

Article

Apparent Greening Masks Ecohydrological Decline: A Multi-Index Multitemporal Assessment of the Sumapaz Páramo, Colombia [†]

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Abstract

The Sumapaz páramo, the most extensive continuous páramo complex on a global scale and a strategic component in the hydrological regulation of central Colombia, is undergoing a progressive ecohydrological degradation whose integrated characterization through multi-temporal biophysical indicators remains limited. To address this gap, the present study examines the transformation dynamics of the system by articulating four analytical components: precipitation modeling based on IDEAM stations (1995–2025), thermal trend analysis from WorldClim grids (2000–2024), multitemporal spectral analysis of four normalized difference indices (NDVI, NDWI, NDSI, NBR) derived from Landsat imagery (2000–2025), and Corine Land Cover cartography (2000–2018). The findings reveal a spatial decoupling between the precipitation distribution, which tends to shift toward lower altitudinal belts, and the storage areas in peat and Andosols of the páramo core, with a consequent reduction in effective recharge regardless of the total precipitated volume. Paradoxically, an almost complete contraction of surfaces with a positive water signal coexists with the expansion of photosynthetic activity, a phenomenon attributable to processes of shrub encroachment, thermophilization, and nutrient enrichment rather than to a functional recovery of the ecosystem. The cartographic analysis, in turn, confirms the advance of agricultural and livestock uses over native regulating covers. The convergence of these vectors configures a multivectorial degradation scenario that escapes monitoring based on a single index and that demands management strategies oriented simultaneously toward anthropic pressure, the spatial redistribution of precipitation, and the implementation of integrated ecohydrological surveillance systems.



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1. Introduction

Climate change figures among the main agents of transformation of high-mountain ecosystems on a global scale. Knight [1] reported that warming rates in these systems may double those observed at the planetary scale over the past five decades; Dragonetti et al. [2], in turn, showed that this differential vulnerability exposes mountain biota to

rates of thermal change that exceed their acclimatization thresholds. Along the same lines, Abbas et al. [3] established that the temperature increase induces a structural reconfiguration of the hydrological cycle, expressed in the spatio-temporal redistribution of water resources, the modification of precipitation regimes, and the intensification of potential evapotranspiration. The IPCC [4], in its Sixth Assessment Report, warned that certain tropical mountain systems are approaching hydrological and ecological tipping points of an irreversible nature, associated with the progressive deterioration of the water mass stored in organic soils and peat horizons. Under high-emission trajectories, Prudhomme et al. [5] projected that more than 40% of the continental surface will face episodes of severe aridity before the end of the century, with impacts preferentially concentrated in basins whose regulation depends on the functional integrity of headwater ecosystems. To this picture is added what Seastedt and Oldfather [6] proposed: that the altitudinal migration of species in response to the displacement of climatic niches faces topographic barriers leading to range contractions and local extinctions, while Palomo [7] emphasized that this process operates with greater intensity in tropical mountains, systematically underrepresented in international scientific output relative to alpine or Himalayan systems.

In the Andean context, páramo ecosystems fulfill a strategic ecohydrological function. Lis-Gutiérrez et al. [8] and Vergara and De Pellegrin Llorente [9] estimated that nearly half of the world's páramos are concentrated in Colombia, distributed across 37 formally delimited complexes that sustain around 70% of the national water supply. Anselm et al. [10] and Molina Benavides et al. [11] characterized three complementary mechanisms that underpin this provision: water retention in soils with a high proportion of organic matter, whose Andosol-type horizons can retain volumes exceeding 80% of their capacity; the interception and regulation of surface runoff by means of specialized vegetation covers; and the delayed release of water toward supply basins, which buffers periods of pluviometric deficit. Pirachicán Grijalba et al. [12] estimated, however, that Colombia has lost approximately 57% of its original páramo cover as a consequence of agricultural expansion, extensive cattle ranching, and various extractive activities. With its 333,420 ha, the Sumapaz páramo constitutes the most extensive continuous páramo complex in the world and concentrates this regulating function in its maximum expression: García Mora et al. [13] confirmed that it directly supplies the Bogotá water system and sustains agricultural activities in the central region of the country. Despite this, Lis-Gutiérrez et al. [8] reported that 9.69% of its surface already shows intervention by human activities, a process in which the advance of the agricultural frontier, extensive cattle ranching, and the expansion of infrastructure converge, a trend also documented by Anzoategui et al. [14] and Monroy-Hernández [15]. To these land-use pressures is superimposed an adverse climatic context: Llambí et al. [16] warned that thermophilization, understood as the gradual replacement of cold-adapted species by communities typical of lower altitudinal belts, produces alterations in the spectral pattern of vegetation that may be erroneously interpreted as improvements in vegetation vigor when, in reality, they conceal a loss of the regulating capacity of the ecosystem.

The characterization of change trajectories in mountain ecosystems today finds in multitemporal satellite-based spectral monitoring its dominant approach. The Normalized Difference Vegetation Index (NDVI), built on the differential relationship between reflectance in the red and the near-infrared bands, allows the quantification of the vigor and density of the vegetation canopy, as documented by Chambe et al. [17] and Whidayanti et al. [18]. The Normalized Difference Water Index (NDWI), which combines the near-infrared with the shortwave infrared, provides an estimate of surface water availability and shows consolidated applications in wetlands and lacustrine systems in the works of Al-Maliki et al. [19] and Sandoval et al. [20]. The Normalized Difference Snow Index (NDSI), although originally designed for snow detection, presents a functionally analo-

gous utility for identifying saturated soils in tropical páramos, as supported by Poussin et al. [21] and Sood et al. [22]. The Normalized Burn Ratio (NBR), in turn, facilitates the assessment of degradation severity and of cover recovery following fire disturbances, in line with what Borrelli et al. [23] reported for Andean páramos. As a complement, land cover cartography developed under the Corine Land Cover methodology makes possible the standardized diachronic comparison at a 1:100,000 scale, according to the reports of López Bolaños et al. [24] and Corredor Gil et al. [25]. On the hydrological plane, spatial interpolation techniques for precipitation constitute a consolidated tool for mapping the pluviometric distribution and examining its temporal reorganization, as Fonseca Carreño [26] described. Despite this methodological availability, the isolated application of such indicators faces recognized limitations: persistent cloud cover reduces the utility of passive optical sensors, the mixed-pixel effect masks small water bodies, and the spectral confusion between topographic shadows and water surfaces restricts analytical precision, as Santechchia et al. [27] and López Bolaños et al. [24] pointed out. The sustainability implications of this diagnostic challenge extend beyond the ecological domain as páramo degradation directly undermines the long-term sustainability of water supply systems serving densely populated Andean cities, including the Bogotá metropolitan area, where regulatory frameworks for territorial planning and climate adaptation depend on scientifically grounded assessments of ecosystem functional status. Monitoring approaches that rely on single greenness indicators systematically overestimate ecosystem health and thus introduce a structural bias into the sustainability evidence base that informs conservation and water management decisions.

Despite the growing evidence of degradation, the integrated reading of the ecohydrological dynamics of the Sumapaz páramo encounters a concrete methodological gap. Llambí et al. [16] identified disciplinary fragmentation as the main epistemological constraint in studies of páramo ecosystems: the available research examines biophysical components in a disaggregated manner, without addressing their interdependencies or their cumulative effects on the water regulation capacity. As an additional constraint, Dourado et al. [28] and López Bolaños et al. [24] pointed to the scarce articulation between vegetation cover radiometry and water body radiometry within the same spatio-temporal unit of analysis; Palomo [7], in complement, warned of the predominance of analyses with two reference dates, which prevents the capture of the interannual variability of the system. In response to this limitation, the present study evaluates in an integrated manner the ecohydrological transformation of the Sumapaz páramo through the articulation of multitemporal series of four spectral indices (NDVI, NDWI, NDSI, NBR) derived from Landsat imagery, official Corine Land Cover cartography, spatial precipitation modeling based on IDEAM stations, and thermal trend analysis from WorldClim climatic grids, for the period between 1995 and 2025 according to the availability of each source. The joint analysis seeks to discriminate whether the changes observed in vegetation vigor respond to a dynamic of ecological recovery or, on the contrary, reflect a transition toward communities adapted to water limitation, with direct implications for regional water security and for territorial risk management.

2. Materials and Methods

2.1. Study Area

The Sumapaz páramo is located in the south-central sector of the Eastern Cordillera of the Colombian Andes, between the approximate coordinates 3°35′–4°25′ N and 73°54′–74°29′ W, with an altitudinal gradient extending between 3200 and 4300 m a.s.l. (Figure 1). The analytical area comprises the official core of the páramo complex and a 15 km perimeter buffer zone with respect to its formal delimitation, which configures a total study surface of 3272.76 km². At the administrative level, the territory involves the Capital District of

Bogotá and 25 municipalities distributed across the departments of Cundinamarca, Meta, Tolima, and Huila. The orographic configuration of the area, organized around a southwest-northeast-oriented massif, operates as a continental divide between the tributary slopes of the Magdalena and Orinoco rivers.

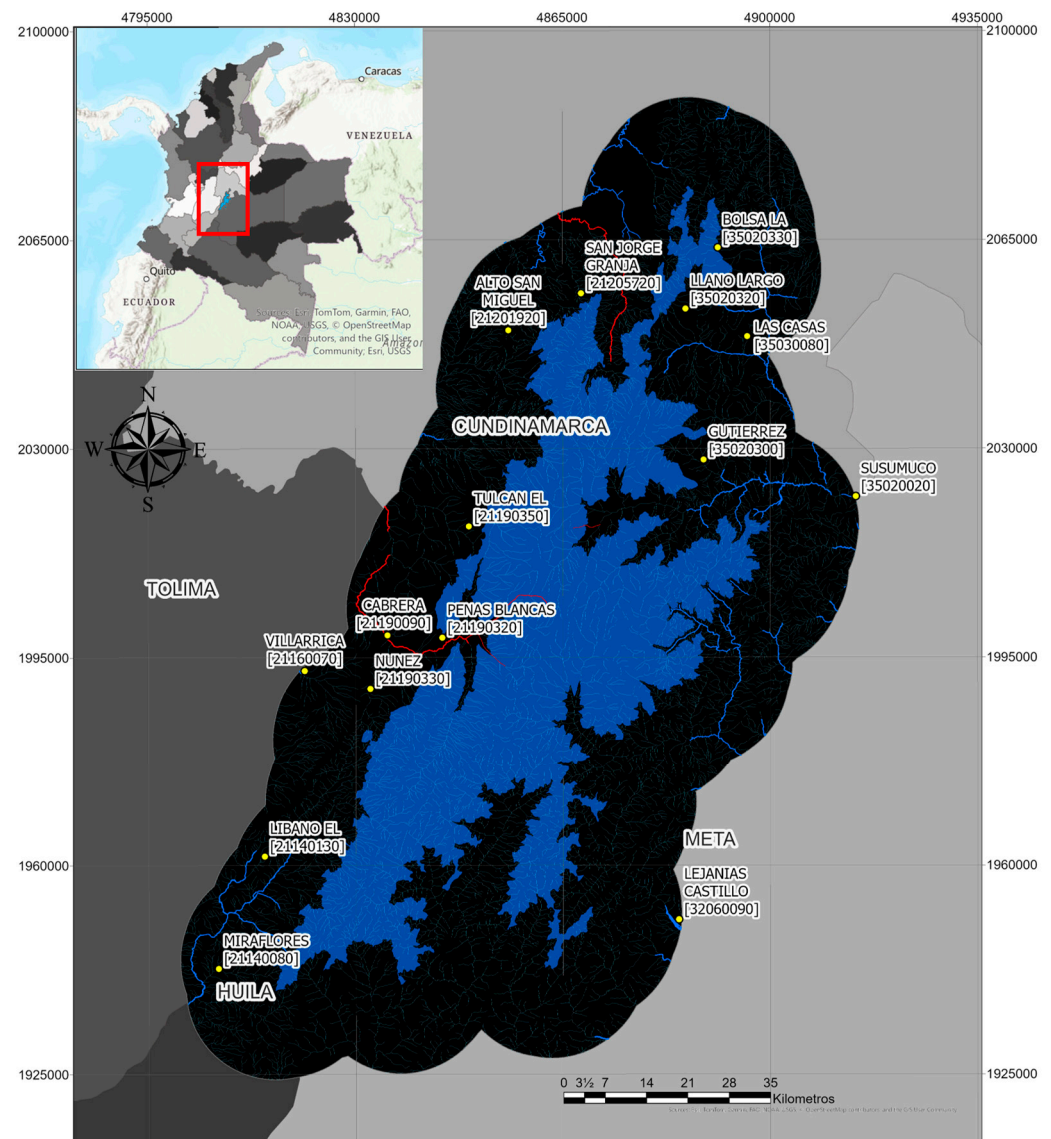


Figure 1. Location of the study area: Sumapaz páramo complex and 15 km buffer zone within the Eastern Cordillera of the Colombian Andes; the values in brackets are the IDEAM code for the Station, EPSG 9377.

The climatic regime corresponds to a cold and humid one, with mean temperatures ranging between 19 °C at 1600 m a.s.l. and 2 °C at 4300 m a.s.l., and diurnal oscillations reaching up to 25 °C. MADS [29] documented that the pluviometric distribution responds to a bimodal pattern on the western slope, with a tendency toward a unimodal pattern on the eastern slope; annual accumulations vary between 800 and 1000 mm at the highest elevations and reach up to 4000 mm in the southeastern sector. Rangel [30] classified the vegetation into three altitudinal belts: subpáramo (3200–3500 m a.s.l.), dominated by shrubby vegetation and scrubland; páramo (3500–4100 m a.s.l.), characterized by frailejones, tussock grasslands, and bamboo formations; and superpáramo (>4100 m a.s.l.), with discontinuous cover and exposed soil. Predominant soils correspond to Entisols, Inceptisols, and Andisols, the latter associated with humid horizons with a high proportion of organic

matter and low fertility. The hydrological system comprises numerous lagoons of glacial origin located between 3500 and 4000 m a.s.l., which feed basins of three main hydrographic regions: Magdalena, Meta, and Guaviare.

2.2. Data Sources

This study integrated four primary information sources, whose characteristics are summarized in Table 1.

Table 1. Summary of data sources, variables, spatial resolution, temporal coverage, and analytical purpose.

Component	Source	Variable(s)	Resolution	Period	Purpose
Pluviometric	IDEAM (15 stations)	Total monthly precipitation	Point-based	1995–2025	Pluviometric trend and variability, isohyets
Climatic	WorldClim v2	Max. Temperature, min. Temperature, monthly precipitation	2.5 min (~4.5 km)	2000–2024	Thermal trend and spatial distribution
Spectral	Landsat 5/7/8/9 (USGS)	Multi-Spectral Bands (visible, NIR, SWIR)	30 m	2000, 2015, 2025	Spectral indices (NDVI, NDWI, NDSI, NBR)
Land cover	IDEAM—CLC Colombia	Lad Cover Units (CLC legend)	1:100,000	2000, 2018	Land use and land cover transitions
Cartographic	IGAC	Delimitation, hydrography, political-administrative limits.	Variable	-	Spatial contextualization

For the pluviometric component, total monthly precipitation records were collected from IDEAM hydrometeorological stations located within the area of influence of the Sumapaz páramo. From an initial inventory, the analysis retained only the 15 stations whose series presented a completeness percentage above 90% for the period 1995–2025, which guarantees the temporal representativeness of the records used in the spatial modeling.

For stations with isolated missing records, gap-filling was performed using the nearest available station meeting two simultaneous selection criteria: a spatial distance of less than 100 km and an altitudinal difference of no more than 200 m above sea level relative to the target station. The combined application of distance and elevation thresholds responds to the documented behavior of precipitation in mountain environments, where orographic forcing can generate strong spatial gradients that reduce inter-station correlation even at short horizontal distances, as Buytaert et al. [31] demonstrated for páramo stations in the Ecuadorian Andes, and as Aieb et al. [32] confirmed in complex mountain basins where geological and topographic heterogeneity govern inter-station similarity more strongly than proximity alone. Within this framework, the literature establishes that inter-station correlation is a more reliable selection criterion for gap-filling quality than geometric distance: Longman et al. [33] showed, using a dense network of 222 stations in topographically complex terrain, that predictor-target correlation predicts gap-filling error more consistently than spatial proximity; Fagandini et al. [34] similarly identified the most correlated neighbor as the standard reference for rainfall gap-filling following FAO guidelines. The altitude criterion applied in this study partially compensates for the absence of an explicit correlation pre-screening, as stations within ± 200 m of elevation in the same orographic system tend to share similar precipitation regimes; this assumption is acknowledged as a simplification and represents a methodological constraint inherent to the available station density in the area of influence of the páramo.

For the climatic component, the study incorporated the global grids of WorldClim version 2 corresponding to total monthly precipitation and to monthly maximum and minimum temperatures, with a spatial resolution of 2.5 arc-minutes (approximately 4.5 km in the study area) for the period 2000–2024. Although these products constitute modeled data and not direct local measurements, they are consistent with the warming trends projected for tropical high-mountain ecosystems and allow the punctual analysis of IDEAM stations to be complemented with continuous spatial coverage.

For the radiometric component, the study acquired Landsat mission images corresponding to six reference dates within the period 2000–2025: February 2000 (40% cloud cover), February 2005 (30%), January 2010 (20%), January 2015 (10%), February 2020 (20%), and January 2025 (20%). The temporal selection prioritized the months with the lowest historical mean precipitation and, within them, the scenes with the lowest cloud cover fraction over the area of interest. The scenes corresponding to 2005, 2010, and 2020 presented intermittent stripes associated with the Scan Line Corrector (SLC-off) failure of the Landsat 7 sensor, which reduced the effective analysis area from 3250.43 km² to 2637.82 km². Consequently, the multitemporal spectral analysis focused on the three dates with complete spatial coverage: 2000, 2015, and 2025.

Three gap-filling strategies were evaluated before reaching this decision. Cokriging with auxiliary bands was ruled out because the SLC-off failure affects all spectral bands simultaneously at the same pixel locations, eliminating the band-to-band spatial complementarity that the method requires. Focal statistics interpolation was discarded on the grounds that the stripe pattern affected approximately 40% of the scene area in the study dates; filling that proportion from weighted spatial averages of adjacent valid pixels would have produced a largely synthetic image rather than a radiometric observation, which was considered methodologically indefensible for spectral index computation. Ordinary kriging was not viable due to the absence of sufficient independent validation points within the affected zones. The acquisition of Landsat 8 scenes from nearby dates as an auxiliary source was also explored; however, the available images for the study months either presented excessive cloud cover over the páramo or did not provide complete spatial coverage of the delimited area. The decision to retain only the three dates with full spatial coverage (2000, 2015, and 2025) was therefore grounded in the principle of preserving the physical integrity of the spectral signal. Spectral indices computed from gap-filled pixels propagate the interpolation uncertainty directly into the index value, making it impossible to distinguish real spectral change from reconstruction artifact; this risk is particularly consequential in an analysis that relies on the divergence between NDVI and NDWI as a diagnostic indicator. Working with fewer but radiometrically complete scenes was considered preferable to expanding the temporal coverage at the cost of introducing systematic estimation bias into the spectral record.

For the land cover component, the study employed the official Corine Land Cover (CLC) maps from IDEAM corresponding to the years 2000 and 2018, produced at a 1:100,000 scale. The complementary cartographic information, comprising the official delimitation of the páramo, administrative boundaries, and the hydrographic network, was obtained from the databases of IGAC.

The four data sources employed in this study span partially overlapping but non-identical temporal windows: the IDEAM pluviometric series covers 1995–2025; the WorldClim grids extend from 2000 to 2024; the Landsat-derived spectral analysis focuses on three reference dates within 2000–2025; and the Corine Land Cover cartography provides snapshots for 2000 and 2018. These differences were reconciled as follows. The IDEAM series was used in its full temporal extent for the analysis of interannual pluviometric variability and for the generation of isohyets at the three reference years (2000, 2015, 2024);

the WorldClim grids provided the continuous spatial and temporal coverage needed for thermal trend analysis, restricted to their available period (2000–2024). The spectral analysis was anchored to the three Landsat dates with complete spatial coverage (2000, 2015, 2025), which fall within the intersection of the pluviometric and thermal windows. The CLC cartography, whose most recent available layer corresponds to 2018, was used as structural land cover evidence for the 2000–2018 period and was not extended to 2025; the absence of post-2018 land cover data is acknowledged as a limitation of the analysis, as the land use transitions occurring between 2018 and 2025 cannot be quantified from official cartographic sources and fall outside the scope of the spectral index analysis conducted for that date. The integrated interpretation of the four components therefore rests on a common analytical core of 2000–2018 for land cover, 2000–2024 for climate, and 2000–2025 for spectral dynamics, with the pluviometric series providing the longest temporal context.

2.3. Processing and Analysis

2.3.1. Precipitation Analysis and Spatial Interpolation

The pluviometric series went through a quality control protocol that included the verification of internal consistency and the completion of missing data through weighted linear combination based on three reference stations, selected by criteria of altitudinal similarity (± 200 m) and geographical proximity (± 100 km). From the depurated series, the procedure calculated the multiannual monthly statistics (minimum, mean, and maximum values) and the multiannual average for the period 1995–2025, together with the verification of the pluviometric regime and the comparison of descriptive statistics with and without estimated data.

The spatial characterization of precipitation was conducted through the generation of mean monthly isohyets for the reference years 2000, 2015, and 2024. Method selection followed a systematic comparative evaluation of six interpolation families (Simple Kriging, Ordinary Kriging, Universal Kriging, Empirical Bayesian Kriging (EBK), Kernel (Local Polynomial) Interpolation, and Inverse Distance Weighting (IDW)) implemented through the Exploratory Interpolation tool of ArcGIS Pro 3.5.2, which assessed thirteen parameter configurations across those families under a single-criterion comparison based on highest prediction accuracy through leave-one-out cross-validation. The Empirical Bayesian Kriging—Advanced configuration yielded the lowest root mean square error (RMSE) across all three reference periods (RMSE = 73.1 mm, 61.4 mm, and 68.7 mm for 2000, 2015, and 2024, respectively), with mean errors (ME) of -1.04 , $+0.97$, and -4.03 mm (indicative of minimal systematic bias). The second-ranked method, Kernel (Local Polynomial) Interpolation, produced RMSE values of 85.2, 75.1, and 83.5 mm for the same periods, representing a margin of 12 to 16% above EBK—Advanced. Ordinary Kriging configurations ranked 11th through 13th across the three evaluations (RMSE range: 94.4–160.0 mm), confirming substantially lower predictive accuracy under the spatial configuration of the available station network. A complete comparison of all methods and configurations is provided in Table S1 of the Supplementary Materials. As a complement, regression analysis through the SPSS software 15.0 allowed the evaluation of the statistical significance of the temporal precipitation trends at each station.

Monotonic precipitation trends also were assessed through the Mann–Kendall non-parametric test, which evaluates the probability that the ranks of a time series follow a consistent directional pattern without assuming normality in the distribution of the data, a requirement that is rarely met by hydroclimatic series subject to high interannual variability and extreme events. The trend magnitude was quantified using Sen's slope estimator, which provides a robust median-based measure of the rate of change in mm per year that is resistant to the influence of outliers. Both procedures are established standards in

hydrology and climatology for the detection of monotonic trends in precipitation series. A significance threshold of $p < 0.05$ was applied. The analysis was implemented in Python 3.11 using the pymannkendall library, applied to the annual total precipitation series of each of the 15 IDEAM stations for the period 1995–2025 ($n = 30$ annual observations per station). Results by station are reported in Table S1.

Prior to applying the Mann–Kendall test, each annual precipitation series was examined for lag-1 serial autocorrelation, which can inflate the variance of the test statistic and bias significance levels in hydroclimatic series. The lag-1 autocorrelation coefficient was computed for every station and tested for significance through a two-tailed Student's *t*-test ($\alpha = 0.05$). For stations exhibiting statistically significant lag-1 autocorrelation, the modified Mann–Kendall test proposed by Hamed and Rao [35], which corrects the variance of the statistic for the effect of serial correlation, was applied instead of the original test; for stations without significant autocorrelation, the original Mann–Kendall formulation was retained. Sen's slope estimator, which is unaffected by this correction, was applied uniformly across all stations. Of the fifteen stations analyzed, five (Alto San Miguel, Cabrera, Gutiérrez, Lejanías Castillo and Miraflores) presented significant lag-1 autocorrelation and were evaluated with the Hamed-Rao modified test; the remaining eleven were evaluated with the original test.

Although the orographic configuration of the Sumapaz páramo exerts strong control over the spatial distribution of precipitation, station elevation was not incorporated as an explicit covariate in the interpolation workflow. The Exploratory Interpolation tool evaluates methods based exclusively on the cross-validation accuracy of the target variable; it does not provide, within the same analytical framework, provisions for integrating external covariates such as a digital elevation model. Beyond this operational constraint, the available network of 15 stations represents a sparse spatial sampling relative to the complexity of the altitudinal gradient of the study area; under such conditions, the additional fitting of an altitude-precipitation regression for Kriging with External Drift would introduce estimation uncertainty that the cross-validation procedure already penalizes implicitly. The superior predictive performance of EBK-Advanced over Universal Kriging (which incorporates polynomial trend functions as a proxy for spatial drift) suggests that the empirical variogram distribution fitted by EBK adequately captured the non-stationary spatial structure of the precipitation field without requiring explicit covariate specification. The absence of elevation as a formal covariate is nonetheless acknowledged as a methodological limitation; Future work in the area should consider regression-kriging or Kriging with External Drift approaches coupled with a high-res DEM, particularly given the marked precipitation-altitude gradient documented in the páramo core.

2.3.2. Thermal Trend Analysis

The climatic temperature grids went through a processing stage by using the raster calculator to obtain mean monthly temperatures from the maximum and minimum records. The post-processing included the resampling of each base raster to the extent of the study area, the extraction by mask, and the derivation of zonal statistics for each monthly climatic grid for the period 2000–2024. The thermal trend was evaluated through regression analysis in SPSS, with the comparison of linear and quadratic models for the series of zonal mean temperatures, with the purpose of determining the magnitude and the statistical significance of the observed warming.

2.3.3. Calculation of Spectral Indices

The selected Landsat scenes went through a transformation to surface reflectance values through radiometric correction and were clipped to the study area. From the

calibrated images, the analysis derived four normalized difference spectral indices through the band arithmetic properties tool of ArcGIS:

The Normalized Difference Vegetation Index (NDVI), formulated as the relationship between the near-infrared (NIR) and the visible red (Red) bands, quantifies the photosynthetic state and the density of the vegetation canopy. Values close to unity indicate photosynthetically active and dense cover, while negative values are associated with non-vegetated surfaces or water bodies.

The Normalized Difference Water Index (NDWI), derived from the relationship between the near-infrared (NIR) and the shortwave infrared (SWIR) bands, provides a proxy for surface water availability and soil moisture conditions. Positive values are spectrally associated with water saturation or the presence of water-bearing surfaces; in a páramo context and at 30 m pixel resolution, these values more precisely reflect saturated organic soils and peatlands than open water bodies in the conventional sense, given that sub-pixel water surfaces return mixed spectral signals that systematically pull the index toward zero or negative values.

The Normalized Difference Snow Index (NDSI), calculated from the green (Green) and shortwave infrared (SWIR) bands, allows the identification of surfaces with water accumulation associated with saturated soils. Although the Sumapaz páramo does not present permanent snow cover, the spectral basis of the NDSI (which contrasts green-band reflectance with shortwave infrared absorption, a combination sensitive to liquid water content at or near the Surface) has been applied beyond strictly nival contexts. Gao et al. [36] incorporated NDSI as a predictor variable in a random forest model for soil moisture downscaling in cold and arid environments, finding that its inclusion improved predictive accuracy by more than 19% relative to models without it; Boschetti et al. [37] demonstrated that NDSI formulations using MODIS shortwave infrared bands were among the most robust indices for detecting surface water in flooded systems; and Bandak et al. [38] identified NDSI alongside NDWI as the most sensitive spectral indices for estimating soil moisture in croplands using Landsat and Sentinel-2 imagery. No study was identified that formally validates NDSI thresholds against measured edaphic moisture in páramo peatlands or tropical high-mountain wetlands without snow cover; its application here as an indicator of surface water saturation is therefore exploratory and analogical, and its formal calibration against in situ soil moisture data in the Sumapaz system represents a priority for future research. Within this study, NDSI is interpreted conservatively as a proxy for the spatial extent and temporal change in moisture-positive surfaces, and its results are used only in convergence with the three remaining indices rather than as independent evidence.

The Normalized Burn Ratio (NBR), obtained from the relationship between the near-infrared (NIR) and the longer-wavelength shortwave infrared (SWIR₂) bands, allows the evaluation of burn severity and the degradation state of vegetation cover, with the possibility of differentiating between actively affected areas and zones in different recovery phases.

The four indices were reclassified into categorical ranges based on thresholds standardized in the literature. The resulting category labels (such as High Saturation Signal, Medium Saturation Signal, or Drought) describe spectral response classes, not directly observed physical conditions; their ecological interpretation requires consideration of sensor resolution, land cover context, and the mixed-pixel effect, particularly for water-related categories in a high-altitude environment with small and fragmented water bodies. With this caveat, the surface extension of each spectral category was quantified in km² for each reference date, enabling the evaluation of change trajectories in the spectral signal over the analytical period.

2.3.4. Land Cover Change Analysis

The CLC maps corresponding to 2000 and 2018 were clipped to the study area while preserving the standard coding of the Corine Land Cover methodology, adapted for Colombia by IDEAM. The procedure estimated the extension in km² of each cover class on both dates and identified the dominant transitions, with particular attention to changes between natural covers with a water regulation function (grasslands, peatlands, water bodies) and covers of anthropic origin (pastures, agricultural mosaics, urban zones).

The integration of the four analytical components (spatial precipitation variability, thermal trend, multi-index spectral dynamics, and cartographic evolution of land cover) allowed contrasting whether the structural transformations of land use recorded by the CLC corresponded spatially with the spectral signals of water stress and change in the vegetation condition, as well as the evaluation of their coherence with the observed pluviometric and thermal patterns. The integrated analytical framework described in this section is designed not only as a diagnostic instrument for the Sumapaz páramo but as a transferable methodological contribution to sustainability science: it demonstrates that the simultaneous application of vegetation, water, and land cover indicators within a unified spatio-temporal unit of analysis substantially improves the capacity to detect concealed trajectories of ecosystem degradation that conventional single-index monitoring would classify as stability or recovery.

3. Results

3.1. Spatial Redistribution of Precipitation

The analysis of mean annual precipitation at the 15 IDEAM stations evidenced patterns of high interannual variability, modulated by climatic cycles such as ENSO, without a uniform linear trend of decrease. The R^2 values obtained in the regression models proved lower than 0.05 in most stations (Table S2), which confirms that the pluviometric variability responds mainly to external climatic forcings rather than to deterministic temporal trends. Nevertheless, three stations located in sectors of lower altitude and orographic transition (El Tulcán, Lejanías Castillo, and Villarica) presented statistically significant relationships ($p < 0.001$), which suggests persistent changes in the precipitation regime in these sectors. By contrast, the stations representative of the high-mountain zone, such as Llano Largo, La Bolsa, and Alto San Miguel, did not present significant relationships between precipitation and time, despite the patterns consistent with water-related deterioration that the spectral analyses registered.

The Mann–Kendall test, applied with a lag-1 autocorrelation diagnostic and the Hamed–Rao variance correction where serial correlation was significant, confirmed that pluviometric variability in the Sumapaz páramo responds predominantly to interannual climatic forcing rather than to deterministic monotonic trends. Ten of the fifteen stations returned no statistically significant trend ($p > 0.05$), including two of the three stations most representative of the high-mountain core, Llano Largo ($\tau = 0.035$, $p = 0.803$) and La Bolsa ($\tau = 0.186$, $p = 0.154$). Five stations presented statistically significant trends ($p < 0.05$), with Sen's slope estimating their rate of change. Alto San Miguel ($\tau = 0.172$, $p = 0.022$, slope = +10.3 mm yr^{−1}), El Tulcán ($\tau = 0.301$, $p = 0.020$, slope = +13.8 mm yr^{−1}), and Las Casas ($\tau = 0.260$, $p = 0.046$, slope = +5.1 mm yr^{−1}) showed significant increasing trends, while Miraflores ($\tau = -0.292$, $p = 0.025$, slope = −15.9 mm yr^{−1}) showed a significant decreasing trend. Notably, the strong lag-1 autocorrelation detected at Lejanías Castillo ($r_1 = 0.742$) reduced its trend to non-significance once the variance correction was applied ($p = 0.070$), demonstrating the relevance of the autocorrelation diagnostic: under the uncorrected test, this station would have been classified as a strong decreasing trend, an inference that the serial-correlation correction does not support. Villarica approached the significance

threshold with an increasing trend ($\tau = 0.251$, $p = 0.054$, slope = $+16.0 \text{ mm yr}^{-1}$). The coexistence of significant increasing trends at lower-altitude and transitional station (Las Casas) with a significant increase at two transitional core station (Alto San Miguel, El Tulcán) and a decrease at another transitional station (Miraflores) reflects spatial heterogeneity in the precipitation regime rather than a uniform regional trend, and reinforces the interpretation that the most ecologically relevant change lies not in the total volume precipitated but in its spatial reorganization relative to the altitudinal gradient of storage capacity. Complete results, including the lag-1 autocorrelation coefficients and the test applied at each station, are reported in Table S3. The comparative analysis from WorldClim evidenced that the maximum monthly precipitation decreased by more than 50% between 2000 (222.6 mm) and 2015 (106.5 mm), with a partial recovery of 25% toward 2024 (169.4 mm) (Table S4). The zonal mean descended from 116.6 mm in 2000 to 51.7 mm in 2015 and recovered to 109.6 mm in 2024, although with a notable reduction in the standard deviation (from 31.5 to 14.0 mm), which indicates a homogenization of the pluviometric field toward lower values.

The isohyets of mean monthly precipitation corresponding to the years 2000, 2015, and 2024 (Figure 2) revealed that the most significant change does not lie in the total volume of precipitation but in its spatial redistribution with respect to the altitudinal gradient. Whereas in 2000 the pluviometric accumulations presented a distribution coherent with topography, with the highest values over the high-mountain core, by 2024 this correspondence breaks down: the maxima relocate to belts of lower elevation ($<2000 \text{ m a.s.l.}$) at the margins of the study area, while the páramo core receives decreasing volumes. The analysis of the average interannual rainfall regime (1995–2024) confirmed the persistence of the bimodal pattern at the regional scale, with maxima in April–May and October–November (Figure S4), which rules out a complete rupture of the seasonal regime. This pattern configures a functional decoupling between the zones of greatest atmospheric capture and the areas with the greatest storage capacity in organic horizons, a phenomenon that reduces the effective recharge of the system regardless of the behavior of the total annual precipitated volume.

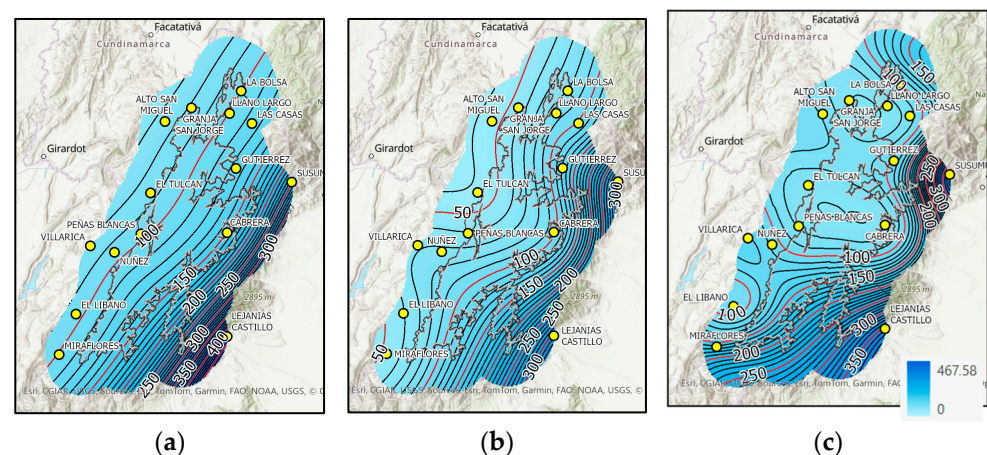


Figure 2. Isohyetal maps of mean monthly precipitation derived from IDEAM station data for (a) 2000, (b) 2015, and (c) 2024, color scale from zero to max made to preserve homogeneous representation for the time lapses; note that isohyets with zero are not the minimum registered.

3.2. Thermal Trend

The WorldClim climatic grids documented a warming of $+1.11 \text{ }^{\circ}\text{C}$ in the mean temperature of the Sumapaz páramo during the period 2000–2024 (Figure 3). This warming presents a preferential diurnal character: the daytime maximum mean temperature increased by $+1.5 \text{ }^{\circ}\text{C}$, while the nighttime minimum mean rose $+1.0 \text{ }^{\circ}\text{C}$ (Table S5), which broadened the daily thermal range by $0.5 \text{ }^{\circ}\text{C}$ between 2015 and 2024. In the high-mountain

core, the thermal intensification manifested in a displacement of the isotherms from magnitudes of 5 °C in 2000 toward values of 7 °C in 2024. The mean annual temperatures shifted from ~8.0 °C in the years close to 2000 to ~9.0 °C in 2024, with a rise in the thermal ceiling (maxima from 13.0 °C to 14.5 °C) and an elevation of the minimum threshold above 6.0 °C. The 90th percentile shifted from 9.6 °C to 11.0 °C (Table S5).

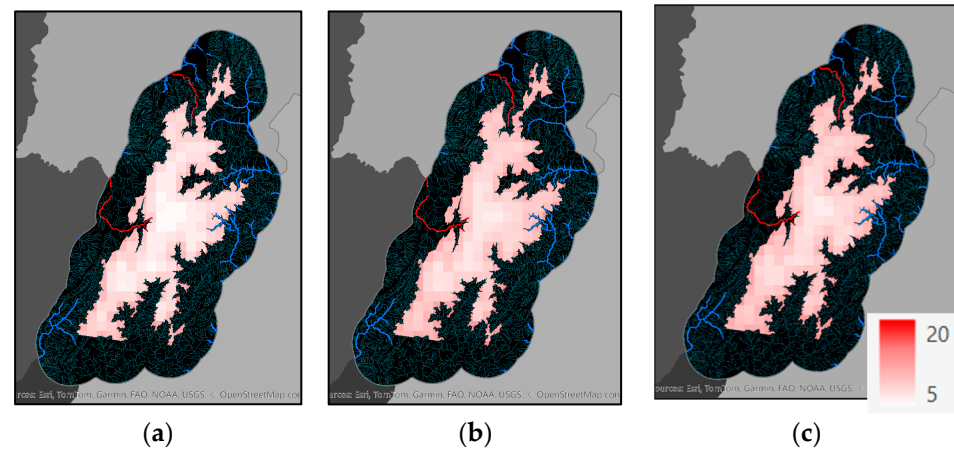


Figure 3. Spatial distribution of mean temperature from WorldClim grids for (a) February 2000, (b) January 2015, and (c) December 2024.

The regression analysis through SPSS (Table S6) yielded an R^2 coefficient of 0.114 with a significance of 0.092 and a slope of 2.42×10^{-2} °C/year for the linear model, which indicates a real warming signal but one modulated by interannual climatic cycles and oscillations. The comparison between linear and quadratic models did not evidence improvements in the fit, which suggests that the thermal change expresses itself as a displacement of the regime toward higher values rather than as a strict linear trend. This thermal configuration, combined with the pluviometric redistribution described in the previous section, establishes the conditions for an increase in evaporative demand and in physiological stress on the vegetation cover of the páramo.

3.3. Water Body Dynamics—NDWI

The quantification of the spectral distribution of surface moisture through NDWI documented a near-complete contraction of surfaces returning a positive water signal between 2000 and 2025, a pattern that warrants careful distinction between what the sensor detects and what that detection implies about actual water conditions on the ground. (Figure 4, Table 2). The categories with NDWI values above 0 (Moisture, Medium Saturation Signal, and High Saturation Signal), which together encompassed 1273.9 km² in 2000, decreased to 0.47 km² in 2015 and to less than 0.02 km² in 2025. Simultaneously, the surfaces classified as Moderate Drought (NDWI between −0.3 and 0) expanded from 1929.9 km² to 2909.9 km², and those of Drought (NDWI < −0.3) grew from 46.8 km² to 340.7 km², with which they together reached 99.3% of the study area in 2025.

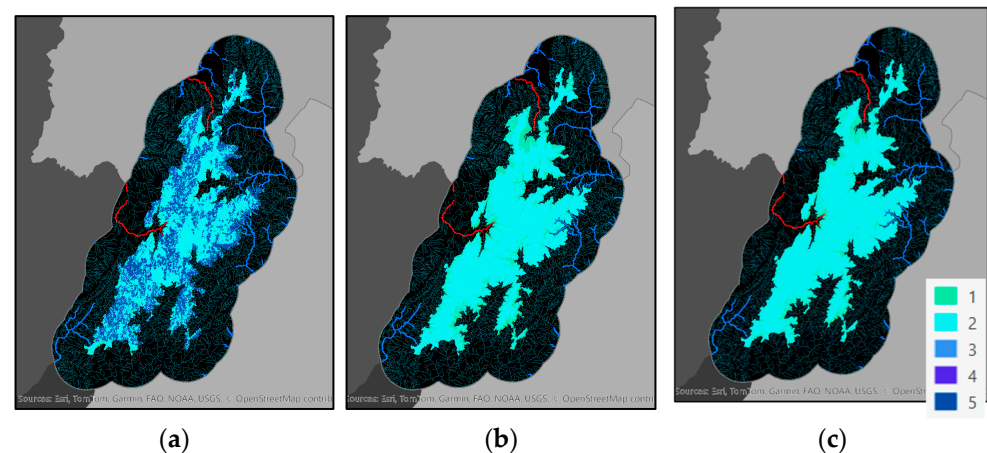


Figure 4. Multitemporal NDWI classification for the Sumapaz páramo: (a) February 2000, (b) January 2015, and (c) January 2025.

Table 2. NDWI-based surface area distribution (km²) across moisture categories for the Sumapaz páramo (2000, 2015, 2025).

Id	NDWI Range	Category	Extension (km ²)		
			2000	2015	2025
1	−1 to −0.3	Drought	46.79	449.03	340.65
2	−0.3 to 0.0	Moderate Drought	1929.86	2801.13	2909.92
3	0.0 to 0.1	Moisture	96.60	0.46	0.02
4	0.1 to 0.2	Medium Saturation Signal	79.42	0.01	0.00
5	0.2 to 1.0	High Saturation Signal	1097.92	0.00	0.00

Two interpretive constraints bear directly on the reading of these figures. First, the Landsat sensor resolves the landscape at 30 m; at this scale, a pixel covering a small water body surrounded by dry organic soil returns a mixed spectral signal that pulls the NDWI toward zero or negative values, regardless of whether water is physically present at the sub-pixel level. Values falling in the Moderate Drought category (NDWI between −0.3 and 0) should therefore not be read as unambiguous evidence of soil moisture deficit: a portion of those pixels likely contains residual water surfaces whose spatial dimensions fall below the detection threshold of the sensor. Second, in a tropical páramo without snow cover, positive NDWI values (above 0.2) reflect saturated Andosols and peatlands rather than open water bodies in the conventional sense; the 1097.92 km² classified as High Saturation Signal in 2000 corresponds predominantly to waterlogged organic soils, a distinction consistent with the CLC cartography, which recorded only 5.12 km² of natural water bodies and wetlands for the same year. The near-disappearance of positive NDWI values by 2015 and 2025 is thus best interpreted as a contraction of the spectral water saturation signal, reflecting a reduction in the extent of surfaces with conditions detectable as moisture-positive by the sensor, a finding that is consistent with, but not equivalent to, the physical disappearance of those water-bearing surfaces. The consistency of the spectral contraction pattern across the three temporal cuts, and its correspondence with the reduction in inland waters documented by the CLC (from 5.1 km² to 4.5 km²; see Section 3.7), support the interpretation of a structural reduction in moisture-positive conditions within the páramo, while acknowledging that the sensor's spatial resolution limits the precision with which residual water surfaces can be quantified, as Santeccchia et al. [27] documented for analogous high-resolution constraints.

3.4. Vegetation Cover Dynamics—NDVI

The multitemporal analysis of NDVI revealed a trend that, evaluated in isolation, would suggest a recovery of vegetation vigor (Figure 5, Table 3). The category of negative values (dead or absent vegetation, NDVI < 0), which dominated 1549.7 km² in 2000, decreased to 1.5 km² in 2015 and to 0.02 km² in 2025. This reduction, however, did not find compensation in an increase in the categories of high photosynthetic activity, but in the expansion of the low activity category (NDVI between 0 and 0.33), which went from 1674.7 km² to 3054.7 km² in 2025, with which it encompassed 93.3% of the study area. The category of moderate activity (NDVI between 0.33 and 0.66) increased from 26.4 km² to 196.0 km², while the cover of high photosynthetic activity (NDVI > 0.66) remained practically nonexistent (< 0.2 km²) throughout the entire period.

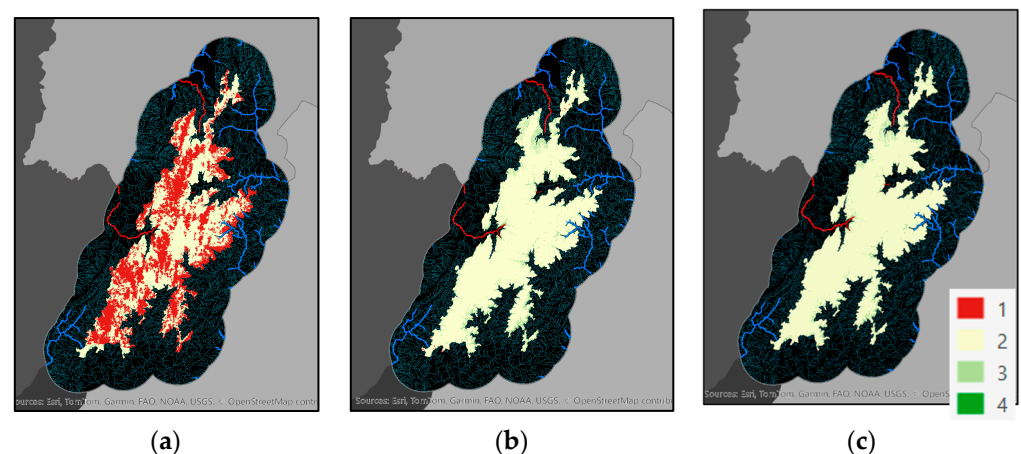


Figure 5. Multitemporal NDVI classification for the Sumapaz páramo: (a) February 2000, (b) January 2015, and (c) January 2025.

Table 3. NDVI-based surface area distribution (km²) across vegetation activity categories for the Sumapaz páramo (2000, 2015, 2025).

Id	NDVI Range	Category	Extension (km ²)		
			2000	2015	2025
1	−1.0 to 0.0	Dead/absent vegetation	1549.67	1.46	0.02
2	0.0 to 0.33	Low photosynthetic activity	1674.66	2987.04	3054.66
3	0.33 to 0.66	Moderate photosynthetic activity	26.42	261.96	195.98
4	0.66 to 1.00	High photosynthetic activity	0.00	0.13	0.00

The divergence between the NDWI signal, which registers a near-complete contraction of moisture-positive surfaces, constitutes the most relevant finding of the spectral analysis. This coexistence indicates that the ecosystem registers a gain in photosynthetic activity at the same time that the spectral water signal contracts, a divergence that is consistent with a reduction in water availability but cannot be equated with it on the basis of spectral indices alone, requiring the multi-index and land cover evidence developed in the Discussion.

3.5. Edaphic Moisture Dynamics—NDSI

The NDSI registered a marked contraction of the surfaces returning a soil water saturation signal (Figure 6, Table 4). In 2000, the categories of greatest water content, functionally interpreted as saturated soils in the context of a tropical páramo without snow cover, summed 1049.0 km²: the category analogous to strong water accumulation (NDSI between 0.4 and 1.0) encompassed 433.2 km², and that of weak accumulation (NDSI between 0 and 0.4) covered 615.8 km². By 2015, these categories contracted to 50.9 km², and

by 2025, they descended to less than 0.8 km². Correspondingly, the category of soil with sparse vegetation and low moisture (NDSI between -0.5 and 0) expanded from 2201.4 km² to 3249.8 km², with which it dominated 99.3% of the study area in 2025.

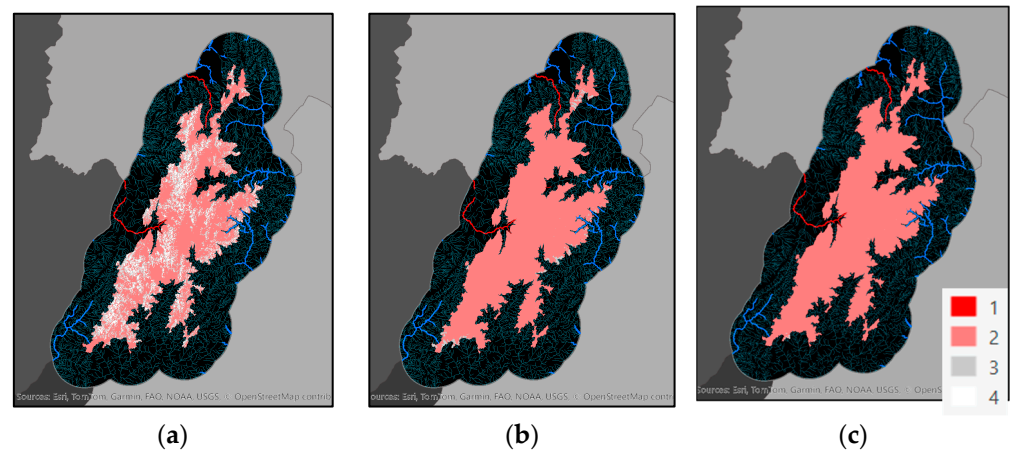


Figure 6. Multitemporal NDSI classification for the Sumapaz páramo: (a) February 2000, (b) January 2015, and (c) January 2025.

Table 4. NDSI-based surface area distribution (km²) across soil moisture categories for the Sumapaz páramo (2000, 2015, 2025).

Id	NDSI Range	Category	Extension (km ²)		
			2000	2015	2025
1	-1.0 to -0.5	Bare soil/rock	0.00	0.25	0.01
2	-0.5 to 0.0	Soil with sparse vegetation	2201.43	3199.32	3249.82
3	0.0 to 0.4	Weak water accumulation	615.81	50.87	0.77
4	0.4 to 1.0	Strong water accumulation	433.18	0.00	0.00

The convergence between the contraction of the water saturation signal recorded by NDSI and the reduction in moisture-positive surfaces documented by NDWI is consistent with a process of progressive edaphic desiccation and strengthens the plausibility of that interpretation when both indices point in the same direction across the same temporal window. If interpreted as reflecting actual edaphic moisture reduction (a reading that the multi-index convergence supports but that would require field validation to confirm), this pattern would carry direct implications for the delayed infiltration capacity of Andosols and for the regulation of baseflow during dry periods.

3.6. Degradation Severity—NBR

The multitemporal analysis of NBR revealed a páramo dominated by degradation and incomplete recovery categories, with an almost total absence of healthy or stable vegetation (Figure 7, Table 5). The temporal trajectory admits the distinction of two phases. In the period 2000–2015, the categories of high and moderate burn ($NBR < -0.1$) decreased from 69.1 km² to 3.7 km², which indicates that burns prior to the year 2000 evolved toward the category of degraded or transitional soil (NBR between -0.1 and 0.1), which increased from 1088.4 km² to 1315.0 km². The categories of early and medium recovery (NBR between 0.1 and 0.44) remained relatively stable at ~1931 km². In the period 2015–2025, the burn categories remained at minimums (<3.4 km²), but the degradation/transition category continued its expansion to 1363.6 km², while those of recovery descended to 1883.3 km². The classes of stable and healthy vegetation ($NBR > 0.44$) contracted from 59.7 km² in 2000 to less than 0.2 km² in 2025.

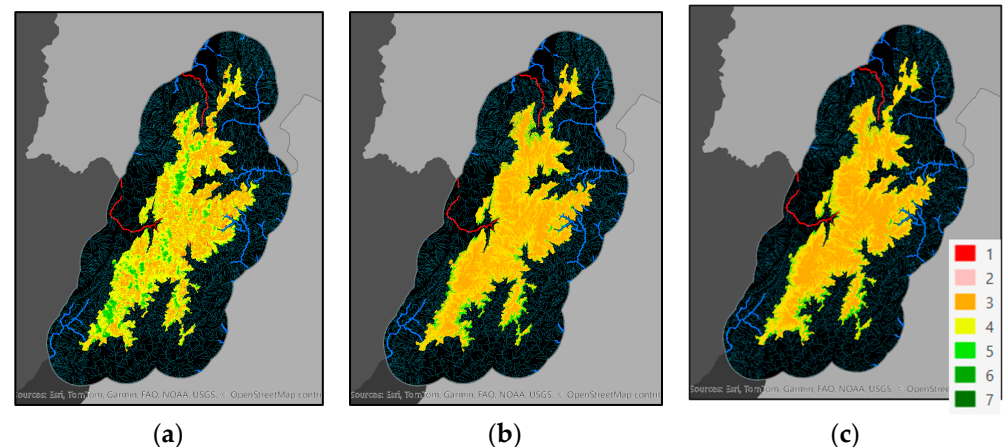


Figure 7. Multitemporal NBR classification for the Sumapaz páramo: (a) February 2000, (b) January 2015, and (c) January 2025.

Table 5. NBR-based surface area distribution (km²) across burn severity and recovery categories for the Sumapaz páramo (2000, 2015, 2025).

Id	NBR Range	Category	Extension (km ²)		
			2000	2015	2025
1	−1.0 to −0.25	High Burn	45.40	0.02	0.04
2	−0.25 to −0.1	Moderate Burn	23.72	3.68	3.37
3	−0.1 to 0.1	Degraded/transitional	1088.41	1314.97	1363.59
4	0.1 to 0.27	Early recovery	1743.75	1688.75	1670.44
5	0.27 to 0.44	Medium recovery	289.43	242.44	212.90
6	0.44 to 0.66	Stable vegetation	59.70	0.62	0.18
7	0.66 to 1.00	Healthy/dense vegetation	0.02	0.00	0.00

This pattern indicates that, although no recent fires of significant magnitude are recorded, the ecosystem finds itself in a state of incomplete recovery with respect to historical disturbances prior to the year 2000, with 70% of the area in conditions of degradation or partial recovery. The moisture deficit suggested by the convergent NDWI and NDSI signal patterns would operate as a plausible limiting factor for full revegetation.

3.7. Land Cover Transitions—CLC 2000–2018

The comparison of the CLC 2000 and 2018 maps provided the framework of structural validation for the spectral patterns described (Figure 8, Table 6). In the agricultural component, clean pastures expanded from 30.9 km² to 51.0 km², and the mosaics of pastures and crops went from 110.3 km² to 171.4 km², accompanied by the appearance of urban fabric (0.2 km²), mining extraction zones (0.2 km²), and lands dedicated to potato cultivation (0.7 km²), categories absent in 2000. In the opposite direction, the mosaics of crops, pastures, and natural spaces decreased from 112.4 km² to 46.3 km², which suggests a process of productive intensification.

In the natural covers, peatlands remained constant, but natural lagoons and wetlands went from 5.1 km² to 4.5 km², which provides structural land-cover evidence consistent with the contraction of the spectral water saturation signal that NDWI registered. Dense mainland non-wooded grasslands tripled (from 325.7 km² to 975.5 km²), while dense grasslands with shrubs remained relatively stable (~930–950 km²). In the transitional fringe bordering the páramo core, the net forest area increased by approximately 48.5 km²; however, this aggregate figure conceals a structural downgrade rather than a recovery. Dense tall mainland forest (the mature formation occupying the outer edge of the study area at the forest-páramo transition) contracted from 401.3 km² to 310.4 km² (−0.8 km²),

while dense low mainland forest expanded from 101.6 km² to 240.9 km² (+139.3 km²), largely within the same transitional belt where tall forest was previously mapped. The spatial coincidence of the loss and the gain indicates that the dominant process was not forest expansion into new territory but the replacement of structurally complex mature forest by shorter, less developed forest cover. Forest plantations also extended from 2.6 km² to 9.0 km² within the same zone.

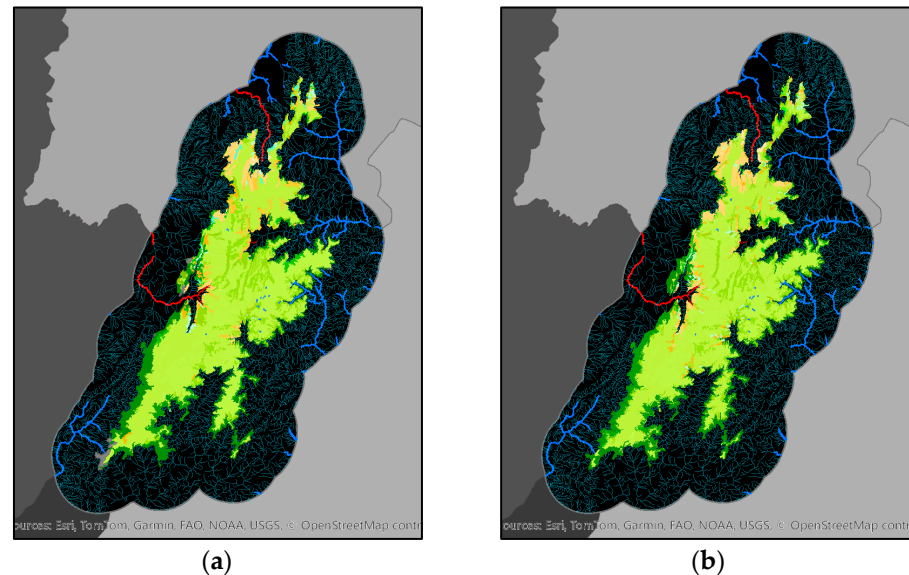


Figure 8. Corine Land Cover classification for the Sumapaz páramo: (a) 2000 and (b) 2018.

Table 6. Major land cover transitions in the Sumapaz páramo between 2000 and 2018 based on Corine Land Cover cartography (classes with highest absolute change).

Cover	2000 (km ²)	2018 (km ²)	Change
2.3.1. Clean pastures	30.95	51.00	+20.05
2.4.2. Mosaic of pastures and crops	110.34	171.38	+61.04
2.4.3. Mosaic of crops, pastures and natural spaces	112.37	46.26	−66.11
3.1.1.1.1. Dense tall mainland forest	401.26	310.43	−90.83
3.1.1.2.1. Dense low mainland forest	101.64	240.93	+139.29
3.2.1.1.1.1. Dense mainland grassland, non-wooded	325.65	975.50	+649.85
4.1.2. Peatlands	0.57	0.57	-
5.1.2. Natural lagoons, lakes and wetlands	5.12	4.46	−0.66

The net redistribution of covers indicates that surfaces with a water storage function (peatlands, wetlands, grasslands associated with saturated soils) yield in front of covers with lower regulating capacity (agricultural mosaics, dry grasslands, plantations) (Table S7), which spatially reproduces the patterns of functional substitution that the NDVI-NDWI divergence suggested and is consistent with the interpretation of a structural transition of the ecosystem.

Taken together, the multi-index and cartographic evidence presented in this section documents a pattern of functional transformation whose sustainability implications operate at two scales: at the ecosystem scale, through the progressive reduction in the regulating services that the páramo core provides; and at the territorial scale, through the structural modification of the transitional buffer zones whose integrity conditions the long-term sustainability of water availability in the downstream basin.

4. Discussion

4.1. Spatial Decoupling Between Precipitation and Ecohydrological Storage

The literature on climate change in Andean páramos has tended to frame water degradation as a direct consequence of the temperature increase or of the reduction in precipitation totals. The results of this study suggest a different and potentially more determining mechanism for the regulating function: the spatial reorganization of precipitation, which decouples the zones of atmospheric capture from the areas of ecohydrological storage. Fonseca Carreño [26] described that the regulating function of the páramo depends on the precipitated water reaching the peat horizons for its delayed retention, and Molina Benavides et al. [11] documented that Andosols only exercise their buffering function when they receive sufficient inputs to maintain the saturation of the edaphic profile. The pluviometric results of this study evidence that, when precipitation reorients toward lower altitudinal belts, as the isohyets of the period 2000–2024 show, the total volume precipitated in the basin may be maintained or even partially recovered, but the conditions for effective recharge of the regulating core progressively deteriorate (a process reflected both in the spatial homogenization of the pluviometric field toward lower altitudinal values and in the convergent spectral signal contraction documented across NDWI and NDSI).

This mechanism of spatial decoupling between capture and storage configures a water risk that conventional indicators of pluviometric variability do not capture. The trend analysis applied to the 15 IDEAM stations, using the Mann–Kendall test with the lag-1 autocorrelation correction, confirmed that precipitation does not show a significant monotonic decrease in the high-mountain core stations ($p > 0.05$ at Llano Largo and La Bolsa), a finding that, read in isolation, could lead to an optimistic evaluation of the state of the system. However, the absence of a statistical temporal trend coexists with a spatial reorganization that both the IDEAM isohyets and the WorldClim grids documented, whose reduction in the zonal standard deviation (from 31.5 to 14.0 mm) reflects a homogenization of the pluviometric field toward lower values in the high-mountain core. Campos-Aranda [39] demonstrated that, even when many long-term pluviometric series do not present significant trends, the quantitative analyses reveal progressive reductions in recent averages associated with the intensification of dry periods. Pérez-Ortiz et al. [40] extended this analysis by documenting that the ENSO phenomenon strongly modulates precipitation in Colombian Andean basins, with marked reductions during the warm phases that increase water vulnerability, especially in high zones. Consequently, the water risk thresholds for the Sumapaz páramo must be evaluated in terms of the spatial distribution of precipitation and not exclusively in terms of the temporal trend of the accumulations.

A methodological qualification of particular relevance concerns the spectral and pluviometric values recorded for January 2015. Martínez et al. [41] documented that the El Niño 2015–2016 event was classified by the World Meteorological Organization as one of the three strongest since 1950, combining, for the first time simultaneously, a warm phase of the Pacific Decadal Oscillation and the highest global surface temperatures in the instrumental record; Thielen et al. [42] reported that the Oceanic Niño Index reached a mean value of 2.22 °C between October 2015 and February 2016, surpassing the corresponding values of the 1982–1983 and 1997–1998 events. At the regional scale, Martínez et al. [41] recorded a severe precipitation deficit across much of Colombia and northern South America from May 2015 through July 2016, and Díaz & Villegas [43] documented that the drought severity of this episode exceeded that of both preceding strong events. From a soil hydrological standpoint, Ávila et al. [44] demonstrated that El Niño-type surface pressure conditions generate negative soil moisture anomalies in Andean systems 9 to 11 months before the event peak, a lead time that places the January 2015 Landsat acquisition within the precursor window of the developing forcing. In páramo ecosystems specifically, Esquivel-Hernández

et al. [45] showed that the El Niño 2015–2016 event substantially disrupted moisture transport and modified the isotopic composition of rainfall across Central American and Andean páramos, while Pacheco et al. [46] identified the 2009–2014 interval as a period of particularly high negative coherence between ENSO indices and drought indicators in high Andean basins, conditions consistent with a progressive antecedent soil moisture deficit already manifesting at the time of the January 2015 acquisition. These circumstances indicate that the extremely low moisture-positive values documented by NDWI and NDSI in 2015 likely reflect the superposition of a structural desiccation trend with the acute hydroclimatic forcing of an exceptionally strong El Niño event; the magnitude of the 2015 values may therefore overestimate the rate of structural decline at that specific temporal cut. The persistence of near-zero moisture-positive surfaces in January 2025 (a scene acquired under ENSO-neutral conditions) supports the interpretation that the structural component of the signal is real, while also confirming that the three-date observational framework does not permit a formal quantification of the relative contribution of cyclic versus non-cyclic forcing to the observed contraction.

The analytical separation between structural trends and interannual ENSO variability is a recognized challenge in Andean hydroclimatology. Díaz & Villegas [43] demonstrated that precipitation variability in the Colombian Andes is organized in coherence bands of 2 to 8 years that account for a large fraction of its total variance, and that ENSO-driven forcing interacts with land use change in ways that amplify drought impacts and complicate the attribution of observed deficits to structural versus cyclic causes. Pomares-Meza et al. [47] further showed that the dominant influence of ENSO on interannual precipitation variability frequently masks or exaggerates underlying structural trends, even when those trends are statistically real, and that water yield deficits can persist with lags of up to nine months after an ENSO-driven drought episode, a delay that in a three-date spectral record is difficult to distinguish from a shift in baseline conditions. In the absence of a longer time series or a formal variance decomposition, the conclusions of this study regarding structural ecohydrological decline rest on the spatial and multi-index convergence of the evidence: the pluviometric reorganization documented across three independent analytical sources, the spectral divergence across four indices, and the cartographic land cover transitions recorded by CLC. This convergence supports the characterization of the direction and multi-causal structure of the transformation; the rate of change, however, should not be extrapolated without explicitly accounting for the contribution of cyclical ENSO variability to the observed magnitudes at each temporal cut.

4.2. *The Vegetation-Water Paradox: Apparent Greenness Under Hydrological Contraction*

The most complex result to interpret, and from the methodological perspective, the one of greatest relevance, is the coexistence of a growing vegetation vigor signal (NDVI) with a near-complete contraction of the spectral water saturation signal (NDWI), a pattern reinforced by the parallel reduction in moisture-positive surfaces as recorded by NDSI and by the persistence of degradation and incomplete recovery categories in the NBR. This divergence among spectral indicators constitutes in itself a diagnostic indicator that the literature has characterized in a fragmented manner. García Mora et al. [13] documented in the Guapé river basin variations in vegetation vigor that did not respond to endogenous ecological dynamics but to anthropic pressure on the water system; Pirachicán Grijalba et al. [12] identified in the La Cortadera páramo signals of apparent spectral recovery that corresponded to the colonization by secondary vegetation of lesser functional value.

In the context of Sumapaz, the confluence of at least four mechanisms allows the explanation of this paradoxical spectral signal. In the first place, Murad et al. [48] associated the expansion of woody shrub communities with greater infrared reflectance that colonizes

previously saturated soils, a process known as shrub encroachment. In the second place, Llambí et al. [16] linked the altitudinal migration of communities from lower belts with the differential warming documented in the páramo, a phenomenon called thermophilization. In the third place, Baldi et al. [49] partially attributed the increase in vegetation vigor to the basal photosynthetic stimulus generated by the rise in minimum temperatures. In the fourth place, Lis-Gutiérrez et al. [8] related the nutritive enrichment of surface water sheets with effluents of agricultural origin, a phenomenon that stimulates biological productivity in the remaining water bodies, an observation reinforced by Chambe et al. [17] in high-Andean lagoons of the Peruvian altiplano. The confluence of these four mechanisms provides a plausible mechanistic basis for interpreting the positive spectral signal as reflecting a progressive displacement of hydrophilic communities of high regulating capacity rather than functional recovery, a hypothesis that the convergence of multi-index and land cover evidence supports, and that the field-based experimental record discussed below contextualizes, but that requires systematic phytosociological monitoring in Sumapaz to be confirmed at the community level.

This finding acquires greater consistency upon being contrasted with the results of the NDSI and the NBR. The reduction of 1049 km² of surfaces returning a water saturation signal (NDSI > 0) between 2000 and 2025 is consistent with the interpretation that the gain in greenness is not accompanied by an improvement in edaphic water conditions, a reading that, while not directly verifiable through spectral indices alone, is coherent with the convergent patterns documented across all four indices; in turn, the persistence of 70% of the area in degradation or incomplete recovery categories (NBR) indicates that the substrate on which the new vegetation cover develops has not recovered its functional integrity. Patil et al. [50] demonstrated that, even in years with normal precipitation, vegetation may remain under conditions of mild or moderate drought when evaluated through the integration of NDVI and NDWI, which is coherent with the patterns observed in the Sumapaz páramo and supports the interpretation that effective water availability in the system cannot be adequately assessed from precipitation volumes alone.

Establishing the epistemic boundaries of this interpretation is necessary before extending the argument. What the spectral data confirm is a change in the direction and spatial extent of the photosynthetically active signal and its sustained divergence from moisture-sensitive indices across three independent temporal cuts. What can be inferred from the multi-index convergence is a functional shift in the character of the vegetation cover, one consistent with a displacement of water-dependent communities. What requires field verification is the species and community-level composition of the areas concentrated in the NDVI gain, the growth forms and functional groups responsible for that gain, and whether they correspond to the substitution processes that the four mechanisms propose. The closest direct experimental evidence available for the Sumapaz páramo itself comes from Lasso et al. [51], who installed open-top warming chambers in two Colombian páramos including Sumapaz and, after three years of in situ warming of approximately 1.7 °C, documented an increase in shrub and graminoid cover within the warmed plots (a structural community response directly consistent with the shrub encroachment and thermophilization mechanisms proposed), and under a thermal forcing of the same order of magnitude as the +1.11 °C trend documented in this study over the period 2000–2024. At the regional scale, Cuesta et al. [52] documented compositional shifts across high-Andean plant communities incorporating species with broader thermal niches and warmer optimums, while Anthelme et al. [53] described the emergence of novel plant communities at Colombian high-altitude sites following glacial retreat, characterized by the displacement of endemic páramo species by assemblages of lower functional specificity. These works establish a regional empirical context for the community substitution hypothesis. Its systematic verification in Sumapaz

demands phytosociological resurveys anchored to the historical baselines established by Cleef [54], whose foundational work in the Colombian Cordillera Oriental (including the paramo de Sumapaz) remains the only comprehensive record of community composition and altitudinal zonation available for direct comparison with present-day conditions.

4.3. Land Use Change as a Structural Co-Causal Factor

A third interpretative line that this study contributes, and that the analyses focused on climatic variability tend to subordinate, is the role of land use change as a co-causal factor of water contraction, operable independently of background climatic trends. The expansion of the agricultural frontier that the CLC documented, with an increase in clean pastures (+20.1 km²), mosaics of pastures and crops (+61.0 km²), and the appearance of urban zones, mining extraction, and potato cultivation, acts upon the regulating capacity of the system through direct edaphic mechanisms. Anzoategui et al. [14] demonstrated that tillage destroys the macroporosity of the Andosol necessary for delayed infiltration; Murad et al. [48] quantified the reduction in water retention capacity by bovine compaction in analogous páramos of Guerrero and Rabanal, with native vegetation losses of 59.96% and 47.96%, respectively.

The forest transition documented in Table 6 deserves particular attention in this interpretive context because its aggregate metric obscures its functional significance. A net gain of 48.5 km² in the transitional forest belt might be read superficially as evidence of ecological recovery; the spatial analysis reveals, however, that this gain resulted from the structural replacement of dense tall mainland forest by dense low mainland forest within the same border zone, not from the colonization of previously open or degraded terrain. The functional distinction between these two formations matters for the hydrological budget of the páramo. Buytaert et al. [55] documented that mature cloud forest at the forest-páramo transition contributes to the water balance of Andean headwaters through the interception of horizontal precipitation (fog and low cloud) a process that depends directly on canopy height, structural complexity, and epiphytic biomass; Berrones et al. [56] specifically quantified the contribution of fog and cloud water to soil moisture in the Andean páramo, confirming that this input pathway is relevant not only for the transitional forests below but for the páramo core itself, where horizontal precipitation maintains the high relative humidity and low evapotranspiration rates that the ecosystem depends on. The replacement of structurally complex tall forests by shorter, less developed forests reduces the effective interception surface and erodes the microclimate buffer between the agricultural frontier and the páramo. Ochoa-Tocachi et al. [57] demonstrated that land use change in tropical Andean catchments consistently reduces the hydrological regulation capacity of transitional zones even when aggregate vegetation cover metrics suggest stability, a finding directly applicable to the structural forest downgrade observed here. This transition is therefore consistent with the overall degradation trajectory documented in this study and illustrates how cartographic area metrics can mask qualitative functional losses that only become apparent when nature, not merely the extent, of the land cover change is examined.

These effects possess a structural character: they do not revert with the interannual variability of precipitation and operate in the same direction as the pluviometric reorganization, which configures a double pressure on the regulating function. The reduction in natural lagoons and wetlands (from 5.1 km² to 4.5 km²) that the CLC recorded constitutes independent evidence that the covers with the greatest water storage function are being replaced by categories of lower regulating capacity. Pirachicán Grijalba et al. [12] confirmed in the La Cortadera páramo that the agricultural expansion over native covers is the degradation vector with the greatest effect on the streamflow regulation capacity, even

in the absence of statistically significant climatic trends. This finding has direct implications for management: conservation measures focused exclusively on emissions reduction or on climate adaptation, without effective control of the agricultural expansion in the area of influence of the páramo, prove insufficient to halt the loss of the regulating function of the system.

4.4. Multivectorial Degradation: Convergence of Climatic and Anthropogenic Factors

The convergence of the three mechanisms that the preceding sections identified, namely, the spatial decoupling of precipitation, the substitution of hydrophilic covers by drought-adapted communities under an apparently positive spectral signal, and the cumulative edaphic deterioration by land use change, configures a scenario of multivectorial ecohydrological degradation. The distinctive characteristic of this scenario lies in the fact that the magnitude of the combined effect exceeds that which any of the individual vectors would generate in isolation: the pluviometric reorganization reduces recharge, the change in use reduces the retention capacity of the soil, and the substitution of covers reduces the regulation capacity of runoff, phenomena that operate synergistically on the regulating function of the system, as Figure 9 synthesizes.

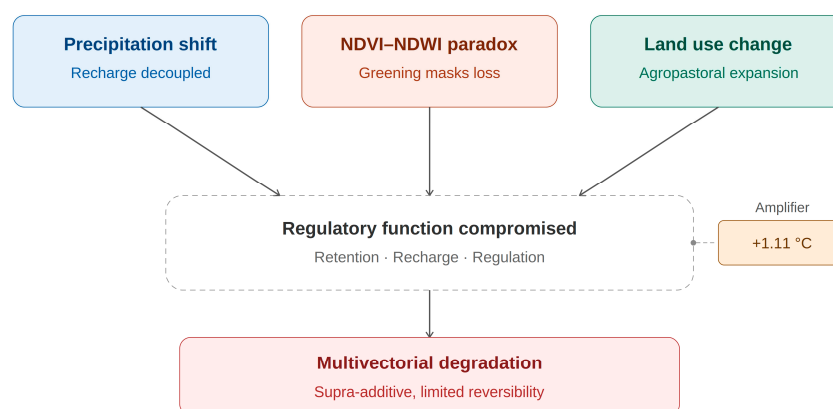


Figure 9. Conceptual diagram of the multivectorial ecohydrological degradation framework identified in the Sumapaz páramo, showing the convergence of precipitation redistribution, vegetation-water paradox, and land use change as interacting drivers.

Figure 9 presents a conceptual framework for the multivectorial ecohydrological degradation documented in the Sumapaz páramo, organizing the three identified drivers and their interactions within a unified interpretive structure. The first vector (the spatial redistribution of precipitation toward lower altitudinal belts) reduces effective recharge of the páramo core independently of trends in total precipitated volume, operating through the mechanism of spatial decoupling between atmospheric capture and ecohydrological storage described in Section 4.1. The second vector (the divergence between the NDVI signal and the moisture-sensitive indexes) reflects the functional substitution of hydrophilic communities by drought-tolerant vegetation under a deceptively positive spectral surface, a process that reduces the runoff regulation capacity of the ecosystem even as conventional greening indicators suggest recovery. The third vector (the cumulative expansion of the agricultural frontier documented by the CLC) acts through direct edaphic mechanisms that reduce the infiltration and retention capacity of Andosols, and through the structural downgrading of the transitional cloud forest belt that provides the microclimate buffer between the agricultural zone and the páramo core. The diagram also represents the transversal role of temperature increase as an amplifying factor that accelerates evaporative demand and reinforces the three primary vectors simultaneously and identifies the fire risk emerging from the persistence of degraded substrates as a potential fourth-order

destabilizing mechanism. The central argument represented (that the combined effect of these drivers exceeds the sum of their individual impacts) is what distinguishes the ecohydrological vulnerability of Sumapaz from scenarios where each stressor operates in isolation and can be addressed through single-factor management interventions.

From the thermal perspective, the warming of $+1.11\text{ }^{\circ}\text{C}$ that was documented in the period operates as a transversal amplifying factor. Beniston [58] and Buytaert et al. [59] documented that warming rates in high-mountain ecosystems may triple those recorded in lowlands; Hurtado Ríos [60] reported in the Cruz Verde-Sumapaz complex itself an increase of up to $3.51\text{ }^{\circ}\text{C}$ in the diurnal surface temperature between 2000 and 2020. The preferential diurnal character of the warming that this study detected ($+1.5\text{ }^{\circ}\text{C}$ in maxima versus $+1.0\text{ }^{\circ}\text{C}$ in minima) increases the thermal amplitude and enhances the evaporative demand, with the consequent acceleration of the desiccation of the upper soil horizons. Abbasian et al. [61] demonstrated that indices based exclusively on precipitation underestimate the real magnitude of drought when the temperature increase acts simultaneously, a finding directly applicable to the scenario that was documented in Sumapaz.

The reversibility of this multivectorial scenario is conditioned by the simultaneity of the interventions. Moazeni and Cerdà [62] and Grillakis [63] warned that the intensification of water stress elevates the susceptibility to fires in mountain ecosystems, a disturbance that the NBR results suggest as a growing risk for Sumapaz: although no recent fires of magnitude are recorded, the persistence of degraded soils and the absence of stable vegetation configure a highly combustible substrate. Barnard et al. [64] demonstrated that the hydrological impacts of fire in mountain basins may exceed the predictive capacity of conventional models, which introduces additional uncertainty in water resource planning. The prevention of this trajectory demands simultaneous intervention on the agricultural expansion, on the management of the water regime, and on the establishment of early warning systems that integrate climatic, spectral, and edaphic indicators.

4.5. Methodological Implications for the Monitoring of Páramos

The spectral limitations of NDVI deserve explicit treatment in a study whose central finding rests on its divergence from water-sensitive indices. NDVI captures the normalized difference between near-infrared and red reflectance, which responds to chlorophyll content, leaf area index, and canopy biomass; it is sensitive to the presence and density of photosynthetically active vegetation but functionally blind to its composition. At 30 m pixel resolution, a single pixel integrates grasses, shrubs, mosses, and bare soil in proportions that can shift over time without the index being able to resolve them independently. This matters because positive NDVI values carry no intrinsic information about the water regulation capacity or ecological integrity of the vegetation producing them: a dense mat of Sphagnum, a stand of encroaching woody shrubs, and a recovering graminoid cover can return similar NDVI values despite their radically different roles in páramo ecohydrological functioning. The indifference of the index to functional composition is precisely the reason the multi-index framework applied in this study is analytically necessary: it is the sustained divergence between NDVI and the moisture-sensitive indicators (NDWI and NDSI) rather than the value of any single index that allows the observed spectral pattern to be interpreted as evidence of functional substitution rather than functional recovery. This also explains why single-index greening studies of tropical high-mountain ecosystems systematically underestimate the degree of ecohydrological degradation: they capture the biomass signal but miss the functional dimension that only emerges when vegetation and water indices are read together.

The results of this study carry direct methodological implications for ecohydrological monitoring systems in Andean páramos. The divergence documented between NDVI

and NDWI is consistent with the hypothesis that evaluating the state of these ecosystems through a single spectral index introduces a systematic bias toward underestimating degradation, a risk that the multi-index framework of this study is specifically designed to reduce. This limitation acquires particular relevance in the context of Colombian páramos, where Llambí et al. [16] pointed out the structural disconnection between biodiversity studies and ecohydrology studies, and Palomo [7] warned about the underrepresentation of tropical mountains in global scientific output. Dourado et al. [28] and López Bolaños et al. [24] identified as a central methodological constraint the scarce articulation between the radiometry of vegetation cover and the radiometry of water bodies within the same spatio-temporal unit of analysis.

The integration of four spectral indices (NDVI, NDWI, NDSI, NBR), land cover cartography (CLC), and climatic modeling (precipitation and IDEAM isohyets, WorldClim temperature) within a unified analytical framework, as developed in this study, reduces that bias by allowing the contrast of the radiometric signal with the functional structure of land use and with pluviometric and thermal patterns, in direct response to the methodological gap that the literature pointed out. This multicomponent approach proves particularly necessary in ecosystems where the spectral signal of vegetation may improve through mechanisms that do not reflect functional recovery (shrub encroachment, thermophilization, eutrophication), and where the temporal resolution of the official land cover cartography, available only for two dates in the Colombian case, imposes restrictions on the detection of intermediate changes.

4.6. Limitations and Future Research

This study presents limitations that should be considered in the interpretation of the results. The spatial resolution of the Landsat images (30 m) introduces the mixed-pixel effect in water bodies of small dimensions, a phenomenon that masks residual water sheets under the dominant signal of the surrounding dry soil, as Santecchia et al. [27] documented. The persistent cloud cover in tropical high-mountain zones reduced the universe of usable scenes to three dates with complete spatial coverage (2000, 2015, 2025), which limited the capacity to capture interannual variability. The available CLC cartography covers up to 2018, a situation that prevents the evaluation of cover transitions corresponding to the last seven years of the analytical period. The WorldClim climatic grids constitute modeled products with a resolution of ~4.5 km, insufficient to capture the microclimatic variability at the slope scale that Anzoategui et al. [14] pointed out as relevant in páramos with pronounced topographic gradients. Finally, the study lacks direct field validation for the spectral categories, which limits the possibility of confirming *in situ* the cover substitution processes inferred from the NDVI-NDWI divergence.

The loss of three intermediate acquisition dates 2005, 2010, and 2020 due to the SLC-off failure of the Landsat 7 sensor imposes a structural constraint on the temporal resolution of the spectral analysis. With observations limited to 2000, 2015, and 2025, the study captures two intervals of ten to fifteen years but cannot resolve changes occurring within those windows. Gradual or non-linear transitions (such as the progressive encroachment of shrub communities or the incremental contraction of saturated soil surfaces) are detectable only if they accumulate sufficient magnitude between the available dates, while transient events or regime shifts occurring in intermediate years remain outside the analytical reach of this study.

The temporal sampling structure also limits the statistical interpretation of change trajectories. With only three observations, it is not possible to distinguish a monotonic trend from an accelerating or decelerating process, nor to determine whether the 2015 snapshot represents a transitional state or an extreme year influenced by interannual climatic vari-

ability. This constraint should be considered when extrapolating the observed trajectories to longer time horizons or to management planning scenarios requiring knowledge of the rate, rather than the net magnitude, of change.

The interpolation of precipitation fields relied on the cross-validation-based selection of the Empirical Bayesian Kriging—Advanced method without incorporating station elevation as an explicit covariate, a constraint inherent to the Exploratory Interpolation workflow employed; this may introduce residual bias in sectors where orographic forcing generates precipitation gradients at a finer scale than that captured by the available station network.

Future research should incorporate Sentinel-2 images (10 m resolution) to reduce the mixed-pixel effect in smaller water bodies, integrate radar data (SAR) to overcome the limitation of persistent cloud cover, and establish field validation campaigns that allow correlating the spectral categories with direct measurements of edaphic moisture and floristic composition. The implementation of compound indices such as the NDDI, which integrates NDVI and NDWI into a single drought indicator, constitutes a promising methodological development line for the operational monitoring of páramos under climate change conditions.

5. Conclusions

The spatial redistribution of precipitation toward lower altitudinal belts constitutes the ecohydrological mechanism of greatest functional relevance that was documented during the study period. The reduction in recharge in the high-mountain core, produced by the progressive decoupling between the zones of atmospheric capture and the storage areas in peat and Andosols, compromises the regulating function of the system regardless of the behavior of the total precipitated volume at the basin scale. This finding suggests that the water risk thresholds for the Sumapaz páramo must be evaluated in terms of the spatial distribution of precipitation and not exclusively in terms of the temporal trend of the accumulations, which demands a reconfiguration of the conventional hydrological warning criteria applied in the region. It should be noted, however, that the three-date observational framework (with the 2015 scene coinciding with the precursor phase of what Martínez et al. [41] and Thielen et al. [42] identified as the strongest El Niño event since 1950) does not permit a formal statistical separation of structural trends from interannual climatic forcing; the direction of the documented ecohydrological transformation is supported by the convergence of independent evidence sources, but the apparent rate of change between 2000 and 2015 should be interpreted with this confounding factor in mind.

The divergence between the vegetation vigor signal, which shows a sustained increase during the period, and the near-complete contraction of the spectral water saturation signal configures a pattern indicative of concealed ecohydrological degradation. The apparent improvement of vegetation vigor consistent with the confluence of shrub encroachment, thermophilization, basal photosynthetic stimulus by rising temperatures, and nutritive enrichment of residual water bodies by agricultural effluents, is most plausibly interpreted as a displacement of hydrophilic communities of high regulating capacity by vegetation adapted to water limitation, rather than as functional recovery; this interpretation is grounded in multi-index convergence, experimental warming evidence from Sumapaz itself, and regional compositional evidence from high-Andean systems, but requires phytosociological field validation at the site level to be established with certainty. The convergence of this pattern with the reduction in moisture-positive surfaces recorded by NDSI and the persistence of degradation categories in the NBR strengthens the plausibility of the interpretation that the ecosystem is on a trajectory of functional loss, one that remains invisible to monitoring approaches based on greenness indicators alone.

The land use change that the CLC cartography documented operates as a co-causal vector of water contraction with structural effects not reversible at an interannual scale. The expansion of agricultural covers over native humid grasslands acts through cumulative edaphic mechanisms, namely, the destruction of the macroporosity of the Andosol and the compaction by trampling, which reduces the delayed infiltration capacity of the system. The convergence of this anthropic vector with the pluviometric reorganization and with the sustained warming (+1.11 °C in the period 2000–2024) configures a multivectorial pressure on the regulating function whose magnitude exceeds that of any of the factors separately.

The present study demonstrates that the evaluation of the ecohydrological state of páramos from a single spectral index introduces a systematic bias of underestimation of the degradation. The integration of multiple spectral indices (NDVI, NDWI, NDSI, NBR), of land cover cartography, and of climatic modeling within a unified analytical framework allows the contrast of the radiometric signal with the functional structure of land use and with the patterns of precipitation distribution, which reduces the risk of erroneous interpretations. This methodological approach responds to the gap that the literature has identified regarding the need to articulate the interdependencies among climate, ecosystem structure, and water availability in tropical high-mountain systems.

In terms of implications for territorial management, the results indicate that conservation strategies for the Sumapaz páramo based exclusively on the control of emissions or on climate adaptation measures prove insufficient if they do not simultaneously incorporate the effective control of the agricultural expansion in the area of influence, the establishment of integrated ecohydrological monitoring systems that overcome the limitations of optical remote sensing under persistent cloud covers, and the generation of long-term technical information that orients the planning of water risk management and territorial planning in the central region of Colombia, whose water security depends on the functional integrity of this ecosystem.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18146971/s1>, Figure S1: Heatmap of mean annual precipitation across 15 IDEAM stations in the Sumapaz páramo area (1995–2025); Figure S2: Regression analysis of total monthly precipitation at Lejanías Castillo station (1995–2025); Figure S3: Spatial distribution of total monthly precipitation from WorldClim grids for (a) February 2000, (b) January 2015, and (c) December 2024; Figure S4: (a) Mean interannual precipitation regime by station (1995–2024); (b) regression analysis of mean annual temperature (2000–2025); Table S1: Cross-validation performance metrics (RMSE and ME) for thirteen interpolation configurations evaluated across the three reference periods (2000, 2015, 2024). Methods are ordered by mean RMSE rank across periods. RMSE: root mean square error (mm); ME: mean error (mm). Evaluation conducted using the Exploratory Interpolation tool of ArcGIS Pro under leave-one-out cross-validation.; Table S2: SPSS regression analysis of total monthly precipitation for 15 IDEAM stations (1995–2025): linear and quadratic model parameters.; Table S3: Results of the lag-1 autocorrelation diagnostic and Mann-Kendall trend test with Sen’s slope estimator, applied to annual total precipitation series (1995–2025) for the 15 IDEAM stations. Stations with significant lag-1 autocorrelation ($p < 0.05$) were evaluated with the Hamed-Rao modified Mann-Kendall test; the remainder with the original test. Significant trends ($p < 0.05$) are in bold. r_1 : lag-1 autocorrelation coefficient; τ : Kendall’s tau; $\dagger$: approaching significance threshold; Table S4: Summary statistics of total monthly precipitation from WorldClim grids for the Sumapaz páramo (2000, 2015, 2024).; Table S5: Summary statistics of mean temperature from WorldClim grids for the Sumapaz páramo, including maximum and minimum temperature trends (2000–2024); Table S6: SPSS regression analysis of mean annual temperature for the Sumapaz páramo (2000–2025): linear and quadratic model parameters.; Table S7: Complete Corine Land Cover classification for the Sumapaz páramo: surface area (km²) by CLC code for 2000 and 2018.

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Abbreviations

The following abbreviations are used in this manuscript:

CLC	Corine Land Cover
IDEAM	Institute of Hydrology, Meteorology and Environmental Studies (Colombia)
IGAC	Geographic Institute Agustín Codazzi
MADS	Ministry of Environment and Sustainable Development (Colombia)
NBR	Normalized Burn Ratio
NDSI	Normalized Difference Snow Index
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NIR	Near-infrared
RMSE	Root Mean Square Error
SLC	Scan Line Corrector
SWIR	Shortwave infrared
USGS	United States Geological Survey

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