

Hydrometeorological Components Affecting Disaster Risk in a High Andean Watershed

Dora Marcela Benitez Ramirez 1, Jonathan Panimboza Deleg 2,

1. University EAN; dbenites74611@universidadean.edu.co; ORCID 0009-0006-1964-4692
2. Pontifical Catholic University of Ecuador; Jonathan.g.ej@gmail.com; ORCID 0009-0005-3365-7679

Abstract: Based on meteorological data from IDEAM and satellite imagery spanning the period 2005-2016, coupled with an in-depth analysis of 2011 data, and cross-referenced with risk management databases from the department of Boyacá, a statistical identification of disaster scenarios impacting the sustainable development of the upper Chicamocha river basin was conducted. The spatiotemporal study reveals a hydrologically dynamic basin characterized by atypical extreme precipitation records influenced by the oceanic components of ENOS (El Niño-La Niña phenomena). The temporal fluctuation trends in flood return conditions expose the vulnerability of communities. Therefore, the generation of timely social response strategies is crucial to mitigate the adverse impacts of these threats. Consequently, examining the anticipation capacities of institutions and citizens is paramount to fostering a resilient culture. Further studies are warranted, incorporating cognitive processes, risk perception assessments, and an investigation of how the temporal and spatial scales of climate change influence the daily lives of basins as units of analysis. This study contributes to a refined understanding of the atmospheric processes that trigger extreme flood events. The exploration of these threats and the development of institutional capacities pave the way for the formulation and implementation of enhanced risk reduction strategies, ultimately promoting the consolidation of the Sustainable Development Goals (SDGs) and environmental stewardship.

Keywords: project management; disaster; floods; natural hazards; sustainable development.

COMPONENTES HIDROMETEOROLOGICOS QUE INCIDEN EN EL RIESGO DE DESASTRES EN UNA CUENCA ALTO ANDINA

Resumen: La variabilidad climática será más intensa y frecuente. Se buscó identificar los elementos atmosféricos capaces de generar eventos hidrometeorológicos extremos, que desencadenan inundaciones. Basados en décadas de información meteorológica del IDEAM, contrastada con bases de datos de Gestión del riesgo de Boyacá, se identifican estadísticamente escenarios de desastres que afectan el desarrollo sostenible de la cuenca alta del río Chicamocha. El estudio espacial y temporal encuentra una cuenca altamente activa hidrológicamente, con registros atípicos de precipitaciones extremas influenciados por las componentes oceánicas del ENOS (Fenómeno de Niño y Niña). Las tendencias de fluctuación temporal de las condiciones de retornos de inundaciones, encuentran a las comunidades desprevenidas; luego, es significativo, generar estrategias de respuesta social oportuna para disminuir el impacto adverso de estas amenazas. Por lo tanto, es importante examinar las capacidades de anticipación de las instituciones y ciudadanos como parte del fortalecimiento de una cultura resiliente. Se requiere, de más estudios que incluyan los procesos cognitivos, evaluaciones de la percepción del riesgo y de cómo las escalas temporales y espaciales del cambio climático influyen en la cotidianidad de las cuencas como unidad de análisis. Este estudio contribuye a una mejor comprensión de los procesos atmosféricos que desencadenan fenómenos extremos de inundación. El estudio de estas amenazas y



el desarrollo de capacidades institucionales permiten desarrollar e implementar mejores estrategias de reducción del riesgo y propenden por la consolidación de los ODS y de la gestión ambiental

Palabras clave: gestión de proyectos; desastre; inundación; amenaza natural; desarrollo sostenible.



Introduction

Situated in northwestern South America, Colombia's continental territory is bordered by the Pacific and Atlantic Oceans, where the Andes Mountains split into three distinct ranges: the Western, Central, and Eastern Cordilleras [1]. This rugged topography renders Colombia vulnerable to natural disasters such as massive floods [2], droughts, landslides, frosts, and storms, among others. According to AQUEDUCT (Global Flood Analyzer), by 2030, the number of people worldwide affected by hydrometeorological phenomena is projected to rise to 54 million, doubling the current global annual average of 21 million [3].

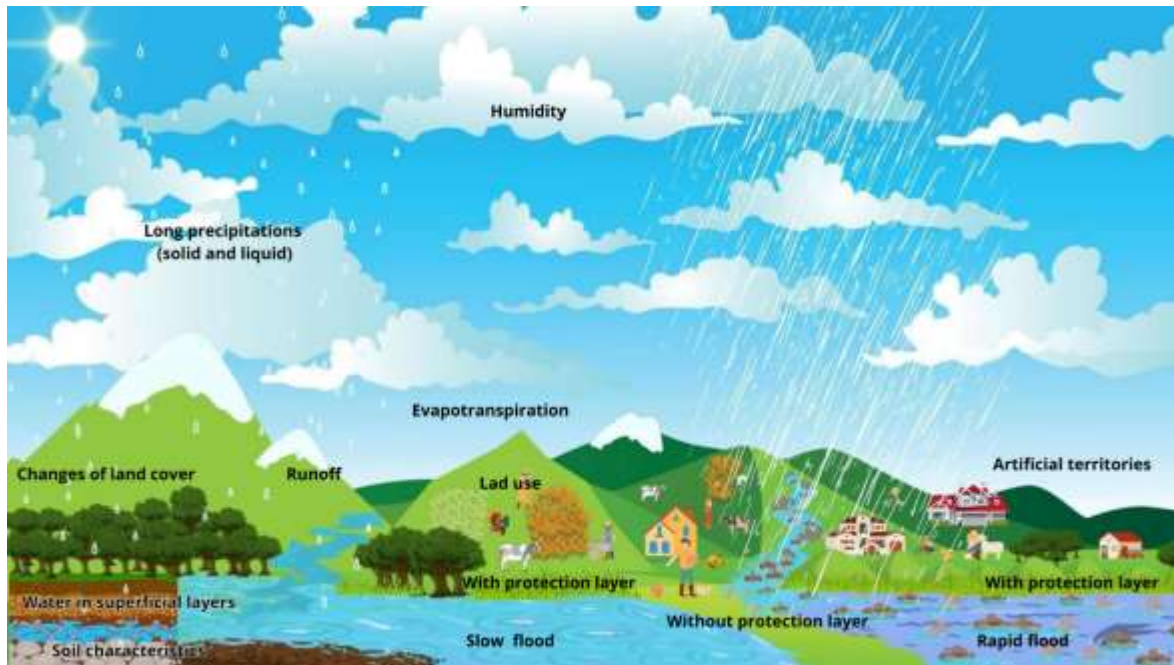
Colombia's Andean basins harbor the nation's most productive areas, driven by industrialization and population density [4]. One such basin is the Cundiboyacense plateau, shaped by the Chicamocha River, which belongs to the Magdalena-Cauca hydrographic area, the Sogamoso hydrographic zone, and the Chicamocha River hydrographic subzone (IDEAM, 2013). The Chicamocha River basin is composed of three subzones: the lower, middle, and upper basins [5]. The latter, encompassing 214,608.71 hectares and 21 municipalities, has an estimated population of 550,715 inhabitants according to DANE's 2015 Population Projections [6, 7].

Specifically, for the upper Andean basin of the Chicamocha River_CARCh, located in the central part of the Boyacá department, Colombia, there is a lack of evidence that contributes to the regional understanding of how hydrometeorological components influence disaster risk. This research product fills this gap, providing significant insights as territorial management strategies vary depending on rural or urban contexts. These contexts present widening gaps exacerbated by climate change, particularly in rural areas where the crisis is intensified due to specific vulnerabilities [8], especially those generated by land use and cover changes, as well as agricultural and livestock activities practiced since the time of the Muisca ancestors.

In 2023, the World Bank, in the context of Disaster Risk Management (DRM), highlights that poor and vulnerable populations are disproportionately affected by natural catastrophes of an atmospheric nature (climate and water), particularly in developing economies [9]. This underscores the importance of DRM as a critical component of local development [10], as it enables the identification of flood hazards and their interactions with social and economic factors [11].

Growing evidence points to the impacts of extreme hydrometeorological events such as floods and droughts [12], with floods ranking first globally in terms of severity and frequency, often triggered by a combination of extreme precipitation and soil moisture [13] (Figure 1). These flood scenarios are influenced by climate change [14] and the expansion of urban areas [15, 16], prompting the development of flood control systems [17] and the study of their characteristics [18]. This underscores the importance of analyzing these events, particularly considering their spatial distribution and interannual variability [19].

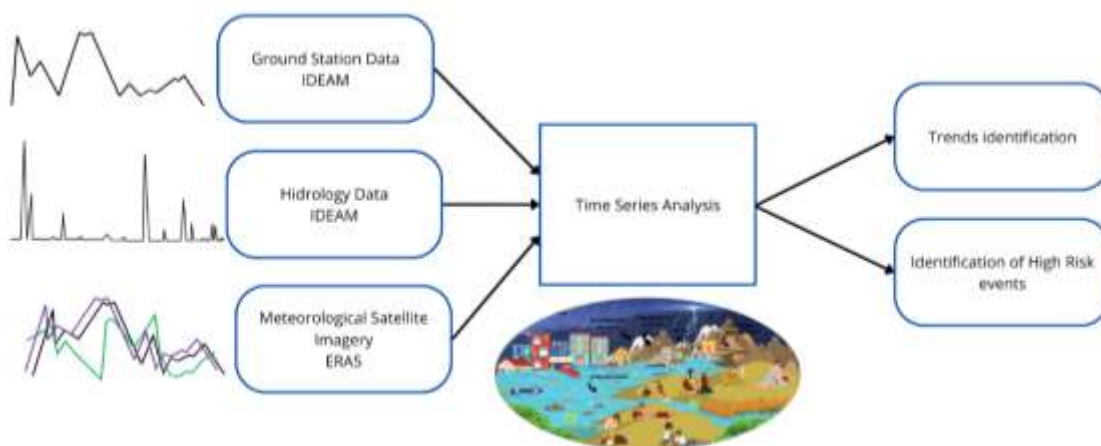
Figure 1. Types of floods: Slow and rapid



Methodology

Utilizing information from IDEAM and UDGRB, the records of atmospheric components and flood events [20] occurring within the upper Andean basin of the Chicamocha River were consolidated. This data was aggregated for the time horizon spanning December 31, 2004, to January 1, 2017, with daily temporal frequency and comprehensive coverage across the entire basin.

Figure 1. Methodology



To effectively distinguish between hydrometeorological threats, the temporal scope was defined to encompass a period of both flood and drought records. This approach facilitates a clearer differentiation between the seasonal patterns associated with these two distinct hazards.

Subsequently, a comprehensive database was constructed for IDEAM stations, as presented in Table 1. This database encompasses a wide range of parameters, including water levels, temperature parameters (maximum, average, and minimum), sunshine duration, evaporation rates, and precipitation records.

Table 1. Meteorological stations within the CARCh upper basin

METEOROLOGICAL GROUND STATIONS						
CODE	NAME	INSTALATION DATE	ALTITUDE	LATITUDE	LONGITUDE	MUNICIPALITY
24037030	EL PALO - AUT *	1955-05-15	2600	5,681722	-73,23113	Tuta
24037070	MAGUNCIA**	1964-01-15	2534	5,741888	-73,19955	Sotaquirá
24037130	LA REFORMA *	1966-06-15	2523	5,748833	-73,18988	Sotaquirá
24037090	SAN RAFAEL **	1964-01-14	2500	5,708388	-73,24216	Tuta
24037270	CHITICUY**	1991-12-15	2500	5,845444	-73,01361	Duitama
24037190	SAN RAFAEL - AUT*	1972-02-15	2500	5,807611	-73,01380	Tibasosa
24037110	LA RESACA**	1964-03-15	2492	5,680333	-72,98961	Firavitoba
24037290	PUENTE CHAMEZA - AUT *	1971-02-15	2490	5,759888	-72,90652	Sogamoso
24037320	LA SIBERIA *	1971-04-15	2248	5,766733	-73,10872	Paipa
24037510	PAZ DE RIO *	1980-11-15	2225	5,98774	-72,74452	Paz De Rio
NIVELES						
24035130	U P T C ***	1962-02-15	2690	5,54307	-73,36081	Tunja
24035150	BELENCITO ***	1967-02-15	2530	5,781583	-72,89430	Nobsa
24035430	TUNGUAVITA - AUT****	2004-12-15	2521	5,74583	-73,11636	Paipa
24035340	AEROPUERTO A LLERAS C ***	1974-01-15	2500	5,676944	-72,96791	Sogamoso
24035120	SURBATA BONZA ****	1944-03-15	2485	5,802444	-73,07447	Duitama

Source: IDEAM, adapted by authors.

Categories: *Limnigraphic ** Limnimetric *** Main climatic **** Agrometeorologic

The ERA5 climate dataset [21] was incorporated into the study to provide a comprehensive representation of atmospheric conditions. This dataset encompasses a range of essential climate parameters, including wind direction and speed, temperature, sunshine duration, albedo, and precipitation. The data is structured into nine grid centers, as shown in Table 2, and covers the entire basin with daily temporal resolution from 1981 onwards. Access to the ERA5 platform was facilitated through Google Earth Engine.

Table 2. Sample points for ERA5

ID	N	W	m.s.n.m.
1	5,751078	73,244503	2586
2	5,804457	73,094431	2637
3	5,814113	72,867051	2587
4	5,646285	73,307221	2751
5	5,660562	73,123325	2753
6	5,685874	72,957381	2477
7	5,48896	73,315585	2976

8	5,482808	73,140881	3572
9	5,459766	72,951918	3484

A comprehensive approach encompassing descriptive and inferential analysis was employed to identify risk-generating factors. Extreme values and amplitude ranges within time series data were examined. Records were contrasted to identify patterns and risk-associated events

Results

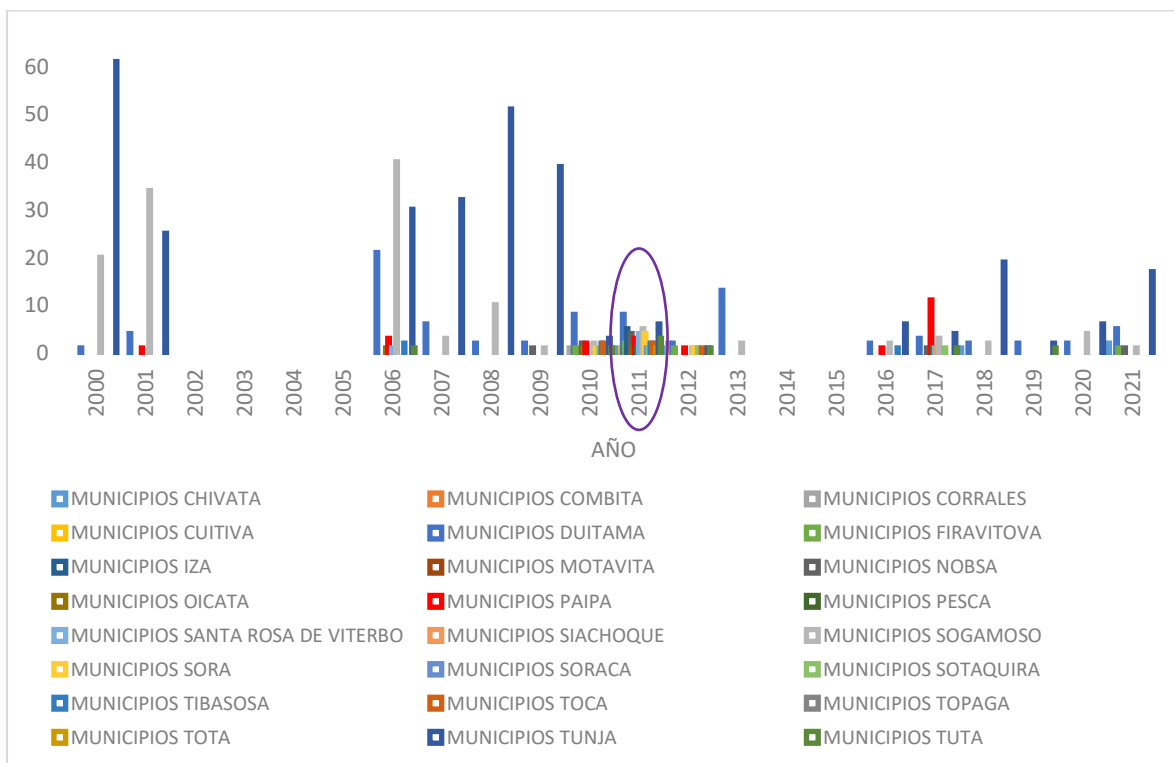
An extensive analysis of flood events in the Boyacá department of Colombia revealed a total of 24,018 incidents over a 21-year period. Notably, 65.2% of these events, representing 15,667 records, occurred within the upper Chicamocha River basin.

In contrast, the CARCh region experienced 612 floods during the same two-decade period, as illustrated in Figure 4. The highest concentration of flood records was observed between 2006 and 2013. Furthermore, in 2011, a staggering 74% (19) of the municipalities within the basin reported being inundated by floodwaters.

The analysis identified three distinct periods of heightened flood activity over the two decades, with the second period spanning eight years and characterized by intermittent drought periods of two to four years.

Tunja, the capital of Boyacá department, emerged as the city most severely impacted by floods, followed by Sogamoso, Duitama, and Paipa.

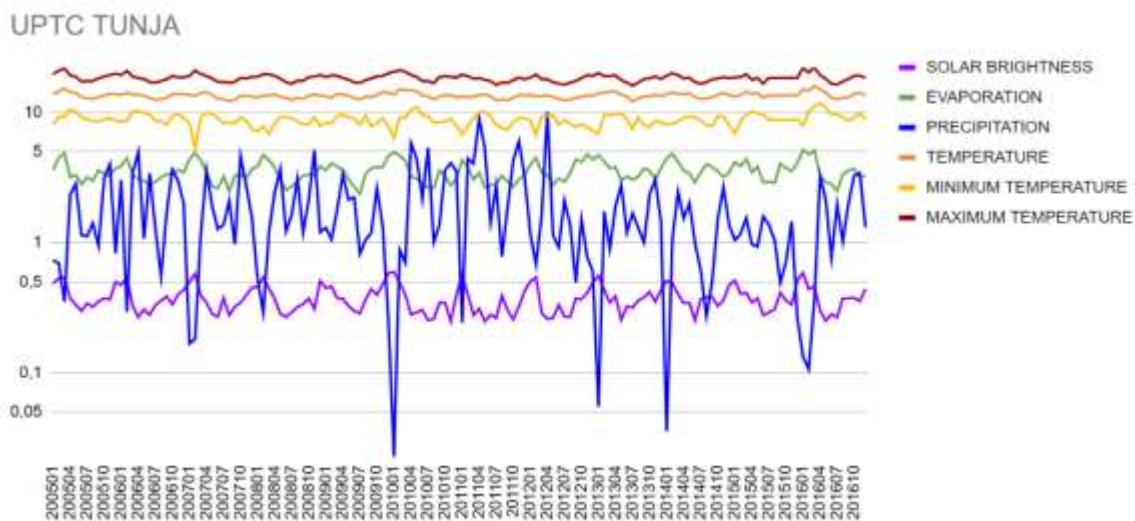
Figure 4. Flood Historical Data



Source: UDGRDB Data, analyzed by authors

A comprehensive analysis of time series data for various climate components was conducted for the period between 2005 and 2016 (Fig. 5), encompassing four meteorological stations. The IDEAM UPTC station revealed a distinct pattern in the atmospheric precipitation component, indicating its role as a flood trigger during the period from 2010 to 2012. The precipitation records exhibit a cyclical pattern with periods of 1, 2, and 5 years, while temperature and maximum temperature exhibit a 1-year cycle. Minimum temperature displays variations with shorter cycles; however, during the high precipitation season, the cycle is 1 year. Evaporation exhibits an inverse relationship with precipitation.

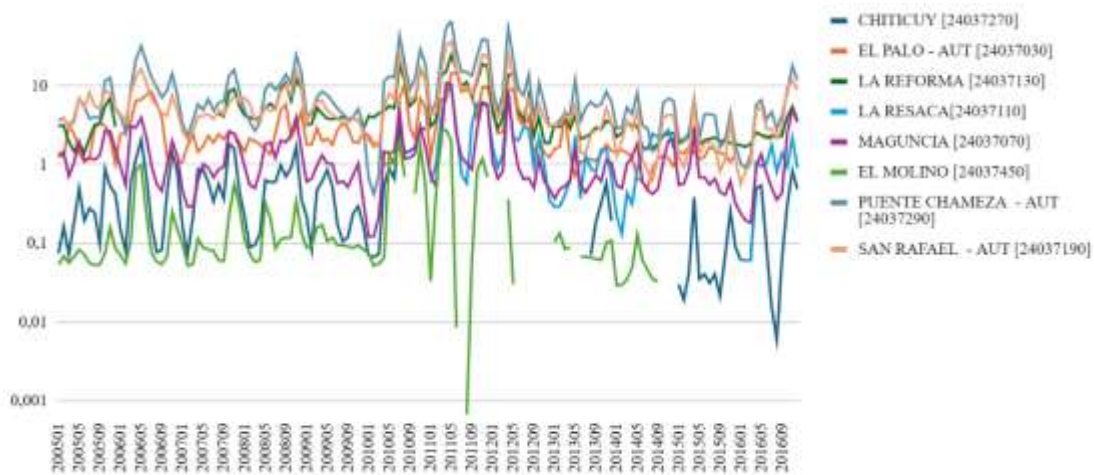
Figure 5. Time Series for UPTC-Tunja’s atmospheric components



Source. IDEAM, analyzed by the authors.

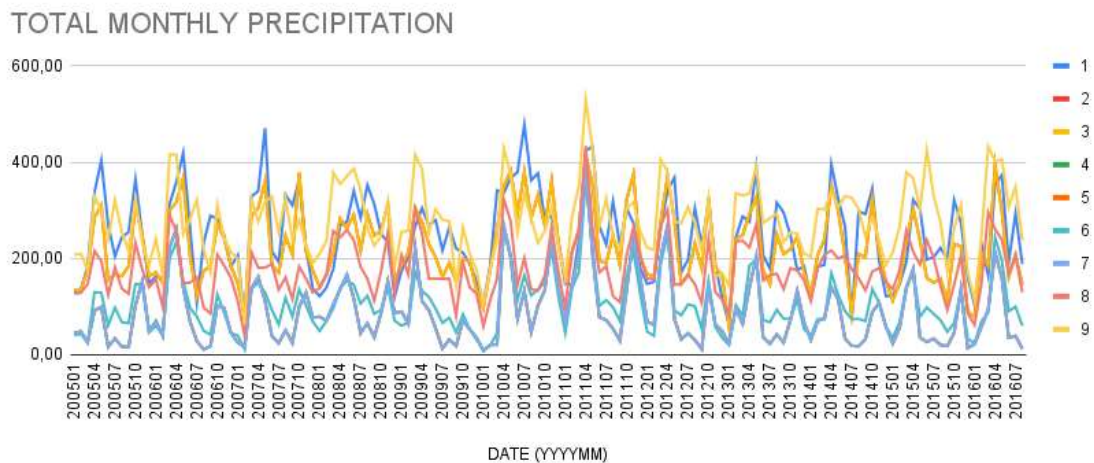
An examination of streamflow data recorded by IDEAM's limnimetric and limnigraphic stations revealed homogeneous sequences interspersed with atypical data interruptions (Fig. 6). These interruptions align with periods of elevated precipitation across the entire basin, as evident in ERA5 data (Fig. 7).

Figure 6. Flow time Series



Fuente. IDEAM, analyzed by the authors.

Figura 7. ERA5 Time Series



Source. ERA5, analyzed by the authors

Conclusions

The Upper Chicamocha River Basin holds a position of national significance within the Colombian Andes. It encompasses territories dedicated to food production and security, both for its own inhabitants and for other regions of the country. Serving as a major production and connectivity hub within the Eastern Cordillera, the basin's rich water resources, diverse ecosystems, and industrial development make it an attractive prospect for both domestic and foreign investors. However, its primary watercourse exhibits a considerable dynamic according to historical records, manifested in slow-onset floods that threaten the basin's potential.

Time series analyses conducted on flood records, climate components, and Chicamocha River flows are subject to data quality limitations [22], which were beyond the control of the researchers. Nonetheless, in terms of flood risk characterization [23], it can be inferred that the basin presents significant hydrological dynamics, as out of

21 years of study, six do not generate floods but maintain average flow values, ensuring sufficient water supply for traditional livestock and agricultural activities.

The presence of the Chicamocha River and its valley has, since pre-Columbian times, been an attractive factor for the establishment of population centers. Over time, as economic and social development processes unfold, the population density increases, necessitating the consolidation of infrastructure for basic sanitation, housing, communications, roads, education, health, and tourism, among others. This seemingly progressive scenario, however, generates increased vulnerability as the number of elements exposed [22] to flood threats continues to rise.

The recurrent presence of extreme precipitation events was evident in both IDEAM and ERA5 data, highlighting the significant and recurrent incidence of flood risk [24] in this high-altitude Andean basin [25], [26]. This is particularly concerning given the basin's susceptibility to oceanic influences and its location within the Intertropical Convergence Zone (ITCZ). Extreme precipitation events, coupled with land use and cover changes in the territories of the micro-basins that form part of the main channel's watershed, lead to overflows of the alluvial plain during these periods, causing impacts on the regional economy.

The study applies a methodology applicable to slow-flowing basins without channel confinement. The study basin regulates its flows through water management systems [26] such as reservoirs, which uniformize water flows while preserving the characteristic of slow flooding. However, as discussed at the beginning of this section, the temporal regimes and trends exhibit uncertainty, which can be reduced by improving data acquisition systems (switching from conventional to automatic), densifying the information recording structure, and providing training to generate uniformity in data processing techniques to generate management indicators for flood risk reduction.

This research scenario, which forms part of a macro early warning system project, favors the pillars of knowledge and risk reduction, including the identification of hydrometeorological antecedents that impact a territory. What makes it unique is the implementation of open data, which makes it feasible for authorities, institutions, and communities to contribute to sustainable development and the strengthening of resilient communities.

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