capacity (CEC), and inherent soil water retention characteristics are generally considered slow-changing properties, particularly under perennial land-use systems such as cocoa plantations. These properties are governed by pedogenic and structural processes that do not typically undergo rapid short-term changes, making them suitable for methodological framework development and functional integration analysis.

In addition, the erosion estimation applied in this study using the Universal Soil Loss Equation (USLE) is based on process-driven relationships among rainfall erosivity, soil erodibility, topography, and land cover. These relationships are conceptually stable and widely applicable across temporal contexts, even though absolute erosion rates may vary under changing climatic conditions or land management practices.

However, it is acknowledged that land-use management practices and climate variability over the past two decades may have influenced soil conditions and hydrological responses within the study area. Changes such as variations in cropping intensity, organic matter inputs, conservation practices, and rainfall patterns may affect soil functional performance over time. Therefore, the present study should be interpreted as a methodological framework demonstration rather than a direct representation of current soil conditions.

Despite these limitations, the dataset provides a robust empirical basis for analyzing the functional integration of hydrological regulation, erosion dynamics, and soil physicochemical properties within a hierarchical soil quality framework. Future applications of the proposed framework would benefit from updated datasets and long-term monitoring to capture temporal dynamics and enhance its applicability under evolving environmental and land-use conditions.

2.1.1 Land unit delineation and soil sampling

Sampling locations were determined using stratified sampling based on land-use systems and topographic characteristics. A total of 13 land units were designated as analytical units (six monoculture and seven agroforestry systems), each represented by three replicate sampling points.

Soil samples were collected at the effective rooting depth of cocoa plants. Undisturbed samples were obtained using cylindrical core rings for BD determination, while disturbed composite samples were collected for soil texture and chemical property analyses. BD was determined using the core method, and particle-size distribution was analyzed using standard laboratory procedures following established soil analytical protocols [16, 17].

2.1.2 Soil physical and chemical parameters

Physical parameters included soil texture, BD, field capacity, and permanent wilting point. Chemical parameters comprised soil pH, soil organic carbon (SOC), CEC, and base saturation (BS). Available Water Capacity (AWC) was estimated based on the difference between field capacity and permanent wilting point adjusted for BD and effective rooting depth:

$$\mathrm{AWC} = (\mathrm{FC} - \mathrm{PWP}) \times \mathrm{BD} \times \mathrm{ERD} \quad (1)$$

where, AWC is the available water capacity, FC is the soil water field capacity, PWP is permanent wilting point, BD is the soil bulk density, and ERD is the effective rooting depth. All expressed in millimeters of water [18, 19]. The inclusion of AWC is consistent with its recognized role in representing soil water storage capacity in tropical environments [5].

2.2 Water balance analysis

Monthly water balance was calculated using a rainfall–reference evapotranspiration (ET_0) balance approach. Rainfall and air temperature data were obtained from the climatological station managed by the Public Works Office of Central Sulawesi Province. Reference ET_0 was estimated using the temperature-based Hargreaves method [20].

Actual ET_0 was determined as a function of soil water storage constrained between zero and maximum AWC, representing seasonal dynamics without explicitly incorporating lateral flow and deep percolation processes. Such simplified seasonal water balance approaches have been widely applied in agro-hydrological assessments [21].

2.3 Soil erosion analysis

Annual soil loss was predicted using the USLE:

$$A = R \times K \times LS \times C \times P \quad (2)$$

where, A is annual soil loss (Mg Ha^{-1}), R the rainfall erosivity factor, K the soil erodibility factor, LS the slope length–steepness factor, C the cover-management factor, and P the conservation practice factor.

The R factor was calculated from annual rainfall data. The K factor was derived from soil texture and organic matter content. The LS factor was determined from field measurements of slope length and gradient, while C and P were assigned according to land-use conditions in each unit. The use of USLE is supported by its broad applicability in erosion modeling across diverse landscapes [22, 23].

2.4 Soil quality index development

2.4.1 Functional domains and indicator normalization

Soil quality evaluation was conducted using a function-based framework comprising three primary domains: 1) Water regulation and storage; 2) Structural stability and degradation control; 3) Nutrient retention and chemical buffering.

Indicators were normalized to a dimensionless scale (0-1) using internal benchmark normalization to ensure comparability among indicators with different measurement units and scales. For positively related indicators, scores were calculated relative to the maximum observed value; for negatively related indicators, inverse normalization was applied using the following equations [10, 24]. The grouping of indicators into explicit functional domains follows recent recommendations for process-oriented soil quality assessment [2-4].

For positively related indicators, normalization was calculated as:

$$N_i = \frac{X_i}{X_{max}} \quad (3)$$

where, N_i is the normalized score of indicator i, X_i is the observed indicator value, and X_{max} is the maximum observed value among all land units.

For negatively related indicators, inverse normalization was applied as:

$$N_i = \frac{X_{min}}{X_i} \quad (4)$$

where, X_{min} represents the minimum observed value of the indicator.

2.4.2 Weighting and hierarchical aggregation

Weight assignment was conducted through a two-level aggregation procedure. At the first level, indicators within each functional domain were weighted according to their conceptual relevance to the represented ecological processes, ensuring that total weights within each function equaled one. The weighting scheme was derived from process-based considerations and established soil function literature rather than purely statistical optimization, thereby preserving interpretative transparency in soil quality assessment [2, 4]. Functional indices were calculated as weighted sums of normalized indicator scores. Each functional index was calculated as the weighted sum of normalized indicator scores using:

$$FI_j = \sum_{i=1}^{n} W_i N_{ij} \tag{5}$$

where, FI_j is the functional index for domain j, W_i is the assigned weight of indicator i, and N_i is the normalized score of indicator i in domain j.

The CSQI was computed as a weighted aggregation of the three primary functional domains, with inter-domain weights also normalized to unity [10, 25]. The CSQI was calculated as:

$$CSQI = \Sigma\,(W_j \times FI_j) \tag{6}$$

where, W_j is the weight assigned to functional domain j and FI_j is the corresponding functional index.

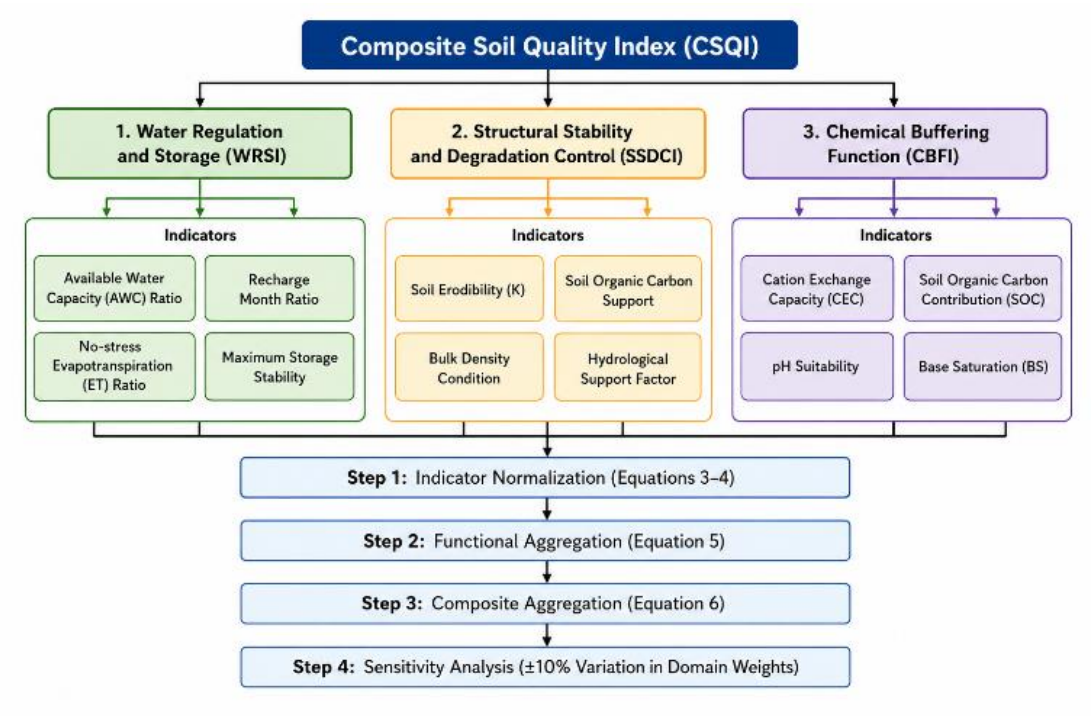

Figure 1. Hierarchical structure of the function-based soil quality framework

This hierarchical structure (Figure 1) explicitly separates parameter measurement, functional interpretation, and systemic integration, reducing black-box aggregation and enhancing reproducibility [21].

2.5 Sensitivity analysis

To evaluate structural robustness and potential subjectivity in weight allocation, sensitivity analysis was performed by applying ±10% variation to the weights of each primary functional domain, with proportional adjustment among the remaining domains.

The composite index was recalculated under each scenario to assess the stability of soil quality classification under moderate weighting changes [26].

2.6 Statistical analysis

Statistical analysis was conducted to evaluate the relationships among soil functional domains and the CSQI. Pearson correlation analysis was applied to quantify the strength and direction of the relationships between each functional domain and CSQI, as well as among the functional domains themselves.

Linear regression analysis was performed to assess the predictive role of water regulation on CSQI and structural stability. The coefficient of determination (R^2) was used to evaluate the proportion of variance explained by the independent variable, while statistical significance was assessed using p-values.

All statistical analyses were conducted at a significance level of $p < 0.05$. The results of these analyses were used to support the interpretation of functional relationships and to validate the hierarchical soil quality framework.

3. RESULTS AND DISCUSSION

3.1 Soil physical and chemical characteristics

The descriptive statistics of selected soil properties across the thirteen land units reveal substantial variability in several key indicators governing soil system performance (Table 1). BD showed relatively low variability (CV 8.3%), indicating that soil structural conditions remain relatively consistent across the watershed. In contrast, effective soil depth exhibited moderate variability (CV 22.1%), reflecting heterogeneity in soil profile development and potential water storage capacity.

SOC displayed considerable spatial heterogeneity (CV 39.5%), suggesting differences in organic matter accumulation related to land-use practices and landscape position. Similar variability was observed in CEC and BS, with coefficients of variation of 31.0% and 40.2%, respectively. These parameters directly influence nutrient retention capacity and soil buffering processes.

Table 1. Descriptive statistics of selected soil physical and chemical properties across land units

Soil Properties	Mean	CV (%)	Range	Functional Domain
BD, g cm^{-3}	1.21	8.3	1.02-1.35	Structural Stability
ESD, cm	113	22.1	78-152	Water Regulation
SOC, %	1.67	39.5	0.95-3.05	Structural & Chemical
CEC, cmol(+) kg^{-1}	33.5	31.0	17.4-48.6	Chemical Buffering
BS, %	38.8	40.2	18.0-72.0	Chemical Buffering
pH	6.0	7.7	55.5-6.6	Chemical Buffering
ER, cm yr^{-1}	2.41	130.2	0.31-8.81	Structural Stability

Notes: 1. BD = bulk density. 2. ESD = effective soil depth. 3. SOC = soil organic carbon. 4. CEC = cation exchange capacity. 5. BS = base saturation. 6. ER = erosion rate. 7. CV = coefficient of variation.

Erosion rate presented the highest variability among all parameters (CV 130.2%), with values ranging from 0.31 to 8.81 cm yr^{-1}. This large dispersion indicates strong spatial heterogeneity in degradation intensity associated primarily with slope gradient and land management practices. Similar observations have been reported in erosion-affected tropical landscapes where slope-driven runoff processes strongly influence soil physical degradation and sediment redistribution [14].

The observed variability highlights that soil quality in sloping tropical agroecosystems is governed by interacting hydrological, geomorphological, and biochemical processes rather than by isolated soil attributes. Such multidimensional variability reinforces the need for integrative soil quality assessment frameworks that explicitly link measurable soil parameters to ecological functions [2, 4].

3.2 Soil water balance and water regulation-storage function

Seasonal water balance analysis revealed a distinct hydrological pattern characterized by alternating recharge and deficit phases. Mean monthly rainfall (approximately 99 mm) was generally lower than reference ET_0 (approximately 127 mm), indicating that water deficit conditions dominate during several months of the hydrological year.

Despite this deficit tendency, the soil profile demonstrated a relatively high AWC of 162.84 mm, enabling substantial internal water storage during the recharge period. As a result, actual ET_0 remained unrestricted during approximately two-thirds of the annual cycle, reflected in a normalized no-stress ET_0 ratio of 0.67.

The weighted integration of hydrological indicators produced a Water Regulation Function Index of 0.78 (Table 2), indicating strong hydrological performance. The high score reflects the ability of the soil system to buffer rainfall variability through internal water storage mechanisms. Such buffering capacity is essential for maintaining hydrological stability in watershed ecosystems, particularly under increasing climate variability that requires adaptive water resource management strategies [27].

Table 2. Indicators and weighted scores for the water regulation and storage function

Indicator	NC	Weight	WC
Available water capacity ratio	0.81	0.35	0.28
Recharge month ratio	0.33	0.08	0.08
No-stress evaporation ratio	0.67	0.17	0.17
Maximum storage stability	1.00	0.15	0.15
Water Function Index		0.78	

Notes: 1. NC = normalized score. 2. WC = weighted contribution.

The role of soil water storage in stabilizing plant productivity in tropical agroecosystems has been widely documented. Soil organic matter and pore structure strongly influence water-holding capacity and infiltration dynamics [28, 29]. Amendments such as biochar have also been shown to enhance soil hydraulic behavior and increase water retention in degraded soils [30, 31].

By integrating seasonal water balance within the soil quality framework, the present study links soil physical properties with hydrological performance, providing a more process-explicit representation of soil functionality compared with static water retention indicators.

3.3 Structural stability and degradation control function

Erosion prediction using the USLE indicated strong spatial variability in soil loss across land units, particularly in areas characterized by high slope length–steepness (LS) factors. This variability reflects differences in runoff generation and soil detachment processes associated with topographic conditions.

The normalized soil erodibility indicator reached an average value of 0.62, suggesting moderate resistance to erosion processes. Soil organic carbon support showed a normalized score of 0.55, while BD conditions demonstrated a relatively favorable structural status with a normalized score of 0.74.

After weighted aggregation, the Structural Stability Function Index reached 0.72 (Table 3), classified as strong. This result indicates that, although certain land units experience elevated erosion pressure, the overall structural condition of the soil system remains within a protective range.

Table 3. Indicators and weighted scores for the structural stability function

Indicator	NC	Weight	WC
Soil Erodibility	0.62	0.40	0.25
Soil Organic Carbon Support	0.55	0.25	0.14
Bulk Density Condition	0.74	0.20	0.15
Hydrological Support Factor	0.78	0.15	0.12
Structural Stability Function Index		0.72	

Notes: 1. NC = normalized score. 2. WC = weighted contribution.

Land-use transitions in tropical landscapes have been consistently linked to alterations in soil organic matter pools, which in turn modulate physical soil conditions and structural resilience [32, 33]. The integration of tree-based systems, such as agroforestry, has been demonstrated to enhance aggregate stability and mitigate structural degradation by promoting continuous organic inputs that reinforce soil matrix cohesion [34, 35]. Consequently, sustained organic residue addition not only improves pore architecture but also strengthens resistance to runoff-induced detachment, thereby supporting long-term degradation control [36].

3.4 Nutrient retention and chemical buffering function

The chemical buffering function was evaluated using four indicators: CEC, SOC, soil pH suitability, and BS. Among these indicators, soil pH exhibited the highest normalized score (0.92), indicating that most land units maintain chemical conditions close to the optimal range for cocoa cultivation.

CEC showed a normalized score of 0.67, reflecting moderate to strong nutrient retention capacity. Soil organic carbon contributed a moderate score of 0.55, supporting both nutrient exchange processes and soil structural stability.

Table 4. Indicators and weighted scores for the chemical buffering function

Indicator	NC	Weight	WC
Cation Exchangeable Capacity	0.67	0.30	0.20
Soil Organic Carbon Contribution	0.55	0.25	0.14
pH Suitability	0.92	0.25	0.23
Base Saturation	0.50	0.20	0.10
Chemical Buffering Function Index			0.73

Notes: 1. NC = normalized score. 2. WC = weighted contribution.

Following weighted aggregation, the Chemical Buffering Function Index reached 0.73 (Table 4). This result indicates that the soil system maintains adequate chemical buffering capacity to sustain nutrient availability under continuous perennial cultivation.

Shifts in land-use management profoundly affect soil organic carbon reservoirs and the subsequent cycling of plant-available nutrients [32, 33]. In particular, diversified agroforestry configurations have been shown to stabilize organic matter fractions and enhance the soil's capacity to retain and buffer essential cations against leaching [34, 35]. These organic inputs simultaneously sustain chemical buffering mechanisms and drive continuous nutrient cycling dynamics, which are critical for maintaining soil fertility under perennial cultivation [36].

3.5 Integrated soil functional performance and statistical validation

The hierarchical integration of the three functional domains—water regulation, structural stability, and chemical buffering—resulted in relatively comparable index values, namely 0.78, 0.72, and 0.73, respectively (Table 5). The limited variation among these indices indicates a balanced soil functional system in which hydrological, structural, and chemical processes operate in a complementary manner. Such balance reflects the characteristics of humid tropical agroecosystems, where water availability plays a dominant role in regulating soil processes [2, 4].

Table 5. Functional domain indices and their contribution to CSQI

Functional Domain	Index Value	Weight	C-CSQI
Water Regulation and Storage	0.78	0.34	0.27
Structural Stability	0.72	0.33	0.24
Chemical Buffering	0.73	0.33	0.24
CSQI			**0.74**

Notes: CSQI = Composite Soil Quality Index; C-CSQI = Contribution to CSQI.

The CSQI reached 0.74, indicating a high level of overall soil functional performance. Among the three domains, water regulation contributed the largest share (0.27), confirming its role as the dominant integrative driver of soil system performance. This finding is consistent with studies highlighting the central role of soil water dynamics in controlling ecosystem functionality and sustainability [7].

Pearson correlation analysis (Table 6) further supports this pattern, with water regulation showing the strongest relationship with CSQI ($r = 0.82$, $p < 0.01$), followed by structural stability ($r = 0.76$) and chemical buffering ($r = 0.74$). These results indicate that soil quality variations are closely linked to hydrological functioning, reinforcing the concept that soil water acts as a central regulator of soil system dynamics [5, 6].

Table 6. Pearson correlation between functional domains and CSQI

Variable	R	p	n
Water Regulation – CSQI	0.82	< 0.01	13
Structural Stability – CSQI	0.76	< 0.01	13
Chemical Buffering – CSQI	0.74	< 0.01	13

In addition, 95% confidence intervals (CI) were calculated to further assess the reliability of the correlation coefficients. The CI values remained within a consistent positive range, confirming the robustness of the observed relationships despite the limited sample size. For example, the correlation between water regulation and CSQI ($r = 0.82$) showed a 95% CI ranging from 0.49 to 0.94, indicating a strong and statistically reliable association.

The regression analysis provides deeper insight into this relationship (Table 7). The Water Regulation and Storage Index (WRSI) explained a substantial Proportion of CSQI variability ($R^2 = 0.67$, $p < 0.01$), indicating strong explanatory power at the system level. As illustrated in Figure 2, the close clustering of data points along the regression line suggests a stable and consistent system response across land units. This indicates that improvements in soil water regulation are systematically associated with improvements in overall soil functional performance.

Table 7. Regression analysis of functional domains

Model	R^2	p
WRSI → CSQI	0.67	< 0.01
WRSI → SSDCI	0.42	< 0.05

Notes 1: WRSI = Water Regulation and Storage Index. 2. SSDCI = Structural Stability and Degradation Control Index.

Although chemical buffering also showed a strong and significant correlation with CSQI, it was not included as an independent variable in the regression analysis. The regression model was intentionally designed to evaluate the dominant role of water regulation as the primary system driver, rather than to construct a full multivariate predictive model. Including all functional domains as predictors could lead to redundancy, as these variables are components of the composite index itself. It may also introduce multicollinearity due to their interdependence.

Given the limited sample size ($n = 13$), statistical inference was based on p-values, coefficients of determination (R^2), and CI, which together provide reliable measures of relationship strength and uncertainty in small-sample studies. Formal statistical comparisons among functional domain indices were not conducted because the indices are components of a hierarchical aggregation system and therefore are not independent variables. Performing inferential tests on such structurally linked variables may lead to biased or misleading interpretations. Instead, the analysis emphasizes the evaluation of relationships, relative contributions, and functional interactions among domains within an integrated framework. This approach is consistent with function-based soil quality assessments that prioritize process-based interpretation over conventional hypothesis testing of mean differences.

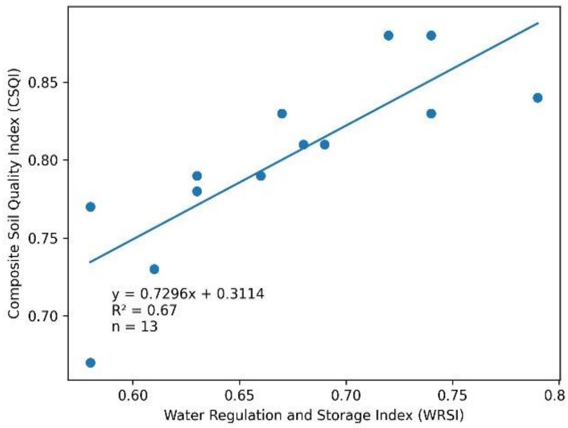

Figure 2. Linear relationship between the Water Regulation and Storage Index (WRSI) and the Composite Soil Quality Index (CSQI)

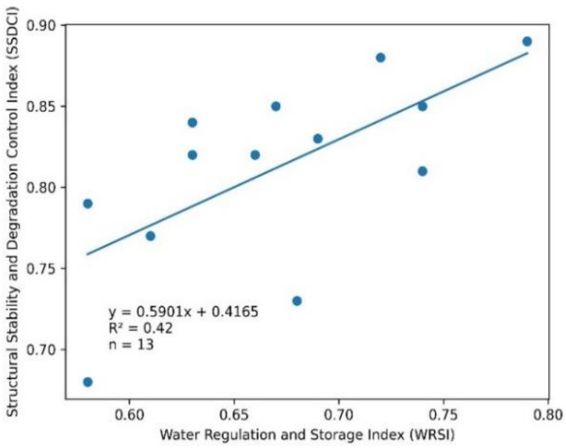

Figure 3. Linear relationship between the Water Regulation and Storage Index (WRSI) and the Structural Stability and Degradation Control Index (SSDCI)

In addition, a moderate but statistically significant relationship was observed between WRSI and structural stability ($R^2 = 0.42$, $p < 0.05$). As shown in Figure 3, the wider dispersion of data points reflects greater variability in structural responses, indicating that hydrological processes significantly influence, but do not solely determine, soil structural conditions. Other factors, particularly soil organic carbon, aggregation processes, and land management practices, also play important roles in determining soil structural stability. These results indicate that hydrological regulation plays a central role in overall soil system performance, whereas structural responses are influenced by interactions among hydrological conditions, soil organic carbon, aggregation processes, and inherent physical properties such as texture and BD [37, 38].

This dominant role of water regulation is supported by process-based studies showing that soil water availability is controlled by integrated physical properties such as BD, porosity, hydraulic conductivity, and aggregate stability, which collectively regulate infiltration and water storage. Strong relationships between these properties and available soil water capacity further indicate that hydrological behavior emerges from the interaction of multiple soil attributes rather than single parameters [39].

The role of soil organic matter is particularly important in explaining the linkage between hydrological, structural, and chemical functions. Organic matter acts as a binding agent that promotes aggregate formation, reduces BD, and increases porosity, thereby enhancing both water infiltration and retention [40]. In addition, organic matter stimulates microbial activity and nutrient cycling, contributing to improved soil structure and chemical buffering capacity [28, 40]. These mechanisms are further supported by empirical findings demonstrating that soil organic carbon exhibits nonlinear relationships with BD, hydraulic conductivity, and soil mechanical resistance, indicating the existence of an optimal range of organic matter for maintaining soil structural stability and hydraulic performance. However, the effectiveness of organic matter depends on its interaction with soil physical conditions and management practices [41]. This indicates that while hydrological processes influence soil structure and chemical functions, these functions are also controlled by intrinsic soil properties, particularly soil organic matter and physical soil conditions.

The regression relationships can be expressed as:

$$CSQI = 0.7296 \times WRSI + 0.3114 \quad (7)$$

$$SSDCI = 0.5901 \times WRSI + 0.4165 \quad (8)$$

where, WRSI and Structural Stability and Degradation Control Index (SSDCI) represent normalized functional scores ranging from 0 to 1 derived from weighted hydrological indicators.

These models indicate that increases in water regulation lead to proportional improvements in both composite soil quality and structural stability, although the magnitude of influence differs between system-level and domain-level responses.

Further analysis of inter-domain relationships (Table 8) revealed moderate but significant positive correlations between water regulation and structural stability ($r = 0.65$, $p < 0.05$), as well as between water regulation and chemical buffering ($r = 0.61$, $p < 0.05$). These findings indicate that soil functions are interconnected, forming an integrated system in which hydrological, physical, and chemical processes interact dynamically [42].

Table 8. Correlation among functional domains

Variable Pair	R	p
WRSI - SSDCI	0.65	< 0.05
WRSI - CB	0.61	< 0.05

Notes 1: WRSI = Water Regulation and Storage Index. 2. SSDCI = Structural Stability and Degradation Control Index. 3. CB = Nutrient Retention and Chemical Buffering.

This interdependence is consistent with findings that soil functions such as water redistribution, biological activity, and filtering–buffering capacity are controlled by overlapping soil physical properties and organic matter dynamics [39]. The strong linkage between AWC, aggregate stability, and nutrient retention further supports the concept that soil quality should be evaluated as an integrated system rather than through isolated indicators [2].

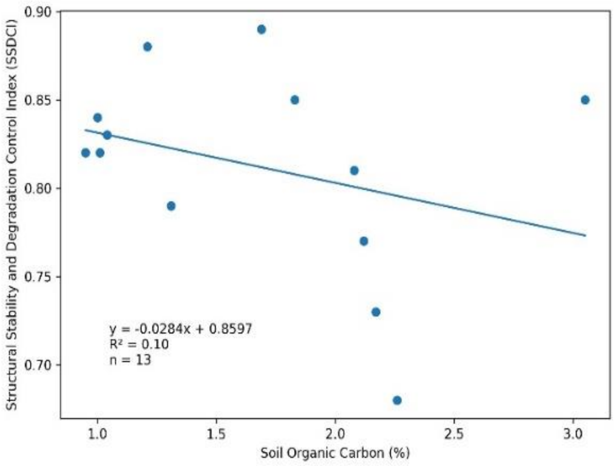

Figure 4. Relationship between soil organic carbon and Structural Stability and Degradation Control Index (SSDCI)

These quantitative results provide a clear statistical basis for interpreting interdependence among soil functional domains, addressing the previously qualitative interpretation.

The relationships among SOC, BD, and SSDCI provide additional insight into the role of soil intrinsic factors in shaping functional interactions. As shown in Figure 4, SOC exhibited a weak relationship with SSDCI, indicating that organic matter alone did not directly determine structural stability.

In contrast, BD showed a clearer negative relationship with SSDCI (Figure 5), confirming that soil compaction is a key limiting factor for structural stability.

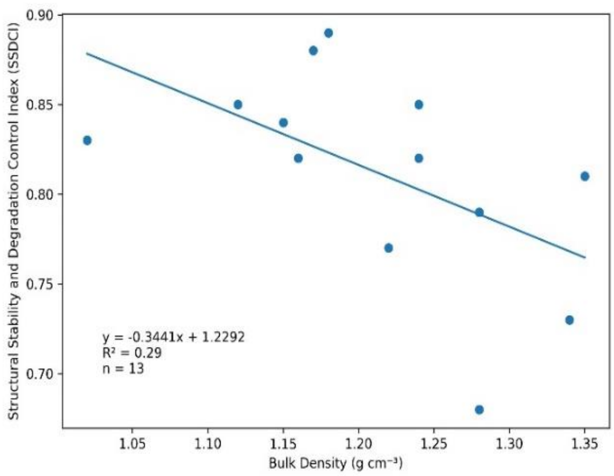

Figure 5. Relationship between bulk density (BD) and Structural Stability and Degradation Control Index (SSDCI)

Furthermore, SOC displayed a weak to moderate positive association with BD (Figure 6), suggesting that higher organic carbon did not consistently correspond to lower soil compaction.

These patterns are closely related to differences in land use. In several monoculture sites, relatively high SOC values were accompanied by high BD and moderate to low SSDCI, indicating that organic matter accumulation did not necessarily improve soil structure under more intensive management conditions. In contrast, agroforestry systems tended to exhibit lower BD and relatively stable SSDCI values, even when SOC levels varied. This indicates that land use plays a critical role in regulating soil physical conditions, particularly soil compaction, which in turn controls structural stability.

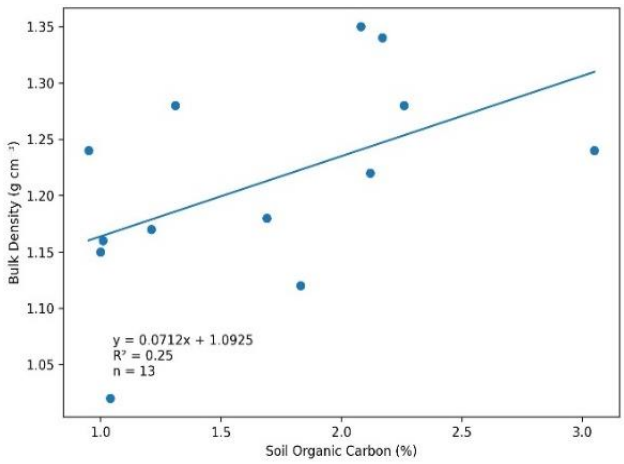

Figure 6. Relationship between soil organic carbon (SOC) and bulk density (BD)

Overall, these results demonstrate that the influence of SOC on structural stability is indirect and depends on soil physical conditions. While organic matter contributes to aggregation processes, its beneficial effects may be constrained when BD is high. This supports the interpretation that soil structural responses are governed by the interaction of multiple soil intrinsic factors rather than by a single variable, reinforcing the integrated nature of soil functional domains within the hierarchical framework.

Importantly, no evidence of trade-offs among functional domains was observed, as all relationships were positive. These consistently positive relationships suggest functional compatibility among soil domains under the studied conditions. However, such relationships may vary under different environmental conditions, particularly where excessive water availability may induce nutrient leaching or structural degradation [43].

The robustness of the proposed framework was evaluated using sensitivity analysis with ±10% variation in domain weights. The resulting CSQI values ranged from 0.71 to 0.77, demonstrating that the framework remained relatively stable under moderate weighting adjustments. This robustness aligns with the need for adaptive and simplified soil quality models capable of supporting land management decisions under complex environmental conditions [39].

From an applied perspective, the framework provides a practical and process-informed tool for identifying priority areas for soil conservation and supporting sustainable land-use planning at the watershed scale. Nevertheless, as detailed in Section 2.1, the analysis relies on a 2004-2005 baseline dataset and focuses on process-based relationships rather than temporal monitoring. The USLE component captures surface erosion only, and biological indicators were not included. Future implementations should integrate contemporary field data, subsurface erosion pathways, and biological metrics to enhance the framework's comprehensiveness.

4. CONCLUSIONS

This study demonstrates that soil quality in the upper Gumbasa watershed is governed by the integrated performance of water regulation, structural stability, and chemical buffering functions within a hierarchical framework. The CSQI value of 0.74 indicates a high level of soil functional performance under the studied conditions.

Among the three domains, water regulation emerged as the dominant driver, exhibiting the strongest relationship with CSQI ($r = 0.82$, $p < 0.01$) and explaining a substantial proportion of its variability ($R^2 = 0.67$). These findings confirm that soil water dynamics play a central role in regulating overall soil system performance. In addition, the moderate relationship between water regulation and structural stability ($R^2 = 0.42$) indicates that hydrological processes significantly influence, but do not solely determine, soil structural conditions.

The results further reveal that soil functions are interconnected while maintaining partial independence. The consistently positive relationships among functional domains indicate a synergistic system in which improvements in one function are associated with improvements in others. No evidence of trade-offs was observed under the studied conditions.

Sensitivity analysis indicates that the CSQI varies within a narrow range (0.71-0.77) under ±10% variation in domain weights, demonstrating the robustness and stability of the hierarchical framework. This supports its reliability for soil quality assessment in complex tropical environments.

From a methodological perspective, this study highlights the advantage of integrating hydrological processes within a structured, function-based framework to improve both interpretability and analytical consistency compared with conventional parameter-based approaches. From an applied perspective, the framework provides a practical tool for identifying priority areas for soil conservation and supporting land-use planning at the watershed scale.

While the framework demonstrates high methodological robustness, interpretations remain bounded by the 2004-2005 baseline dataset and the surface-erosion focus of the USLE model. Future validation with contemporary monitoring data, inclusion of biological indicators, and integration of dynamic process-based modeling will further strengthen its temporal transferability and spatial applicability.

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