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RESEARCH ARTICLE

Integrated Assessment of Water Resource Sustainability in the Upper Amojú River Basin, Northern Peruvian Andes

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Abstract: This study presents a comprehensive, statistically robust assessment of water resource sustainability in the upper section of the Amojú River Basin, Province of Jaén northern Peruvian Andes, using the Sarandón multi-cirteria methodology. A stratified convenience sample of n = 887 households distributed across 22 localities was surveyed, achieving a margin of error of ±2.61% at the 95% confidence level (finite-population correction applied; N = 2391). Sustainability was assessed across social, environmental, and economic dimensions on a standardised ordinal scale (0–4). Statistical analyses included Shapiro Wilk normality tests, Wilcoxon signed-rank tests against the sustainability threshold ($\mu_0 = 2.0$), Spearman rank correlations, Kruskal Wallis tests, Cronbach's α for internal consistency, and Principal Component Analysis (PCA) to provide empirical support for the indicator weighting structure. The General Sustainability Index (I = 2.32±0.52; median = 2) confirmed that the basin operates at the minimum threshold of sustainability, with 97.4% of respondents classified as sustainable. The Social (SI = 2.52±0.75), Environmental (EI = 2.18±0.39), and Economic (KI = 2.30±0.67) indices all met the threshold criterion (≥2.0). Wilcoxon tests identified three sub-indicators as significantly below the sustainability threshold (all $p<0.001$): Conservation Zones (mean = 0.59±0.78; 89.4% of respondents scored <2), Solid Waste Management (mean = 1.23±0.89; 68.3% scored <2), and Water Flow Perception (mean = 1.16±0.52; 90.9% scored <2). All three dimension indices were significantly intercorrelated ($\rho = 0.271–0.388$, $p<0.001$) and contributed significantly to the general index ($\rho = 0.510–0.705$, $p<0.001$). Kruskal Wallis tests confirmed that sub-indicators differed significantly within each dimension ($H>971$, $p<0.001$ for all). These findings underscore the urgent need for integrated watershed governance encompassing solid waste management programmes, biodiversity conservation zones, and equitable water tariff policies in Andean headwater basins.

Keywords: Water Resource Sustainability, Sarandón Multi-Criteria Methodology, Watershed Assessment, Amojú River Basin, Peruvian Andes, Wilcoxon Signed-Rank Test, Principal Component Analysis

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Introduction

Tropical Andean headwater basins represent some of the most biologically diverse and ecologically sensitive ecosystems on Earth. These montane freshwater systems harbour exceptional levels of endemism, serve as critical dispersal corridors for aquatic and terrestrial biota, and provide essential ecosystem services that underpin both biodiversity conservation and human livelihoods. The eastern slopes of the Peruvian Andes, in particular, constitute a global biodiversity hotspot where the confluence of Amazonian and Andean biota creates uniquely rich assemblages of freshwater fish, amphibians, macroinvertebrates, and riparian plant communities [1, 2]. However, these ecosystems are increasingly threatened by accelerating land-use change, agricultural expansion, deforestation, artisanal mining, and the compounding effects of climate change, all of which compromise both hydrological function and biological integrity [3–5].

Headwater streams are particularly vulnerable to anthropogenic pressures because upstream land-use decisions directly determine downstream water availability, quality, and ecological functioning [6, 7]. In these systems, the loss of riparian vegetation, alteration of flow regimes, and pollution from inadequate waste management have documented cascading effects on aquatic communities, including declines in macroinvertebrate diversity, shifts in fish assemblage structure, and reduced ecosystem resilience. Furthermore, the biological integrity of Andean headwater streams is tightly coupled to hydrological stability, which is increasingly compromised by glacier retreat, reduced infiltration capacity, and altered precipitation patterns [8, 9]. Community-detected changes in water availability, such as perceptions of declining flow, often serve as early warning signals of broader ecological degradation that warrant systematic investigation [10, 11].

In northern Peru, growing tensions over water resources between rural communities, urban centres, and extractive industries have been documented across several Andean basins [12]. The Amojú River Basin, located in the Province of Jaén (Department of Cajamarca), is emblematic of these challenges. Situated in a transitional Andean-Amazonian zone, the basin supports a predominantly rural population engaged in coffee, cacao, and subsistence agriculture. This region is ecologically significant due to its position within the broader Marañón River system, which harbours high levels of freshwater fish endemism and serves as an important corridor for biodiversity connectivity between Andean and Amazonian ecosystems [13]. Despite its ecological importance, the basin has experienced intensifying deforestation, improper solid waste disposal, and reported declines in water flow, as documented by local communities and preliminary investigations [14, 15]. A prior study employing the Watershed Sustainability Index (WSI) during 2017–2021 provided baseline assessments of policy and environmental components [16]; however, no integrated assessment has linked community-level social, economic, and environmental indicators to biological and ecological endpoints in a statistically validated framework for this upper basin.

Effective watershed conservation requires assessment methodologies capable of capturing the multidimensional nature of ecological integrity, incorporating both measurable biophysical parameters and community-level indicators that reflect local ecological knowledge and land-use practices [5, 10, 17]. The multi-criteria framework proposed by [18] provides a structured approach for constructing composite sustainability indices through the weighting of dimension-specific indicators and sub-indicators on a standardised ordinal scale (0–4). Although this methodology has been applied primarily to agroecosystem sustainability assessment in Latin America, its application to watershed contexts, particularly for identifying community-detectable threats to aquatic and terrestrial biodiversity, remains limited, especially in Andean headwater systems.

The present study addresses this gap by conducting a statistically rigorous, community-based assessment of water resource sustainability in the upper Amojú River Basin, with explicit emphasis on sub-indicators of ecological condition and biodiversity conservation. The specific objectives were:

(i) To quantify the General Sustainability Index and dimension-specific indices (social, environmental, economic) using the Sarandón methodology, with emphasis on environmental sub-indicators that directly affect biological integrity

(ii) To statistically identify sub-indicators significantly below the sustainability threshold using Wilcoxon signed-rank tests, with biological interpretation of their ecological implications

(iii) To assess inter-dimensional relationships through Spearman rank correlation to understand how social and economic factors mediate ecological outcomes

(iv) To provide empirical justification for the indicator weighting structure through principal component analysis

The findings are intended to inform evidence based watershed governance strategies that prioritise conservation of riparian buffers, improved solid waste management, and hydrological sustainability as essential measures for safeguarding the biodiversity and ecological functioning of Andean headwater ecosystems.

Materials and Methods

Study Area

The study was conducted in the upper section of the Amojú River Basin, within the Province of Jaén, Department of Cajamarca, northeastern Peru (05°42'15″ S, 78°48'29″ W). The province covers an area of 5,232.57 km² with an average altitude of 766 m a.s.l. (range: 8.5–36.0°C mean annual temperature). The Amojú River originates at approximately 1,800 m a.s.l. on the western slopes of the basin and flows in a broadly northeasterly direction before discharging into the Marañón River system.

Ecologically, the upper Amojú Basin is situated within a transitional zone between Andean montane forests and Amazonian lowland ecosystems, rendering it a region of high biodiversity significance. The Marañón River system, of which the Amojú is a tributary, is recognised for its high levels of freshwater fish endemism and supports diverse assemblages of aquatic macroinvertebrates, amphibians, and riparian flora [2, 13]. The study area encompassed 22 rural populated centres, hamlets, and annexes distributed across the municipalities of Jaén and Las Pirias (Figure 1). These localities are characterised by smallholder agricultural systems in which coffee (Coffea arabica), cacao (Theobroma cacao), and mixed subsistence crops predominate. Land-use change in the basin, particularly deforestation for agricultural expansion, has been identified as a primary driver of habitat fragmentation, reduced riparian connectivity, and altered hydrological regimes, all of which have documented negative effects on aquatic and terrestrial biodiversity [6, 7].

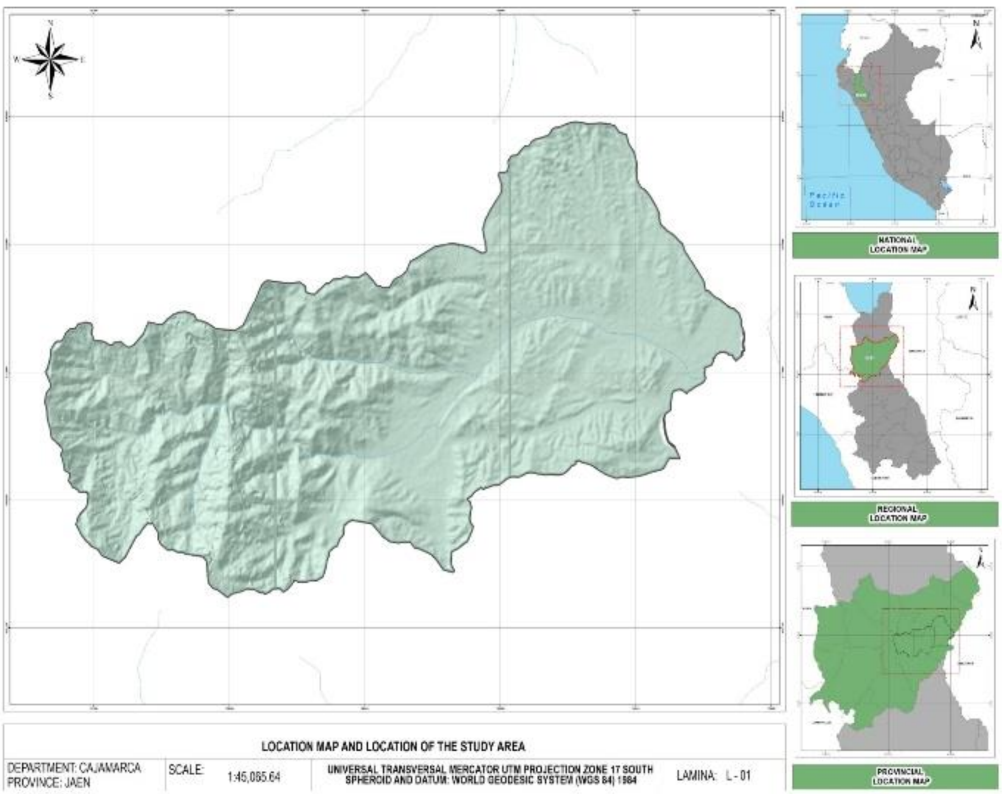

Fig. 1: Location map of the province of Jaén and the study area. The upper Amojú River Basin lies within a transitional Andean-Amazonian ecotone, supporting high biodiversity and endemism but facing intensifying anthropogenic pressures

Population, Sample Design, and Sampling Adequacy

The target population comprised households located within the upper Amojú River Basin. Population projections for 2023 were derived from the 2007 and 2017 National Population Censuses [19], applying district-specific annual rural growth rates (Jaén: −1.4%; Las Pirias: +1.8%) using the compound growth formula:

$$Pf = P0 * (1 + \frac{Tc}{100})^t$$

Where, *Tc* = growth rate, *Pf* = final population, *P0* = initial population, and *t* = time.

The projected total population across 22 localities was N = 2,391 persons (2023). Sample size was determined using the finite-population formula:

$$n = \frac{z^2 \times P \times Q \times N}{E^2 \times N + z^2 \times P \times Q}$$

Applying a conservative maximum-variance proportion (*P* = *Q* = 0.50), a 95% confidence level (*z* = 1.96), and a target margin of error of 3.0% (*E* = 0.030) yielded a required minimum sample of *n* = 738. The study obtained *n* = 887 complete responses, surpassing this minimum. Applying the finite-population correction factor:

$$FPC = \sqrt{\frac{\boldsymbol{N-n}}{\boldsymbol{N-1}}},$$

the achieved margin of error was ±2.61% at the 95% confidence level, a precision level substantially exceeding conventional survey standards for applied ecological and conservation research. Proportional allocation was used to distribute the sample across the 22 localities. Data were collected through structured face-to-face household surveys administered between January and June 2023. All survey protocols were approved by the institutional ethics committee, and informed consent was obtained from all participants prior to data collection.

Sarandón Multi Criteria Sustainability Framework

Water resource sustainability and its implications for ecological integrity were evaluated using the multi-criteria indicator framework proposed by [18], adapted to the hydrological, socioeconomic, and ecological context of the Amojú Basin. This approach assesses sustainability through three complementary dimensions: Social (SI), Environmental (EI), and Economic (KI). Each dimension is operationalised through hierarchically organised indicators, which in turn comprise specific sub-indicators rated on a standardised ordinal scale (0 = non-sustainable; 4 = highly sustainable). A composite dimension score ≥2.0 (the midpoint of the scale) is defined as the minimum sustainability criterion, provided no individual dimension falls below this threshold [18].

Crucially, within the Environmental dimension, several sub-indicators possess direct biological and ecological relevance:

- Conservation Zones (C1): This sub-indicator directly measures the presence or absence of designated conservation areas (e.g., riparian buffers, forest refugia, or protected habitat). The absence of such zones has well-documented negative effects on biodiversity, including loss of habitat connectivity, reduced refugia for endemic species, and impaired ecosystem functioning [20, 21]
- Solid Waste Management (A3): Inadequate waste disposal practices (burning, open-field disposal) introduce persistent organic pollutants, heavy metals, and microplastics into watersheds, with documented toxic effects on aquatic biota, including macroinvertebrates, fish, and amphibians [22–26].
- Water Flow Perception (D1): Community perceptions of declining water flow serve as early warning signals of hydrological alteration, which has cascading effects on instream habitat availability, flow-adapted species, and overall aquatic ecosystem integrity [10, 11]
- Water Quality Parameters (E1–E6): Conductivity, pH, turbidity, COD, BOD_5, and coliforms are standard bioassessment parameters with known relationships to aquatic biota. Elevated turbidity, for example, reduces light penetration and primary productivity, while high BOD_5 and coliform counts indicate organic pollution that can deplete dissolved oxygen and harm sensitive species

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Table 1 presents the complete indicator and sub-indicator framework with annotations linking each environmental sub-indicator to its biological or ecological relevance.

Table 1: Sarandón Multi-criteria Framework: Dimensions, Indicators, and Sub-indicators, with Biological/Ecological Annotations

Dimension	Indicator	Sub-indicators (Code)	Scale	Biological/Ecological Relevance
Social	A. Satisfaction of Basic Needs	A1. Education Access; A2. Housing Quality; A3. Basic Services; A4. Health Coverage	0–4	Indirect mediators of community capacity for conservation action
	B. Social Integration	B1. Org. Membership; B2. Org. Commitment	0–4	Reflects community collective action potential for watershed stewardship
	C. Environmental Acceptance	C1. Watershed Perception	0–4	Community attitudes towards conservation; positive attitudes facilitate biodiversity protection
Environmental	A. Soil & Environment Conservation	A1. Vegetative Cover*; A2. Crop Diversification; A3. Solid Waste Management	0–4	Vegetation cover directly affects habitat connectivity; waste management affects aquatic toxicity
	B. Erosion Risk	B1. Predominant Slope; B2. Soil Conservation	0–4	Soil loss affects water quality, sedimentation of instream habitats, and benthic communities
	C. Biodiversity Management	C1. Conservation Zones	0–4	Direct measure of habitat refugia and biodiversity conservation areas
	D. Water Perception	D1. Water Flow Perception; D2. Water Source Access*	0–4	Perception of hydrological alteration; affects instream habitat and flow-adapted biota
	E. Water Quality Parameters (†)	E1. Conductivity; E2. pH; E3. Turbidity; E4. COD; E5. BOD_5; E6. Coliforms	0 or 4	Standard bioassessment parameters; direct measures of aquatic ecosystem health
Economic	A. Net Family Income	A1. Net Monthly Income; A2. Economically Active Members	0–4	Income affects capacity for sustainable land management and conservation investments
	B. Economic Risk	B1. Water Service Payment†; B2. Product Diversification; B3. Social Conflicts; B4. Public Investment	0–4	Economic stability mediates community resilience and conservation capacity

*Notes: Constant across all respondents (uniform score assigned to all localities). † Constant sub-indicator (eco_pago_agua = 1 for all n = 887 respondents; reported separately as a uniform critical condition). E-group parameters reflect a single basin-wide water quality measurement; excluded from within-respondent statistical analyses

The weighting formulae for each dimension are as follows (where indicator scores represent the mean of their respective sub-indicators):

$$SI = \frac{2A+B+C}{4}$$ (Social: A double-weighted, range 0–4)

$$EI = \frac{2A+B+C+D+2E}{7}$$ (Environmental: A and E double-weighted)

$$KI = \frac{2A+B}{3}$$ (Economic: A double-weighted)

$$I = \frac{SI+EI+KI}{3}$$ (General Sustainability Index)

The double-weighting assigned to specific indicators (Satisfaction of Basic Needs in the Social dimension; Soil & Environment Conservation and Water Quality Parameters in the Environmental dimension; Net Family Income in the Economic dimension) reflects their primacy in determining sustainability outcomes, as established through expert consultation with technical specialists in watershed management, conservation biology, and rural sustainability. The empirical support for this weighting structure was further investigated through principal component analysis, as detailed in Section 2.4.

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Statistical Analysis

All statistical analyses were performed in Python 3.12 using the pandas, NumPy, SciPy, scikit-learn, and matplotlib/seaborn libraries. The analytical protocol comprised the following procedures:

(i) Normality assessment. The Shapiro Wilk test was applied to all sub-indicators and dimension indices (subsamples of *n* = 200 used where required). All variables exhibited significant departures from normality (*p*<0.05 in all cases), justifying the exclusive use of non-parametric inferential tests throughout

(ii) Descriptive statistics. For each sub-indicator, the mean, standard deviation, median, Interquartile Range (IQR), mode, and proportion of respondents scoring below the sustainability threshold were computed

(iii) Wilcoxon signed-rank tests. Each sub-indicator was tested against the sustainability threshold (μ_0 = 2.0) using a bilateral Wilcoxon signed-rank test (zero-method = 'wilcox'). Effect sizes were estimated as the rank-biserial correlation coefficient ($|r_e|$). The familywise error rate was controlled using the Bonferroni correction (α_adj = 0.05/18 = 0.003). Sub-indicators with a median score <2.0 and a significant test result were classified as 'critical'. For biological interpretation, critical sub-indicators were further evaluated for their documented ecological implications based on published literature

(iv) Spearman rank correlations. Pairwise Spearman ρ coefficients were computed among all variable sub-indicators and between the three dimension indices and the general index. These correlations were used to assess the extent to which social and economic factors mediate ecological outcomes

(v) Kruskal–Wallis test. Within each dimension, the distributions of sub-indicator scores were compared using the Kruskal–Wallis H-test to assess whether sub-indicators exhibited significantly different score profiles, thereby justifying their separate treatment in the composite index.

(vi) Internal consistency. Cronbach's α was computed for the sub-indicator sets of each dimension as a measure of scale reliability, using only items with non-zero variance. It is acknowledged that in multi-criteria composite indices designed to capture heterogeneous sustainability dimensions, particularly when some sub-indicators are intended to measure distinct ecological endpoints, lower α values are expected, as the sub-indicators are intentionally constructed to measure distinct aspects rather than a single latent construct [27, 28]. Internal consistency is therefore presented as an auxiliary diagnostic rather than a validity criterion

(vii) Principal Component Analysis (PCA). PCA was applied to the full set of variable sub-indicators (*n* = 18; standardised prior to decomposition) to investigate the latent structure of the data and to evaluate whether the empirical variance structure supported the a priori weighting assigned to indicators within the Sarandón framework. In the context of this biological assessment, PCA served to identify whether sub-indicators with explicit ecological relevance (e.g., Conservation Zones, Solid Waste Management, Water Flow Perception) loaded onto distinct principal components, thereby confirming their unique contribution to the environmental dimension and justifying their independent treatment in conservation planning

Results

Sample Adequacy and Descriptive

A total of n = 887 valid household questionnaires were collected across 22 localities in the upper Amojú River Basin. With a projected population of N = 2391 and applying the finite-population correction, the achieved margin of error was ±2.61% at the 95% confidence level, providing a precision standard appropriate for applied ecological and watershed conservation research. The Shapiro Wilk test confirmed significant departures from normality in all sub-indicators (p<0.05), validating the non-parametric analytical approach. Table 2 presents descriptive statistics for all sub-indicators and sustainability indices, with particular emphasis on environmental sub-indicators that carry direct biological and ecological implications.

Internal Consistency and Structural Validity

Cronbach's α was computed for each dimension's sub-indicator set: Social dimension (α = 0.648; *k* = 7 items), Environmental dimension (α = 0.339; *k* = 6 items), and Economic dimension (α = 0.059; *k* = 5 items). The Social dimension achieved a questionable-to-acceptable α, whereas the Environmental and Economic dimensions exhibited lower values,

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consistent with the design principle of multi-criteria composite indices wherein sub-indicators intentionally represent heterogeneous sustainability domains, including distinct ecological endpoints, rather than a unidimensional latent construct [27, 28]. The Kruskal–Wallis test confirmed that sub-indicator score distributions differed significantly within each dimension (Social: H = 971.9, *p*<0.001; Environmental: H = 3385.8, *p*<0.001; Economic: H = 1383.7, *p*<0.001), supporting the rationale for assigning differential weights to individual indicators within the composite formula. Critically, this within-dimension heterogeneity confirms that environmental sub-indicators with direct ecological relevance (Conservation Zones, Solid Waste Management, Water Flow Perception) capture distinct aspects of ecological condition that warrant independent treatment in conservation planning.

Table 2: Descriptive Statistics for All Sub-indicators and Sustainability Indices (*n* = 887), with Emphasis on Environmental Sub-indicators of Ecological Significance

Variable	Dimension	Mean	SD	Median	IQR	% Below Threshold (< 2)
Education Access	Social	3.15	0.86	3.0	3.0–4.0	5.1%
Housing Quality	Social	2.56	0.93	3.0	2.0–3.0	8.5%
Basic Services	Social	1.73	0.62	2.0	1.0–2.0	33.6%
Health Coverage	Social	1.81	1.47	2.0	0.0–3.0	45.7%
Org. Membership	Social	2.08	2.00	4.0	0.0–4.0	48.0%
Org. Commitment	Social	1.90	1.87	2.0	0.0–4.0	48.3%
Environmental Acceptance	Social	3.20	0.80	3.0	3.0–4.0	2.3%
Crop Diversification	Environmental	2.13	0.55	2.0	2.0–2.0	7.1%
Solid Waste Management	Environmental	1.23	0.89	1.0	1.0–2.0	68.3%
Slope/Erosion Risk	Environmental	2.68	0.54	3.0	2.0–3.0	1.1%
Soil Conservation	Environmental	2.96	0.65	3.0	3.0–3.0	3.8%
Conservation Zones	Environmental	0.59	0.78	0.0	0.0–1.0	89.4%
Water Flow Perception	Environmental	1.16	0.52	1.0	1.0–1.0	90.9%
Net Monthly Income	Economic	1.79	1.12	2.0	1.0–3.0	41.1%
Economic Cooperation	Economic	2.52	1.03	3.0	2.0–3.0	14.0%
Product Diversification	Economic	2.46	0.57	2.0	2.0–3.0	2.5%
Absence of Conflicts	Economic	3.75	0.97	4.0	4.0–4.0	6.3%
Public Investment	Economic	2.59	1.91	4.0	0.0–4.0	35.2%
Net Monthly Income	Economic	1.79	1.12	2.0	1.0–3.0	41.1%
Economic Cooperation	Economic	2.52	1.03	3.0	2.0–3.0	14.0%
Product Diversification	Economic	2.46	0.57	2.0	2.0–3.0	2.5%
Absence of Conflicts	Economic	3.75	0.97	4.0	4.0–4.0	6.3%
Public Investment	Economic	2.59	1.91	4.0	0.0–4.0	35.2%
idx_social	Index	2.52	0.75	2.0	2.0–3.0	5.9%
idx_ambiental	Index	2.18	0.39	2.0	2.0–2.0	0.0%
idx_economico	Index	2.30	0.67	2.0	2.0–3.0	11.7%
idx_general	Index	2.32	0.52	2.0	2.0–3.0	2.6%

SD = standard deviation; IQR = interquartile range. Indices (idx_) display % of respondents with index score <2.0. All distributions are non-normal (Shapiro–Wilk p<0.05). Bolded rows indicate environmental sub-indicators with direct biological and ecological significance

PCA of the 18 variable sub-indicators identified 11 components required to explain ≥80% of total variance, and 13 components to explain ≥90% (Figure 7). The first three principal components collectively accounted for 41.2% of variance. The structure of PC1 loadings demonstrated that sub-indicators receiving double-weighting in the Sarandón formula

(Satisfaction of Basic Needs and Net Family Income) contributed amongst the highest absolute loadings, providing empirical corroboration for the a priori weighting scheme. Notably, the environmental sub-indicators with direct ecological relevance, Conservation Zones, Solid Waste Management, and Water Flow Perception, loaded onto distinct components, confirming that they capture unique dimensions of ecological risk that are not fully represented by other sub-indicators.

Figure 7: Principal component analysis of 18 variable sub-indicators (standardised; *n* = 887):

(A) Scree plot showing individual and cumulative variance explained

(B) Biplot of PC1 vs PC2 loadings and respondent scores

Arrow colours correspond to sustainability dimensions. Environmental sub-indicators with direct ecological relevance (Conservation Zones, Solid Waste Management, Water Flow Perception) show distinct loading patterns, indicating they capture unique dimensions of ecological condition. Dashed line = 80% cumulative variance threshold.

Social Sustainability Assessment (SI)

The Social Sustainability Index (SI) yielded a mean of 2.52±0.75 (median = 2), with 94.1% of respondents achieving SI ≥2.0 (Figures 2, 8). Education Access (mean = 3.15±0.86) and Environmental Acceptance (mean = 3.20±0.80) were the highest-scoring sub-indicators, reflecting adequate educational infrastructure and a predominantly favourable attitude towards the rural environment (Figure 4). This high Environmental Acceptance is a positive indicator for future conservation interventions, as community attitudes towards the environment are known to mediate the success of biodiversity protection programmes [17, 29, 30]. Wilcoxon tests confirmed that both sub-indicators were significantly above the threshold (*p*<0.001).

Conversely, Basic Services (mean = 1.73±0.62; 33.6% below threshold) and Health Coverage (mean = 1.81±1.47; 45.7% below threshold) remained at the threshold level, indicating deficits in utility services and healthcare proximity for a substantial proportion of the population (Figure 3). Of the total surveyed population, 64% reported access only to primary education, 31% to both primary and secondary levels, and 5% to no formal educational facility within their locality. Only 23% of households were situated within 1 km of a health centre, whilst 26% were located more than 10 km from the nearest medical facility, a condition of particular concern for emergency healthcare access in remote headwater communities. These social deficits may indirectly affect ecological outcomes by limiting community capacity for participation in conservation programmes and reducing adaptive capacity to environmental change.

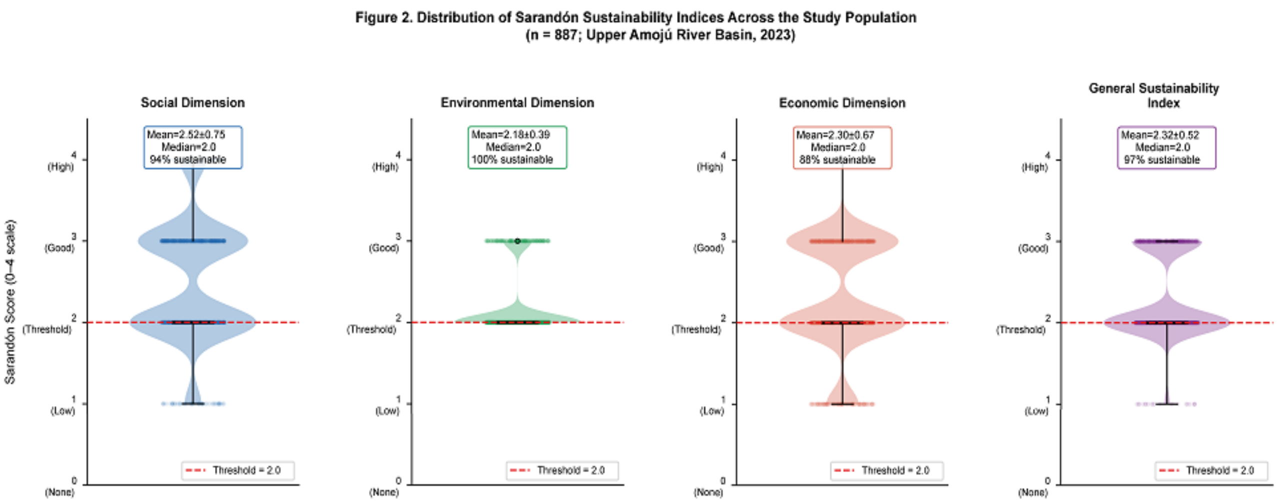

Fig. 2: Distribution of Sarandón sustainability indices across all respondents (*n* = 887). Violin plots show kernel density estimates; embedded box plots indicate median, interquartile range, and outliers. Dashed red line = sustainability threshold (score = 2.0). The Environmental Index (EI) shows the lowest variability, reflecting the homogenising effect of constant water quality parameters. Statistical summaries are displayed within each panel

Figure 8. Sustainability category distribution by dimension index and general index (*n* = 887). Percentages are annotated above each bar. Categories follow the Sarandón classification: score = 1 (non-sustainable), score = 2 (threshold), score = 3 (sustainable), score = 4 (highly sustainable).

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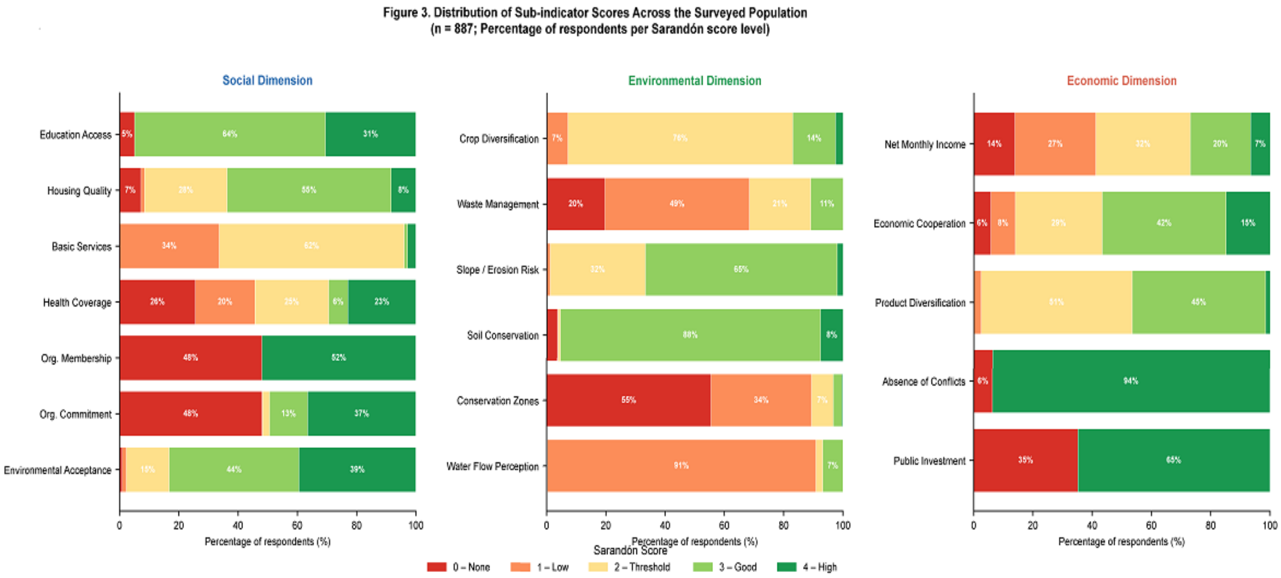

Fig. 3: Response frequency distributions for all sub-indicators, stratified by Sarandón score level (0–4; *n* = 887). Percentage of respondents at each score level is annotated for bars exceeding 6%. Environmental sub-indicators with direct ecological relevance, Conservation Zones, Solid Waste Management, and Water Flow Perception, show the highest proportions of scores below the sustainability threshold

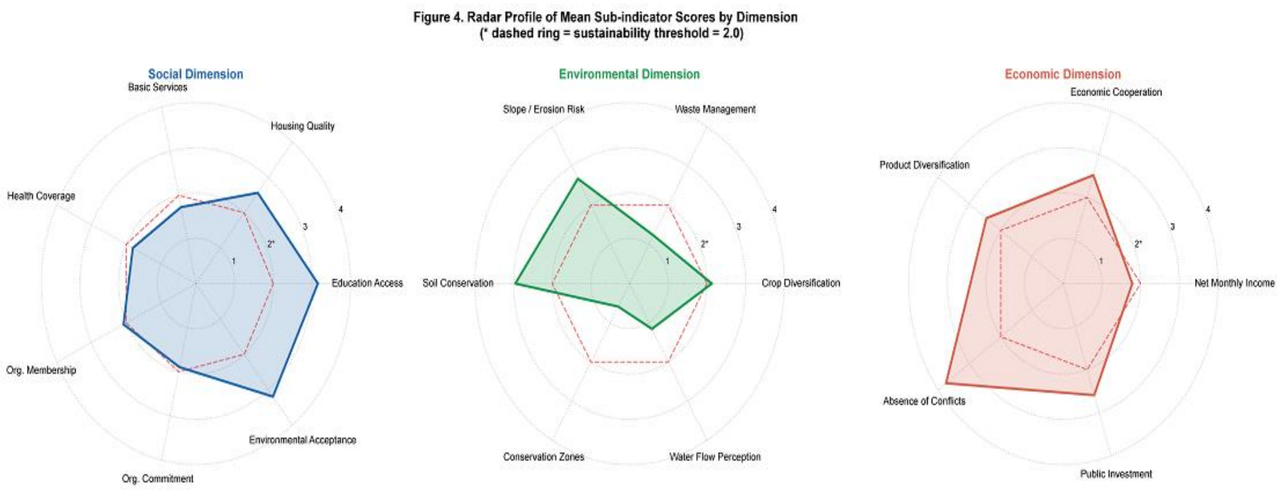

Fig. 4: Radar profiles of mean sub-indicator scores by sustainability dimension. The dashed concentric ring denotes the sustainability threshold (score = 2.0). Environmental sub-indicators with direct biological relevance, Conservation Zones (C1), Solid Waste Management (A3), and Water Flow Perception (D1), fall within the non-sustainable region (scores <2.0). Values are means across *n* = 887 respondents

Environmental Sustainability Assessment (EI)

The Environmental Sustainability Index (EI) yielded a mean of 2.18±0.39 (median = 2), with all 100.0% of respondents achieving EI ≥ 2.0. The notably low standard deviation (SD = 0.39) reflects the homogenising effect of the water quality constant parameters (sub-indicators E1, E3–E6: score = 4; E2-Turbidity: score = 0 basin-wide) and the uniform vegetative cover score (amb_cob_vegetal = 3 for all respondents), which collectively constrain the distributional variability of EI (Figure 3).

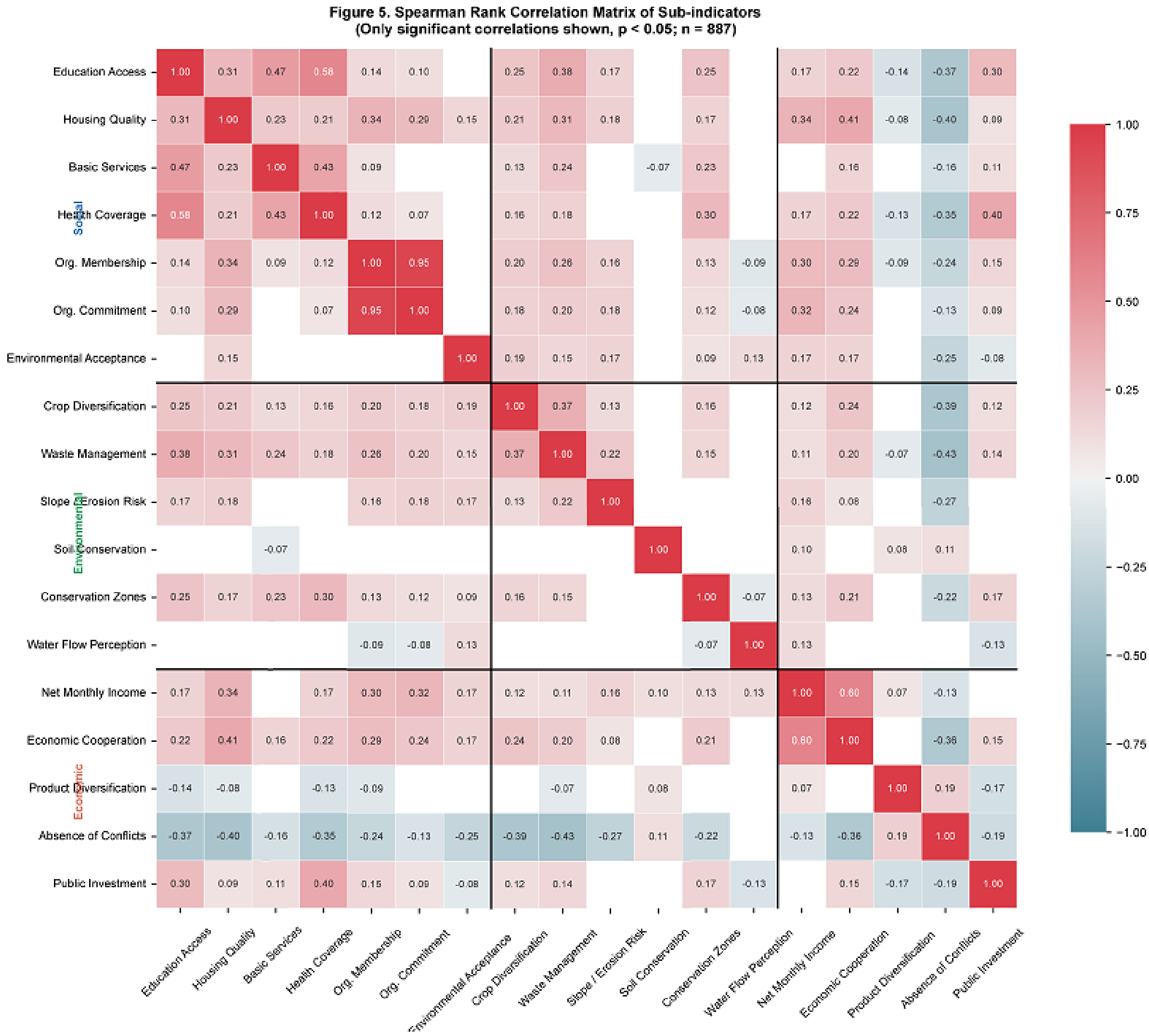

Fig. 5: Spearman rank correlation matrix of sub-indicators (*n* = 887). Only statistically significant correlations are displayed (*p*<0.05). Black lines separate the three sustainability dimensions. Environmental sub-indicators with direct ecological relevance (Conservation Zones, Solid Waste Management, Water Flow Perception) show limited correlation with other sub-indicators, indicating they capture unique dimensions of ecological risk. Colour scale: blue = positive correlation; red = negative correlation

Three environmental sub-indicators were statistically identified as critically non-sustainable (Wilcoxon *p*<0.001, all with large effect sizes $|r_e|$ >0.5). These three sub-indicators represent the most significant threats to the biological integrity of the upper Amojú River Basin and warrant urgent conservation intervention:

(i) Conservation Zones (mean = 0.59±0.78; median = 0): The lowest-scoring sub-indicator across the entire framework. A total of 89.4% of respondents maintained no designated conservation area on their land, reflecting the near-complete absence of buffer zones free from agricultural activity. This finding has profound biological implications: the absence of conservation zones, including riparian buffers and forest refugia, directly threatens habitat connectivity, reduces refugia for endemic Andean species, and compromises the ecological functioning of headwater streams (Allan, 2004). The Marañón River system, of which the Amojú is a tributary, is known for high freshwater fish endemism; the loss of riparian habitat in the upper basin may have cascading effects on downstream biodiversity [2].

(ii) Water Flow Perception (mean = 1.16±0.52; median = 1): Ninety-one per cent of respondents reported perceiving a decrease in water flow from their primary water source relative to previous years. This perceptual indicator provides a robust community-based signal of hydrological alteration, which has documented negative effects on instream habitat

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availability, flow-adapted species, and overall aquatic ecosystem integrity [10, 11]. Reduced base flows can lead to habitat fragmentation, increased water temperatures, and reduced dissolved oxygen concentrations, all of which adversely affect sensitive aquatic biota, including macroinvertebrates and fish

(iii) Solid Waste Management (mean = 1.23±0.89; median = 1): A total of 49% of respondents reported burning solid waste (including plastics), 21% used a home recycling pit, and 19% practised open-field disposal, with only 11% reporting any form of municipally or locally coordinated waste management. The absence of institutional solid waste management constitutes a direct risk to surface water quality and aquatic ecosystem health. Open burning releases persistent organic pollutants and heavy metals, while open-field disposal and burning introduce microplastics and toxic leachates into watersheds [22]. These contaminants have documented toxic effects on aquatic biota, including macroinvertebrates, amphibians, and fish, and can bioaccumulate through food webs

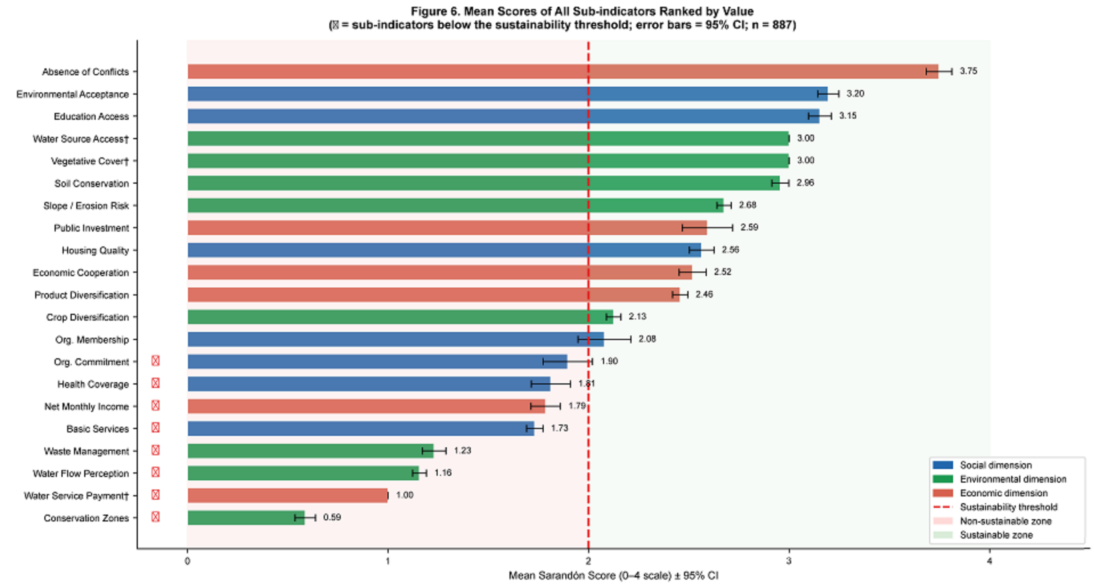

Fig. 6: All sub-indicators ranked by mean score (ascending). Error bars = 95% confidence intervals. ★ = sub-indicators with median < 2.0 (critical). The dashed vertical line denotes the sustainability threshold (score = 2.0). The three lowest-scoring sub-indicators, Conservation Zones, Solid Waste Management, and Water Flow Perception, are environmental sub-indicators with direct biological and ecological implications, indicating severe threats to aquatic and terrestrial biodiversity. Shaded zones: red = non-sustainable region; green = sustainable region. *n* = 887

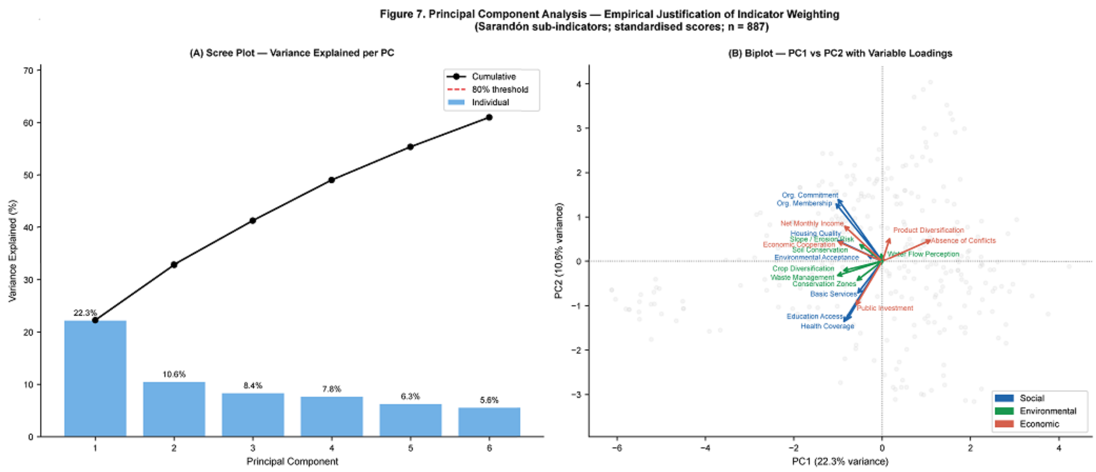

Fig. 7: Principal component analysis of 18 variable sub-indicators (standardised; *n* = 887). (A) Scree plot showing individual and cumulative variance explained. (B) Biplot of PC1 vs PC2 loadings and respondent scores. Arrow colours correspond to sustainability dimensions. Environmental sub-indicators with direct ecological relevance (Conservation Zones, Solid Waste Management, Water Flow Perception) show distinct loading patterns, indicating they capture unique dimensions of ecological condition. Dashed line = 80% cumulative variance threshold

Economic Sustainability Assessment (KI)

The Economic Sustainability Index (KI) yielded a mean of 2.30±0.67 (median = 2), with 88.3% of respondents classified as economically sustainable. Economic factors are critical mediators of conservation outcomes, as household income and economic stability influence the capacity of communities to invest in sustainable land management practices.

The most critical economic sub-indicator was Water Service Payment, which was constant at score = 1 across all 887 respondents (eco_pago_agua = 1): All households reported monthly water service fees of between S/. 1 and S/. 5, with no respondent exceeding S/. 3 per month. This uniform and critically low payment level structurally precludes cost-recovery for infrastructure maintenance and service improvement, representing a systemic economic risk to long-term water service sustainability. Inadequate water tariffs constrain investment in water treatment and watershed protection, indirectly affecting aquatic ecosystem health by limiting resources for conservation activities.

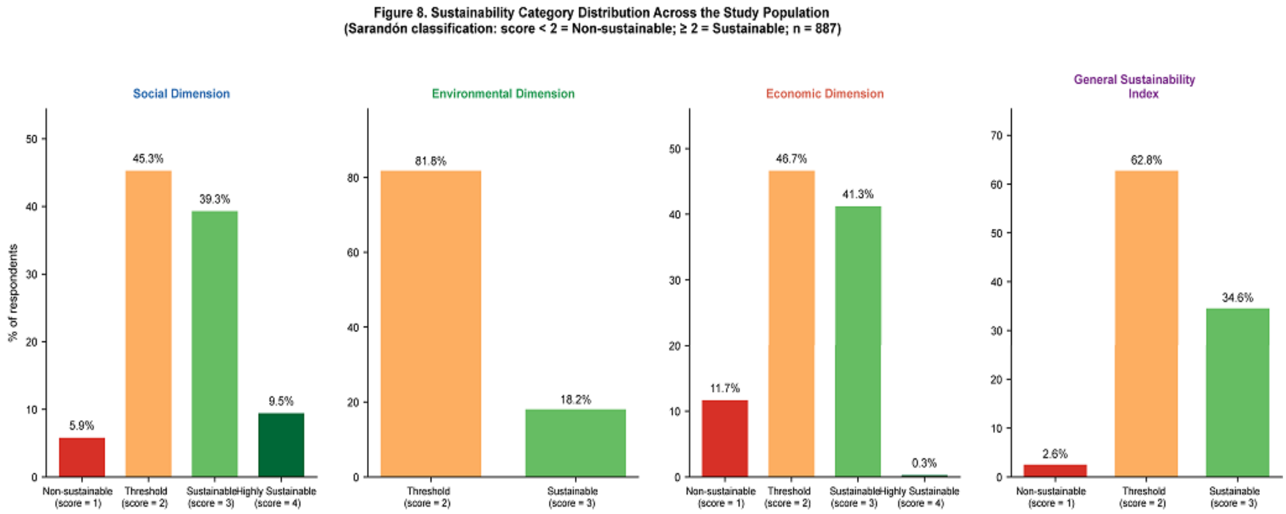

Fig. 8: Sustainability category distribution by dimension index and general index (*n* = 887). Percentages are annotated above each bar. Categories follow the Sarandón classification: score = 1 (non-sustainable), score = 2 (threshold), score = 3 (sustainable), score = 4 (highly sustainable)

Net Monthly Income showed a mean of 1.79±1.12, with 41.1% of respondents below the sustainability threshold. Of these, 14% reported incomes below S/. 400 and 27% between S/. 400 and S/. 650, reflecting precarious economic conditions relative to the national rural poverty line. Low household incomes limit the capacity of communities to participate in conservation programmes that may require foregone agricultural income or direct investment in sustainable practices.

Conversely, Absence of Social Conflicts (mean = 3.75±0.97) and Public Investment (mean = 2.59±1.91) were the strongest economic sub-indicators, with 93.7% and 64.8% of respondents, respectively, scoring at the maximum level [4]. The high Absence of Social Conflicts score is a positive indicator for community-based conservation, as social cohesion is a prerequisite for successful collective action in watershed management [29, 31].

General Sustainability Index (I) and Dimension Distributions

The General Sustainability Index yielded a mean of 2.32±0.52 (median = 2). Of the 887 respondents, 97.4% achieved I ≥2.0, with 34.6% scoring I = 3 (sustainable) and 62.8% scoring I = 2 (threshold). Only 2.6% of respondents (*n* = 23) were classified as non-sustainable (I = 1). Table 3 summarises the dimension and general index scores.

While the General Sustainability Index suggests that the basin operates at the minimum sustainability threshold, this aggregate score masks the severe deficits in ecologically critical sub-indicators. The high proportion of respondents achieving I≥2.0 (97.4%) reflects the mathematical structure of the composite index, in which strong performance on some sub-indicators (e.g., Absence of Conflicts, Education Access) offsets critically low scores on others. The identification of three environmental sub-indicators with mean scores below 1.5, Conservation Zones (0.59), Water Flow Perception (1.16), and Solid Waste Management (1.23), indicates that the biological integrity of the basin is at significant risk.

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Table 3: Sarandón Sustainability Dimension and General Index Results

Dimension	Index	Mean±SD	Median	% Sustainable (≥2.0)	% Non-sustainable (<2.0)	Ecological Interpretation
Social	SI	2.52±0.75	2	94.1%	5.9%	Community capacity for conservation action is at threshold level
Environmental	EI	2.18±0.39	2	100.0%	0.0%	Ecological condition is at minimum threshold; critical sub-indicators indicate severe biodiversity threats
Economic	KI	2.30±0.67	2	88.3%	11.7%	Economic constraints mediate conservation investment capacity
General	I	2.32±0.52	2	97.4%	2.6%	Overall basin condition at minimum sustainability threshold; urgent intervention required for ecologically critical sub-indicators

Wilcoxon Signed-Rank Test Results: Critical Sub Indicator Identification

Application of bilateral Wilcoxon signed-rank tests against the sustainability threshold ($\mu_0 = 2.0$) with Bonferroni correction (α_adj = 0.003) identified three sub-indicators as significantly below the threshold (Table 4). All three exhibited large effect sizes, confirming the practical as well as statistical significance of their non-sustainable status. Critically, these three sub-indicators, Conservation Zones, Solid Waste Management, and Water Flow Perception, are environmental sub-indicators with direct biological and ecological implications.

Additionally, Basic Services, Health Coverage, Organisational Commitment, Net Monthly Income, and Crop Diversification were at-threshold (median = 2.0, significantly below threshold without Bonferroni correction), indicating structural fragility warranting targeted policy attention. While these at-threshold sub-indicators do not directly measure ecological endpoints, they represent social and economic mediators that influence the capacity of communities to engage in biodiversity conservation and watershed protection.

Table 4: Wilcoxon Signed-Rank Test Results: Sub-indicators vs. Sustainability Threshold (μ_0 = 2.0), with Biological/Ecological Interpretation

`	Dimension	Mean±SD	Median	p-value	Effect $\|r_e\|$	Status	Biological/Ecological Interpretation
Education Access	Social	3.15±0.86	3.0	< 0.001	0.833	✓ ABOVE	Enables community participation in conservation programmes
Housing Quality	Social	2.56±0.93	3.0	< 0.001	0.616	✓ ABOVE	Indirectly affects community well-being and adaptive capacity
Basic Services	Social	1.73±0.62	2.0	< 0.001	0.656	≈ THRESHOLD	Limits community capacity for participation in conservation
Health Coverage	Social	1.81±1.47	2.0	0.010	0.111	≈ THRESHOLD	Affects community resilience and adaptive capacity
Organisational Membership	Social	2.08±2.00	4.0	0.240	0.039	✓ ABOVE	Indicates associative potential for collective conservation action
Organisational Commitment	Social	1.90±1.87	2.0	0.001	0.116	≈ THRESHOLD	Limited mobilisation for watershed stewardship
Environmental Acceptance	Social	3.20±0.80	3.0	< 0.001	0.951	✓ ABOVE	Positive attitudes facilitate biodiversity conservation
Crop Diversification	Environmental	2.13±0.55	2.0	< 0.001	0.474	≈ THRESHOLD	Affects agricultural landscape heterogeneity and habitat diversity
Solid Waste Management	Environmental	1.23±0.89	1.0	< 0.001	0.792	⚠ CRITICAL	Direct risk to aquatic ecosystem health via pollution, leachate, and microplastics
Slope/Erosion Risk	Environmental	2.68±0.54	3.0	< 0.001	0.965	✓ ABOVE	Moderate erosion risk; soil loss affects instream habitat quality
Soil Conservation	Environmental	2.96±0.65	3.0	< 0.001	0.859	✓ ABOVE	Adequate practices limit sedimentation of aquatic habitats

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Conservation Zones	Environmental	0.59±0.78	0.0	< 0.001	0.965	⚠ CRITICAL	Absence of refugia threatens biodiversity, habitat connectivity, and endemism
Water Flow Perception	Environmental	1.16±0.52	1.0	< 0.001	0.862	⚠ CRITICAL	Hydrological alteration affects instream habitat and flow-adapted aquatic biota
Net Monthly Income	Economic	1.79±1.12	2.0	< 0.001	0.252	≈ THRESHOLD	Limits household investment in sustainable land management
Economic Cooperation	Economic	2.52±1.03	3.0	< 0.001	0.557	✓ ABOVE	Supports collective action for watershed conservation
Product Diversification	Economic	2.46±0.57	2.0	< 0.001	0.902	≈ THRESHOLD	Economic resilience at threshold; affects ability to adopt conservation practices
Absence of Conflicts	Economic	3.75±0.97	4.0	< 0.001	0.874	✓ ABOVE	Social cohesion enables community-based conservation
Public Investment	Economic	2.59±1.91	4.0	< 0.001	0.297	✓ ABOVE	Supports infrastructure for conservation and watershed protection

Note: The three sub-indicators classified as CRITICAL, Conservation Zones, Solid Waste Management, and Water Flow Perception, all lie within the Environmental dimension and possess direct biological and ecological relevance. Conservation Zones directly measure habitat refugia and biodiversity conservation areas. Solid Waste Management reflects pollution risk to aquatic ecosystems through leachate, microplastics, and persistent organic pollutants. Water Flow Perception indicates community-detected hydrological alteration, which affects instream habitat availability and flow-adapted aquatic biota. All three exhibit large effect sizes ($|r_e| \geq 0.792$), confirming the practical significance of their non-sustainable status. Bonferroni correction was applied to control familywise error rate ($\alpha\_adj = 0.003$)

Inter-Dimensional Spearman Correlation Analysis

All pairwise Spearman rank correlations between the three dimension indices and between each dimension index and the General Sustainability Index were statistically significant (*p*<0.001; Table 5; Figure 5). The Social and Economic indices showed the strongest mutual association (ρ = 0.388), followed by Social Environmental (ρ = 0.369) and Environmental–Economic (ρ = 0.271). All three dimension indices contributed significantly to the General Sustainability Index, with the Social and Economic indices exhibiting the strongest associations (ρ = 0.705 and ρ = 0.698, respectively) and the Environmental index showing a moderate contribution (ρ = 0.510).

The moderate inter-dimensional correlations indicate that whilst the dimensions are related, each captures a distinct sustainability domain, validating their separate treatment in the composite index. Importantly, these correlations demonstrate that social and economic factors mediate ecological outcomes: communities with stronger social organisation and economic stability tend to score higher on environmental sub-indicators, including those with direct biological relevance. This finding reinforces the need for integrated watershed governance that addresses social, economic, and ecological dimensions simultaneously.

Table 5: Spearman Rank Correlations Between Sarandón Sustainability Indices (*n* = 887), with Ecological Interpretation

Index Pair	Spearman ρ	p-value	Interpretation	Ecological Significance
Social (SI) – Environmental (EI)	0.369	< 0.001	Moderate, significant	Social organisation mediates ecological outcomes
Social (SI) – Economic (KI)	0.388	< 0.001	Moderate, significant	Socio-economic interdependence
Environmental (EI) – Economic (KI)	0.271	< 0.001	Moderate, significant	Economic factors influence ecological condition
Social (SI) – General (I)	0.705	< 0.001	Strong, significant	Social dimension strongly influences overall sustainability
Environmental (EI) – General (I)	0.510	< 0.001	Moderate, significant	Ecological condition contributes substantially to general index
Economic (KI) – General (I)	0.698	< 0.001	Strong, significant	Economic stability strongly influences overall sustainability

Discussion

Overall Ecological Condition and the Threshold Interpretation

The General Sustainability Index (I = 2.32±0.52; median = 2) confirms that the upper Amojú River Basin operates at the minimum threshold of ecological integrity as defined by the Sarandón methodology. This result is consistent with sustainability assessments conducted in comparable Andean headwater basins, where composite scores at or near the threshold value are commonly associated with significant anthropogenic pressure coexisting with residual natural capital [5, 17]. However, the finding that 97.4% of respondents achieved a sustainable classification (I ≥2.0) must be interpreted with considerable caution: this figure reflects the mathematical structure of the composite formula, in which strong performance on some sub-indicators (e.g., Absence of Social Conflicts: mean = 3.75; Education Access: mean = 3.15) offsets critically low performance on others.

From an ecological perspective, the aggregate index masks severe deficits in sub-indicators with direct biological relevance. The identification of three environmental sub-indicators, Conservation Zones (mean = 0.59), Solid Waste Management (mean = 1.23), and Water Flow Perception (mean = 1.16), as significantly below the sustainability threshold (all Wilcoxon *p*<0.001) represents a more diagnostically valuable output than the aggregate index alone. These three sub-indicators are not merely measures of environmental quality; they are direct proxies for the biological integrity of the basin's aquatic and terrestrial ecosystems. The near-absence of conservation zones, the prevalence of inadequate waste disposal, and the community-detected hydrological alteration collectively signal that the basin's capacity to support biodiversity and maintain ecosystem functioning is severely compromised.

Ecologically Critical Sub Indicators: Threats to Biological Integrity

The identification of Conservation Zones (mean = 0.59), Water Flow Perception (mean = 1.16), and Solid Waste Management (mean = 1.23) as the three most critical non-sustainable sub-indicators is consistent with previously documented environmental pressures in Andean agricultural watersheds [11]. however, the biological implications of these findings extend beyond simple resource management concerns and directly implicate the conservation of Andean biodiversity.

Conservation Zones and Biodiversity Loss

The finding that 89.4% of respondents reported no designated conservation area on their land reflects the near-complete absence of riparian buffers, forest refugia, and habitat corridors in the upper basin. This is ecologically consequential: headwater streams in the tropical Andes are known to support exceptionally high levels of endemism, particularly among freshwater fish, amphibians, and aquatic macroinvertebrates [2]. The Marañón River system, of which the Amojú is a tributary, is recognised as a centre of freshwater fish endemism, with many species having restricted distributions that are highly vulnerable to habitat loss.

[32] demonstrated a direct relationship between vegetative cover and water availability in Costa Rican forest reserves (32), a dynamic directly relevant to the upper Amojú context. The erosion of riparian and buffer zones through agricultural encroachment is a primary driver of reduced infiltration capacity, declining base flows, and habitat fragmentation. Loss of riparian vegetation eliminates critical habitat structure, reduces allochthonous inputs that support aquatic food webs, and disrupts connectivity between terrestrial and aquatic ecosystems. The absence of conservation zones therefore represents not merely a land-use deficit but a fundamental threat to the biological integrity of the basin.

Solid Waste Management and Aquatic Ecosystem Health

Regarding solid waste management, [33] reported that rural communities in Peru disproportionately rely on open burning and field disposal of domestic waste in the absence of formal municipal collection services [33], a pattern replicated in the upper Amojú Basin where 49% of respondents reported burning solid waste and 19% open-field disposal. These practices carry significant biological implications for surface water quality and aquatic biota through leachate infiltration and atmospheric deposition, particularly during rainfall events.

Open burning of waste, including plastics, releases Persistent Organic Pollutants (POPs), heavy metals, and dioxins into the environment [22]. Open-field disposal introduces microplastics and toxic leachates directly into the watershed. These contaminants have documented toxic effects on aquatic organisms, including disruption of endocrine function in fish, reduced macroinvertebrate diversity, and bioaccumulation through food webs [22]. The absence of institutional solid waste management constitutes a direct and ongoing threat to aquatic ecosystem health and the conservation of sensitive species in the basin.

Hydrological Alteration and Instream Biota

The Water Flow Perception sub-indicator, with 91% of respondents reporting decreased flow relative to previous years, provides a robust community-based signal of hydrological alteration. This finding is biologically significant: reduced base flows

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in headwater streams lead to habitat contraction, increased water temperatures, reduced dissolved oxygen concentrations, and fragmentation of populations of flow-adapted species [10, 11].

In Andean headwater systems, many aquatic species, particularly endemic fish and macroinvertebrates, have narrow physiological tolerances and are adapted to specific flow regimes. Hydrological alteration disrupts spawning cues, reduces habitat availability for benthic organisms, and can lead to local extirpations of sensitive taxa. The community perception of declining flow, when interpreted alongside the near-absence of conservation zones, suggests a synergistic degradation of the basin's hydrological and ecological functions that requires urgent intervention.

Economic Constraints and Conservation Finance

The universal Water Service Payment score of 1 (all 887 respondents paying S/. 1–S/. 5 per month, with no respondent exceeding S/. 3) represents a structural economic constraint on basin sustainability that operates independently of other economic indicators. [34] documented comparable patterns of low water service willingness-to-pay in the Cachi River Basin (Ayacucho), noting that insufficient tariff structures preclude cost-recovery for basic infrastructure maintenance [34].

Social Dimensions and Community Conservation Capacity

The Social Sustainability Index (SI = 2.52±0.75) reflects a community characterised by relatively strong educational infrastructure and positive environmental attitudes, but constrained by limited access to healthcare and incomplete basic utility services. The high Environmental Acceptance score (mean = 3.20) indicates that the population is broadly satisfied with their rural environment, a precondition for effective community-based conservation programmes.

However, Organisational Commitment (mean = 1.90) and Organisational Membership (mean = 2.08) remain at threshold levels, suggesting that whilst associative capacity exists, it has not yet been fully mobilised for watershed management and biodiversity conservation purposes. [29, 35] emphasise the pivotal role of collective action frameworks in achieving sustainable watershed outcomes, highlighting the need to strengthen water committee structures as platforms for participatory basin governance [29, 35].

In the context of biological conservation, strengthening community governance structures is essential for implementing and enforcing conservation measures such as riparian buffer protection, waste management regulations, and sustainable land-use practices. The moderate correlations between the Social and Environmental indices ($\rho = 0.369$, *p*<0.001) observed in this study support the interpretation that social organisation mediates ecological outcomes: communities with stronger social capital tend to score higher on environmental sub-indicators, including those with direct biological relevance.

Study Limitations

Several limitations of this study warrant explicit acknowledgement, particularly in the context of biological and ecological interpretation.

First, the study lacks direct biological data. While the environmental sub-indicators used in the Sarandón framework are proxies for ecological condition, they do not replace direct bioassessment measures such as macroinvertebrate community indices, fish population surveys, or vegetation transects. Future research should integrate bioassessment with the community-based indicators employed in this study to provide a more comprehensive evaluation of the basin's biological integrity.

Second, the convenience-based sampling strategy, whilst pragmatically justified by the geographical dispersion of the 22 localities, may introduce selection biases that limit strict probabilistic inference. The achieved margin of error of ±2.61% (95% CI) provides a reasonable precision guarantee for the reported proportions, but causal inferences regarding the drivers of ecological degradation should be made with caution.

Third, the Water Flow Perception sub-indicator is based exclusively on self-reported community perceptions of hydrological change, without corroboration from instrumental streamflow records or remote sensing-derived vegetation/land-use change data. Whilst perceptual indicators have established validity as proxies for community-detected environmental change [10], future studies should integrate gauge station data and remote sensing analyses to provide objective hydrological validation and quantify the magnitude of hydrological alteration affecting aquatic biota.

Fourth, the water quality parameters (E-group) were derived from a single basin-wide measurement and treated as constants across all respondents. This homogenises the Environmental Index (EI, SD = 0.39) and limits the capacity to detect spatial variation in water quality that may affect biological communities. Future research should incorporate spatially and temporally replicated water quality sampling, including biological water quality indicators (e.g., macroinvertebrate indices, algal bioassays), to complement the community-based assessment.

Fifth, the Sarandón framework applies uniform weightings and scale thresholds across all localities, without accounting for spatial heterogeneity in ecological conditions or socioeconomic vulnerability within the 22 study communities. Spatially disaggregated analyses using GIS-based vulnerability mapping would strengthen the spatial interpretive capacity of future assessments and enable targeted conservation interventions.

Sixth, as noted in Section 2.4, the low Cronbach's α for the Environmental (α = 0.339) and Economic (α = 0.059) dimensions reflects the inherent multi-dimensionality of the Sarandón framework rather than a validity deficit. In the context of biological assessment, the heterogeneity among environmental sub-indicators is actually desirable: it confirms that different ecological threats (habitat loss, pollution, hydrological alteration) are captured as distinct dimensions of risk. However, future instrument development might benefit from exploratory factor analysis to refine the sub-indicator structure and reduce redundancy or scale-range constraints.

Future Research Directions

Based on the findings and limitations identified, the following research directions are recommended to advance understanding of the biological integrity and conservation needs of the upper Amojú Basin:

(i) Bioassessment Integration: Conduct systematic bioassessment surveys, including macroinvertebrate community sampling, fish population assessments, and riparian vegetation transects, to provide direct biological validation of the environmental sub-indicators identified in this study. Development of an Index of Biotic Integrity (IBI) for the basin would provide a powerful tool for monitoring ecological condition

(ii) Longitudinal Monitoring: Establish longitudinal monitoring of the Sarandón sustainability indices across multiple survey rounds to detect temporal trends and evaluate the effectiveness of policy interventions for biodiversity conservation

(iii) Hydrological Validation: Integrate instrumental hydrological data (streamflow gauging, water quality monitoring) with community-based indicator assessments to develop a validated hybrid framework for ecological assessment

(iv) Spatial Sustainability Mapping: Conduct spatial sustainability mapping using GIS-based multi-criteria evaluation at sub-basin and locality levels, following the approach of [36] in northern Peru [36], to identify priority areas for conservation intervention

(v) Ecosystem Service Valuation: Model ecosystem service values associated with upper basin conservation zones to support MERESE implementation and evidence-based water tariff reform. Quantifying the biodiversity benefits of conservation interventions will strengthen the economic case for watershed protection

(vi) Regional Comparative Analysis: Extend the Sarandón framework to adjacent Andean sub-basins (e.g., Utcubamba, Chinchipe) to enable regional comparative sustainability benchmarking and identify best practices for biodiversity conservation in Andean headwater system

(vii) Climate Change Vulnerability Assessment: Conduct climate change vulnerability assessments that integrate projected hydrological changes with biological sensitivity data for endemic Andean species, to identify conservation priorities under future climate scenario

Synthesis: Implications for Conservation

The findings of this study have clear implications for the conservation of biological diversity in the upper Amojú River Basin. The three ecologically critical sub-indicators, Conservation Zones, Solid Waste Management, and Water Flow Perception, represent distinct but interconnected threats to the basin's biological integrity:

Critical Sub-indicator	Primary Threat	Biological Consequence
Conservation Zones (mean = 0.59)	Loss of habitat refugia and connectivity	Reduced biodiversity, loss of endemic species, impaired ecosystem functioning
Solid Waste Management (mean = 1.23)	Pollution of aquatic habitats	Toxicity to aquatic biota, bioaccumulation, reduced ecosystem health
Water Flow Perception (mean = 1.16)	Hydrological alteration	Habitat loss for flow-adapted species, population fragmentation

Integrated watershed governance that simultaneously addresses these three threats is essential for safeguarding the biological diversity of this Andean headwater system. Specific conservation priorities include.

Establishment of Conservation Zones: Creation of riparian buffers, forest refugia, and habitat corridors through land-use planning, conservation easements, and incentive programmes such as MERESE.

Solid Waste Management Infrastructure: Development of municipal and community based waste collection, recycling, and composting programmes to eliminate open burning and field disposal, reducing pollution threats to aquatic ecosystems.

Water Flow Protection: Implementation of land-use practices that enhance infiltration and groundwater recharge, including reforestation of degraded areas, conservation of natural vegetation, and sustainable agricultural practices.

Community Engagement: Strengthening water committee structures and community governance capacity to enable participatory conservation planning and implementation.

Economic Incentives: Implementation of payment for ecosystem services mechanisms to compensate communities for conservation actions that benefit biodiversity and water security.

Conclusion

This study provides the first statistically rigorous, community-based integrated assessment of ecological condition and water resource sustainability in the upper Amojú River Basin, incorporating Wilcoxon signed-rank testing, Spearman rank correlation, principal component analysis, and Cronbach's α within the Sarandón multi-criteria framework. By linking community-level social, economic, and environmental indicators to biological and ecological endpoints, this research establishes a foundation for evidence-based biodiversity conservation and watershed governance in Andean headwater systems. The following conclusions are drawn:

The General Sustainability Index (I = 2.32±0.52; median = 2) confirms that the upper Amojú River Basin operates at the minimum threshold of ecological integrity (I ≥ 2.0), with 97.4% of respondents classified as sustainable. All three dimension indices (Social: 2.52±0.75; Environmental: 2.18±0.39; Economic: 2.30±0.67) met the sustainability criterion, though all remain at the minimum threshold level. Critically, the aggregate index masks severe deficits in sub-indicators with direct biological and ecological relevance, underscoring the need for targeted conservation interventions rather than reliance on composite scores alone.

Three environmental sub-indicators were statistically identified as significantly non-sustainable and ecologically critical (Wilcoxon *p*<0.001, Bonferroni-adjusted).

Conservation Zones (mean = 0.59; 89.4% below threshold): The near-complete absence of conservation areas, including riparian buffers and habitat refugia, represents the most severe threat to biodiversity, habitat connectivity, and endemic species conservation in the basin.

Water Flow Perception (mean = 1.16; 90.9% below threshold): Community-detected hydrological alteration signals reduced instream habitat availability for flow-adapted aquatic biota, including fish and macroinvertebrates, with cascading effects on aquatic ecosystem functioning.

Solid Waste Management (mean = 1.23; 68.3% below threshold): Inadequate waste disposal practices, including open burning and field disposal, introduce persistent organic pollutants, heavy metals, and microplastics into the watershed, posing direct toxicity risks to aquatic organisms and threatening aquatic ecosystem health.

These three sub-indicators represent the primary targets for evidence-based conservation intervention in the basin.

Water Service Payment (eco_pago_agua = 1 for all respondents; S/. 1–3 per month) constitutes a structural economic barrier to sustainable water service provision and limits financial resources available for watershed protection and biodiversity conservation. Implementation of the MERESE ecosystem services mechanism and progressive tariff reform are recommended as priority policy instruments to generate conservation finance for riparian buffer restoration, solid waste management, and habitat protection.

All three dimension indices were significantly intercorrelated (ρ = 0.271–0.388, *p*<0.001) and contributed significantly to the General Sustainability Index (ρ = 0.510–0.705), demonstrating the internal coherence of the multi-dimensional assessment framework. The moderate correlations between Social and Environmental indices (ρ = 0.369) and Economic and Environmental indices (ρ = 0.271) indicate that social organisation and economic stability mediate ecological outcomes, reinforcing the need for integrated conservation strategies that address social, economic, and ecological dimensions simultaneously.

PCA provided empirical support for the Sarandón weighting structure, demonstrating that double-weighted indicators (Satisfaction of Basic Needs; Net Family Income) exhibited the highest PC1 loadings across the full sub-indicator set. Kruskal Wallis tests confirmed significant within-dimension heterogeneity among sub-indicators (H>971, *p*<0.001 for all dimensions), further justifying the differential weighting approach. Importantly, the environmental sub-indicators with direct ecological relevance loaded onto distinct principal components, confirming they capture unique dimensions of ecological risk that require independent conservation planning.

Conservation Priorities

The collective commitment of all societal stakeholders, local communities, water user committees, district municipalities, and regional authorities, is indispensable for translating these findings into conservation action. Based on the identification of ecologically critical sub-indicators, the following priority conservation actions are recommended.

Priority Action	Ecological Rationale	Target Sub-indicator
Establishment of conservation zones (riparian buffers, forest refugia, habitat corridors)	Restore habitat connectivity, provide refugia for endemic species, enhance ecosystem functioning	Conservation Zones (mean = 0.59)
Implementation of municipal solid waste management systems (collection, recycling, composting)	Reduce pollution inputs to aquatic ecosystems, eliminate toxicity risks to aquatic biota	Solid Waste Management (mean = 1.23)
Strengthening water committee structures and community governance capacity	Enable participatory conservation planning, enforce sustainable land-use practices	Social Dimension (SI = 2.52)
MERESE implementation and payment for ecosystem services	Generate conservation finance, incentivise stewardship of conservation zones	Economic Dimension (KI = 2.30)
Integrated watershed governance coordinating social, economic, and ecological dimensions	Address synergistic threats to biological integrity	General Index (I = 2.32)

The upper Amojú River Basin operates at the minimum threshold of ecological integrity, with three critical sub-indicators, Conservation Zones, Solid Waste Management, and Water Flow Perception, representing severe and interconnected threats to the basin's biological diversity and ecosystem functioning. An environmental awareness programme targeting the entire upper and middle basin population, strengthened water committee structures, coordinated solid waste management schemes, and the establishment of conservation zones through MERESE or complementary mechanisms represent the most urgent priority actions identified by this study. Without immediate and coordinated intervention, the biological integrity of this Andean headwater system will continue to degrade, with irreversible consequences for endemic biodiversity and the ecosystem services that depend on healthy, functioning watersheds.

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Author’s Contributions

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Carranza Montenegro: Designed the research plan and organized the study. They also participated in all experiments, coordinated data analysis, and contributed to the writing of the manuscript.
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Ethics

This study was conducted in accordance with the ethical principles of voluntary participation, informed consent, and data confidentiality. All references used in the preparation of this manuscript have been appropriately cited in the bibliography.

Conflict of Interest

The authors declare no conflict of interest.

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