

Original Article

Resilience to Landslides in the Lower Shullcas River Basin under Climate Change

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Abstract - The lower Shullcas River basin has a medium-high to low level of risk from landslides. This risk is made worse by geological, climatic, and topographic factors. Climate change, especially through intense rainfall and higher temperatures, increases this risk and makes it necessary to use proper mitigation strategies and more efficient urban development plans. Even so, there are still weaknesses in how risk management is integrated among the people and institutions involved in the territory. The purpose of this research was to identify the areas with the highest risk through mapping, and also to measure the resilience of the population exposed to the highest level of risk, in order to understand how they might respond and act during a possible disaster. For this purpose, methodologies based on risk prevention systems were used, aligned with SIGRID, CENEPRED, and INGEMMET. The results show favorable findings in some respects, since the study area, which includes the districts of Huancayo and El Tambo, presents medium-to-low landslide risk levels, with slopes ranging from 2% to 8%. The most critical zones are located along the marginal strip of the Shullcas River, where slopes reach up to 90% and where conditioning factors such as rainfall, river undercutting, and geomorphology turn these areas into constant hazards. The resilience evaluation shows less encouraging results, since most of the 50 residents surveyed near the highest-risk zone showed low levels of resilience compared with the coastal population of the country. Finally, it is recommended that more studies be carried out on different types of risk, including other triggering factors such as earthquakes, informal human activity, and geological aspects. It is also recommended to study wider areas because of the rapid population growth.

Keywords - Mass-movement landslides, Climate change, Rainfall, Resilience.

1. Introduction

Mass movements represent a constant and significant threat to territorial stability at the global, regional, and local levels, especially in areas where geological, topographic, geomorphological, and climatic conditions favor their occurrence. As a result, natural hazards continue to cause significant environmental and territorial changes [1]. In addition, poorly planned urbanization, together with the ongoing effects of climate change, is increasing the frequency and intensity of meteorological events affecting urban areas [2]. In this context, developing countries are particularly vulnerable to major economic losses and material damage due to the informal expansion of fragile and poorly located settlements. A large proportion of these settlements are located in hazard-prone areas. Latin America is the second most disaster-prone region in the world, and the most common events include mass movements and floods [3]. Peru is one of the countries located in a zone highly susceptible to various risks, the geological instability of the Andes, and its

vulnerability to climatic phenomena [4]. Therefore, it is necessary to specify the imminent risk. Notably, the lower Shullcas River basin, located in the province of Huancayo and the department of Junín, stands out as an area with recurrent vulnerability associated with climate change, where the frequency and intensity of events can result in alarming risks [3].

Therefore, assessing disaster perception and resilience involves identifying and reducing risk through measures such as infrastructure improvement, land-use planning, and financial protection mechanisms [5]. For this reason, integrated and inclusive actions are required, encompassing economic, structural, legal, social, health, cultural, educational, environmental, technological, political, and institutional dimensions. The aim is to reduce hazard exposure, decrease disaster vulnerability, and strengthen preparedness and recovery capacities through an adequate level of resilience [6].



This research analyzes the importance of risk characterization in the study area and its relationship with resilience to mass movements. Through a careful review of the land-use planning instruments of the municipalities in the lower Shullcas River basin, this study seeks to evaluate the extent to which risk management has been integrated into territorial planning, while identifying the areas of greatest risk and assessing the population's response to adverse events.

The current situation in the districts of Huancayo and El Tambo regarding landslide hazards remains critical despite the availability of urban development plans and hazard maps. Although hazard information is available at both regional and local levels, a gap persists in the practical implementation and detailed updating of these information tools, as preventive decision-making and actions remain insufficiently effective in addressing the recurrent overflows of the Shullcas River, which destabilize the surrounding slopes. Furthermore, the main information gap lies in the disconnect between the existing technical cartography and the social reality of the area. In addition, despite emergency drills and training programs, the population responds inconsistently and lacks a unified and feasible course of action during hazardous events. Therefore, assessing the resilience of residents living along the riverbanks should be prioritized in order to optimize community preparedness through the effective use of local planning tools. This analysis will provide an integrated understanding of risk perception in the study area, as well as the strategies implemented to reduce it. Ultimately, this study aims to provide information that strengthens risk management in the region, promotes a culture of risk prevention, and supports more resilient territorial planning in the face of the growing threat of landslides exacerbated by climate change.

2. Materials and Methods

2.1. Location of the Study Area

The lower Shullcas River basin is located on the western flank of the Western Cordillera of the Andes, descending from the Huaytapallana snow-capped mountain. It includes urban and rural areas of the districts of Huancayo and El Tambo, in the department of Junin, Peru. Its extreme coordinates are: source, 496017 E, 8664501 N; mouth, 474298 N, 8687084 N.

In this descriptive-explanatory research, the section of the basin corresponding to the districts of Huancayo and El Tambo was prioritized, mainly the urban area. The purpose was to analyze the importance of risk characterization in the study area and its relationship with resilience to mass movements [7].

Climate change plays a fundamental role in this context, as variations in average global temperature, driven by the increasing concentration of greenhouse gases in the atmosphere, are causing a continuous intensification of erosion and weathering processes [8]. These changes increase the territory's susceptibility to slope displacements and other

landslide events, highlighting the need to implement adaptation and mitigation strategies in areas exposed to significant risk [9].

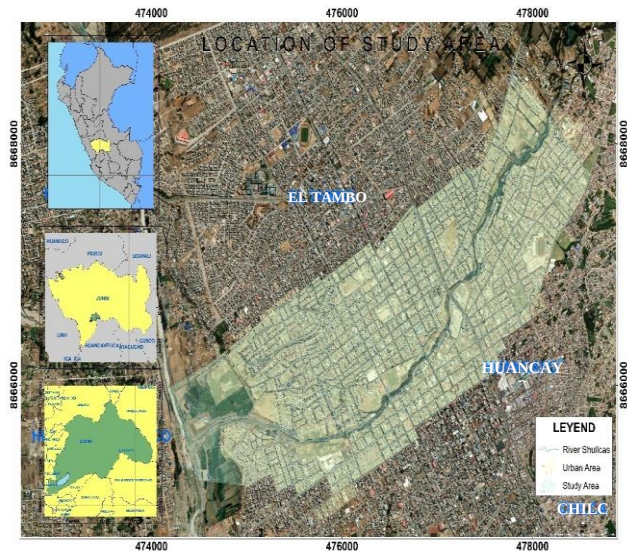


Fig. 1 Location of the study area, lower Shullcas river basin

Figure 1 shows the study area, which is located within the lower Shullcas River basin and includes the urban area of the districts of Huancayo and El Tambo, together with the main river channel that separates them. The study basin is constantly changing and growing, and it is also exposed to the effects of climate change.

2.2. Landslides and Climate Change

In the study of landslides, several fields agree that their dynamics are highly complex, which has led to multiple definitions and approaches. According to the Peruvian Geological, Mining and Metallurgical Institute (INGEMMET), landslides involve the downslope movement of materials such as soil, rock, debris, or earth driven by gravity, occurring at different rates and through various mechanisms.

Flooding, on the other hand, refers to the temporary inundation of areas that are normally dry, caused by the overflow of rivers, streams, or intense surface runoff [10].

In the study area, landslides occur when a considerable amount of debris, such as soil, stones, and other materials, moves from a higher location to lower levels due to different factors. These causes may be internal, such as the presence of unstable material that weakens the ground, or triggering factors, such as adverse climatic conditions like heavy rainfall. When these conditions combine, they may trigger an unpredictable release of material.

The most common types of landslides are rockfalls, material movement (translational and rotational), flows, and

mud creep, as shown in Figure 2. This natural phenomenon, closely related to urban and social development, is a constant

concern for the population, so there is a strong need to mitigate and prevent its impact on society [11].

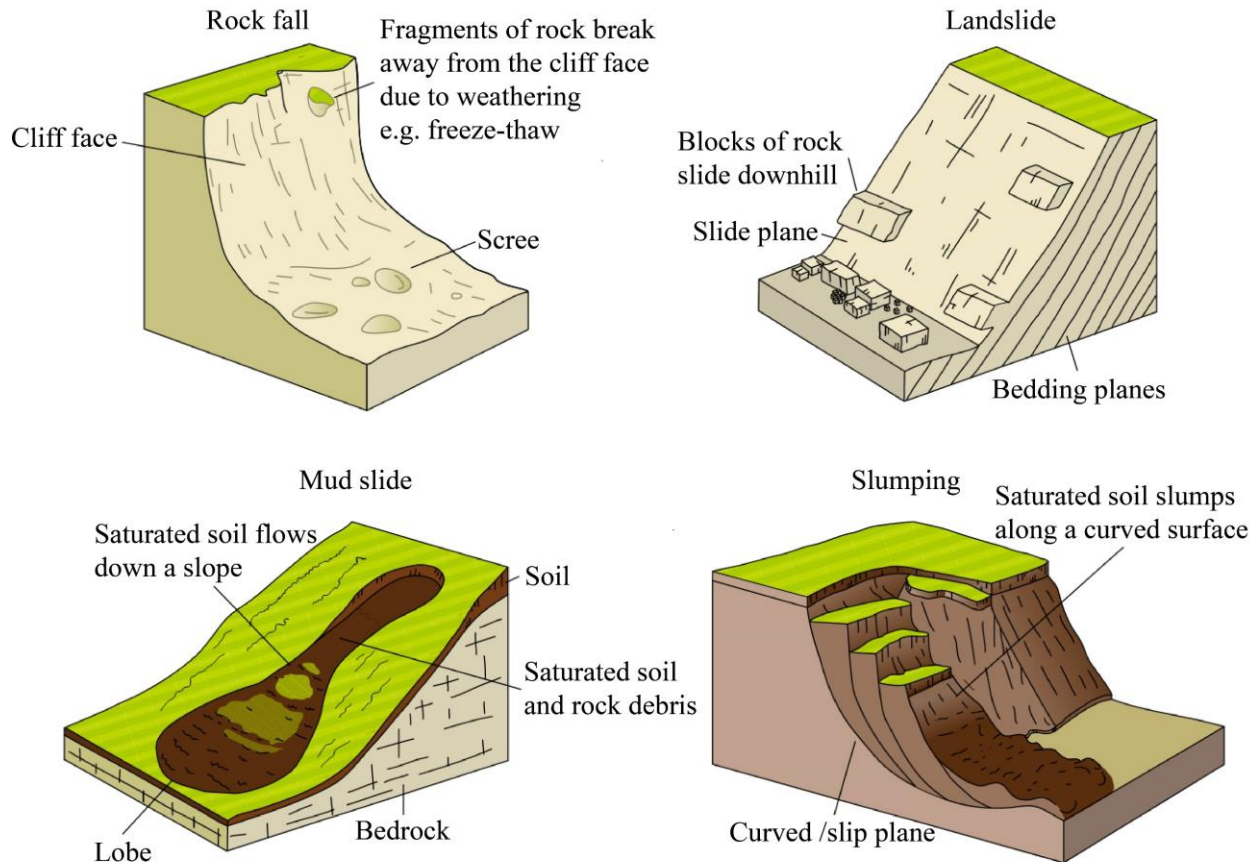


Fig. 2 Types of mass-movement landslides

In the specific case of the lower Shullcas River basin, there are areas prone to landslides and flooding. These are situations where unplanned urban development increases the risk of material loss, economic loss, and loss of life. This research, therefore, seeks to locate the areas most exposed to these events, measure the level of risk, and observe the population's resilience to possible natural disasters.

In the study area, climate conditions are strongly influenced by altitude, topography, and the relationship between precipitation and temperature values. One of the main triggering factors for landslides and floods in this zone is the increase in the intensity and variability of rainfall, which is associated with climate change. Extreme rainfall can saturate the soil, reducing its cohesion and stability, which increases the probability of landslides and other erosive processes. As a result, constant and progressive temperature variability could increase rock weathering and soil degradation, affecting slope stability and the territory's resilience to these events [12].

There are different factors that contribute to climate change, including external influences such as solar fluctuations, orbital changes, and meteorite impacts, as well as

internal influences such as continental drift, atmospheric composition, and the electromagnetic field. However, astronomical changes are considered the most relevant, as they alter the spatial distribution of solar energy reaching the Earth's surface [13]. In addition, human activities play a significant role in climate change. Activities such as deforestation, the burning of fossil fuels, mass production, and large-scale industrial operations contribute substantially to climatic alterations, generating a negative impact on the global climate balance [14].

2.3. Risk and Vulnerability Framework

Risk is defined as the condition of an environment exposed to the possibility of a disaster. It appears within a geographic space through the interaction between society and nature over a given period of time. It is not limited mainly to the magnitude or severity of a natural phenomenon; rather, it depends on the elements exposed to the event, their level of vulnerability, and the system's capacity to face the impact and recover. Among the human actions that favor slope collapse are increased loading due to construction, deforestation, and changes in infiltration and drainage patterns.

Table 1. Population from the lower Shullcas river basin

Zone	Homes	Population
Huancayo	7507	28025
El Tambo	10089	37290

2.3.1. Methodological Approach

The methodological approach of Disaster Risk Assessment, as regulated by Peru's National Center for Estimation, Prevention and Reduction of Disaster Risk (CENEPRED), was applied. The analysis is based on the Analytic Hierarchy Process (AHP) proposed by Thomas Saaty, a multicriteria statistical approach that enables the assessment of both qualitative and quantitative variables to support spatial decision-making. Risk is numerically defined as the probability that a population or its components will suffer adverse consequences due to the interaction between hazard and vulnerability. This relationship is expressed as follows:

$$R = P \times V$$

Where:

R (Risk): Level of potential damage (Low, Medium, High, Very High).

H (Hazard): A function of Susceptibility and the Evaluation Parameter.

V (Vulnerability): A function of Exposure and Fragility to the impact.

2.3.2. Statistical Rigor: Multicriteria Analysis (AHP)

To determine the weights (W_i) of the factors involved, Pairwise Comparison Matrices were constructed using Saaty's scale. To ensure the statistical validity of the weightings and minimize subjective bias, the Consistency Ratio (CR) was calculated using the following equation:

Table 3. Saaty matrix and prioritized weights

Variable / Criterion	Slope (Topography)	Geology (Lithology)	Geomorphology	Prioritization Vector (W_i)	Priority (%)
Slope	1	3	5	0.663	66.30%
Geology	0.33	1	2	0.26	26.00%
Geomorphology	0.2	0.5	1	0.106	16.60%
Total	1.53	4.50	8.00	1.00	100%

Additionally, the statistical basis and consistency assessment were determined as follows:

- Number of variables (n): 3
- Maximum eigenvalue (λ_{max}): 3.038
- Consistency Index (CI): 0.019
- Random Index (RI): 0.58 (Saaty's standard value for $n = 3$)
- Consistency Ratio (CR): 0.032 (3.2%)

After determining the values using Saaty's methodology, the mathematical model yielded a Consistency Ratio (CR) of 3.2%. This value fully satisfies the threshold established by CENEPRED's EVAR methodology ($CR < 0.10$), thereby validating the internal consistency of the assigned pairwise

$$CR = \frac{CI}{IR}$$

Where CI is the Consistency Index, calculated as: $CI = \frac{\lambda_{max} - n}{n - 1}$ and IR is the Random Index corresponding to the number of variables (n). According to CENEPRED guidelines, only matrices satisfying the statistical consistency criterion $CR < 0.10$ were considered valid.

2.3.3. Classification of Risk Levels

The resulting hazard, vulnerability, and risk levels were standardized and classified into four categories defined by numerical thresholds.

Table 2. Risk stratification

Risk Levels	Numerical Range (Thresholds)		
Very high risk	0.282	<R<	0.454
High risk	0.198	<R<	0.282
Medium risk	0.151	<R<	0.198
Low risk	0.12	<R<	0.151

2.3.4. Statistical Rigor: Hazard Pairwise Comparison Matrix (Saaty)

To validate the spatial weightings used in risk determination, a Pairwise Comparison Matrix (Saaty Matrix) was constructed using three factors derived from geographic modeling: Slope, Geology, and Geomorphology.

The pairwise judgments were mathematically normalized to obtain the global priority vector.

judgments and minimizing potential bias or random errors in the map development process. Regarding the resulting weights, slope accounts for 66.3% of susceptibility, followed by Geology at 26.0% and Geomorphology at 10.6%.

2.4. Characterization of Rainfall Intensity

According to data from the 2017 census reported by the National Institute of Statistics and Informatics (INEI), the study area was delimited to determine the number of households and inhabitants in the area, as presented in Table 1.

2.5. Data and Information Collection

For this research, the physical-geographic characterization of the conditioning factors in the study area was considered, together with the main triggering factor, precipitation. For this purpose, different sources of information were used, including databases from INGEMMET, SIGRID, and CENEPRED. ArcGIS was used to analyze the spatial configuration of climatic variables in the study area, and urban coverage information provided by IGN was used to visualize the different exposed elements. In addition, geological, geomorphological, and slope data for Peru at a scale of 1:50,000 were used to characterize the influencing factors in a general way and to understand the risk conditions of the zone. A mass-movement landslide risk map was then prepared.

Using the risk-level map, the most relevant critical points were identified. These points have characteristics that could lead to a possible disaster event, and the zones were located according to their level of risk for later evaluation.

The general slope classification was based on a Digital Elevation Model (DEM) with a spatial resolution of 12.5 x 12.5 m, processed with the ArcGIS 'Slope' tool (Figure 3). This made it possible to analyze the relief distribution of the study area. The analysis shows that the dominant morphodynamic environment in the study area is structural. Toward the northeast of the study area, slopes are moderate to low, while the central and southeastern parts show moderate to high values, mainly in the geological formations along the river. The slope classification was divided into five categories,

following the criteria of the CENEPRED geomorphological study [15] and methodological contributions for generating a slope-class map [16].

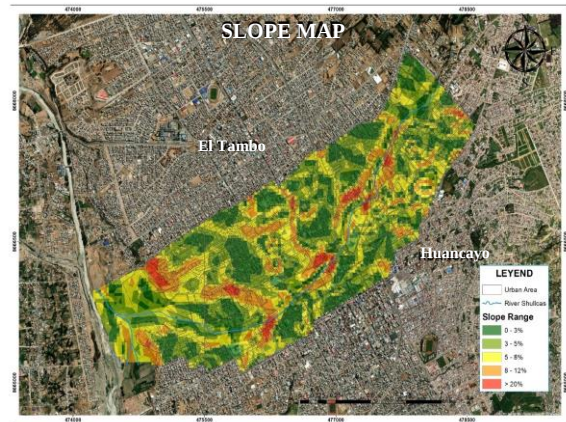


Fig. 3 Slope map of the watershed

Regarding climate variability associated with climate change in Peru [20], the precipitation records show that the moving average of the station with the highest rainfall does not present major fluctuations. This indicates that precipitation in the region does not vary drastically in response to changes in the surface temperature of the Pacific Ocean (Figure 3). However, the multiannual monthly precipitation maps reveal strong average spatial variations between months (Figure 2), which highlights the importance of the region in terms of morphodynamics and mass movement processes [15].

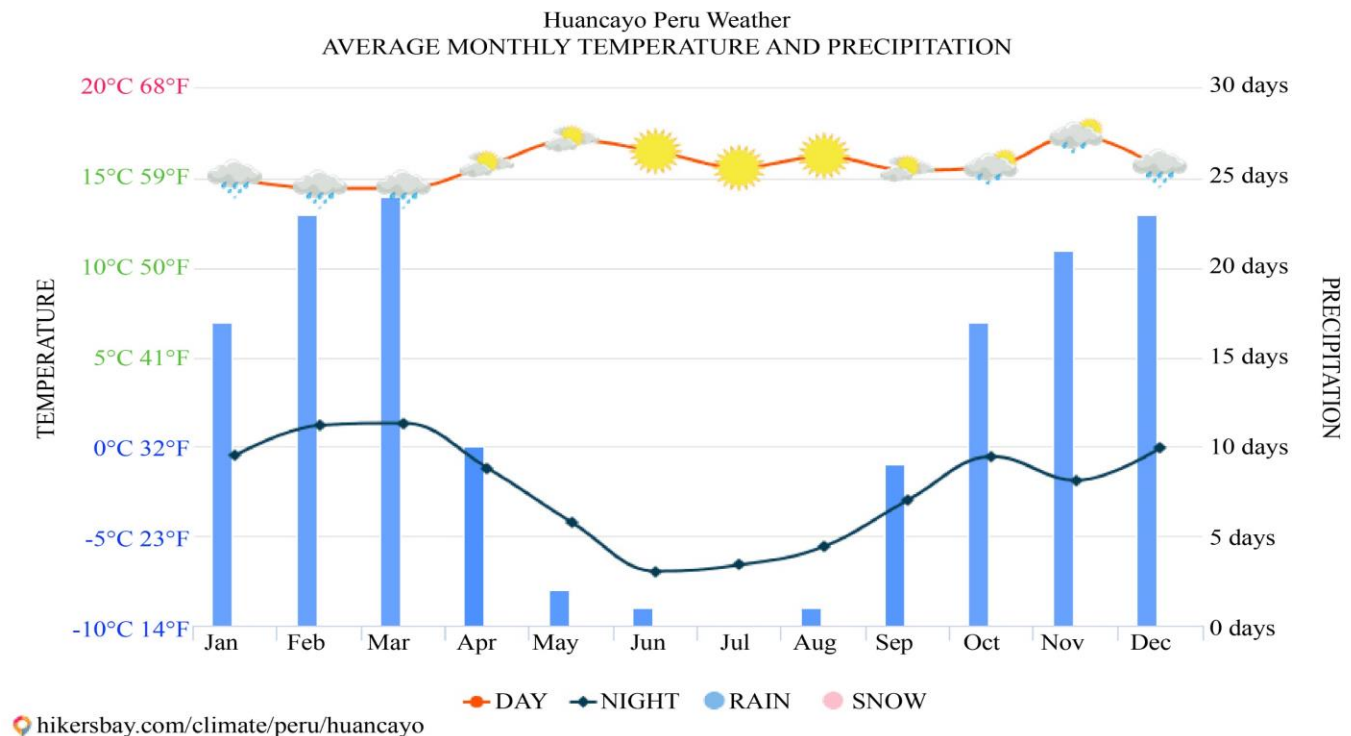


Fig. 4 Monthly average temperature and precipitation in Huancayo

According to the climate change scenario projected by SENAMHI for the central region, an increase in mean annual temperature between 1°C and 1.5°C is expected, together with a 35% increase in rainfall. Considering these factors, it is foreseeable that by 2050 and beyond, weathering and erosion processes will increase.

This means a rise in the frequency and magnitude of phenomena. Likewise, a reduction in the return period of extreme events is projected, increasing the risk related to slope instability and damage to infrastructure and communities in the region [17].

2.6. Identification of Risk Characteristics

One way to show how prepared a territory is for extreme phenomena is through land-use planning tools. These tools require multidisciplinary methodologies, involving geologists, sociologists, economists, physicists, and engineers, to identify and plan alternatives for dealing with the

complexity of urban areas, basins, and departments. Resilience plays a fundamental role because it is one of the risk variables in which society can participate to reduce the territory's vulnerability.

Resilience is an indicator of how easy or difficult it is for an element of the system, usually a community, to resist and recover from a disaster. It involves the search for strengths, principles, and policies that influence the economic and social system, including education, awareness, and the implementation of mitigation and disaster-prevention projects [18].

The next step in the analysis consists of assigning a qualitative score to the findings extracted from the reviewed documents. This evaluation will be carried out on a scale from 1 to 5, as shown in Table 4, and it allows the level of detail with which the risk component is addressed in the different land-use planning instruments to be assessed.

Table 4. Geotechnical classification of slopes

Level	Description
1	Accumulation of gravel, sand, silt, and clay with subangular to angular clasts of different composition
	Moraine deposits, angular blocks filled with clay, silt, and sand
2	Schist
	Schist, gneiss
3	Sandy limestone, calcareous sandstones. Gray or black shales
	White limestones in medium to thick beds, sandy limestones, and calcareous sandstone
	Medium-bedded limestones, nodular limestones, marls, and calcareous sandstones
	Bluish-gray limestones in medium to thick beds with chert nodules
	Gray micritic limestones and nodular limestones
4	Polymictic conglomerates
	White porphyritic tuffs, friable, interbedded with lapilli and pyroclastic bombs
5	Sandstones, conglomerates, breccias, lavas, and ash tuffs
	Whitish quartz sandstones and coal layers
	Greenish-gray sandstones, black shales, and brown siltstones
	Sandstones, silty-clayey shales, calcareous conglomerates with reddish to brownish cores, andesitic flows and basalts
	Gray and black shales, nodular bituminous limestones
	Lagoon

2.7. Data Analysis

Efficient data management was carried out through the use of open-source computer tools. Software for text processing was used mainly for statistical analysis (IBM SPSS Statistics 25).

In addition, geospatial technologies (ArcGIS 10.5 and Google Earth) were included for the exploration and visualization of data in geographic contexts, providing a spatial perspective for the research.

This was done to determine the risk levels present in the study basin, as well as the number of homes and residents affected by each level of risk.

2.8. Measuring Resilience

To measure resilience in people living near risk zones, in this case near the Shullcas River, the Wagnild and Young Resilience Scale was used. This instrument measures resilience through approaches and dimensions such as adaptation to risk and stress scenarios, environment and social collaboration, and leadership capacity. The test uses scores based on response capacity: 14-56 points indicate low resilience, 57-81 points indicate moderate resilience, and 82-98 points indicate high resilience [19]. For the central zone of Peru, which includes Junin, Huancavelica, Pasco, Huanuco, and part of Lima, resilience is generally moderate to low due to limitations in terrain conditions, immediate response, and urban and rural population knowledge [20].

Table 5. Sample selection for diagnosis

Sectors (River Section)	Length(Meters)	Elevation Level on the Hillside (Transversal Axis)	Assigned Surveys	Sample Percentage (%)
San Carlos Sector (Start: km 0.0 - 0.8)	800	Crest (5) / Slope (5) / Riverbank (4)	14	28
Salcedo Sector (Middle-Upper: km 0.8 - 1.6)	800	Crest (4) / Slope(5) / Riverbank (6)	15	30
Santa Rosa Sector (Middle-Lower): km 1.6 - 2.4)	800	Crest(5) / Slope (4) / Riverbank (4)	13	26
La Florida Sector (Final: km 2.4 - 3.2)	800	Crest (2) / Slope (3) / Riverbank (3)	8	16
TOTAL	3200	Representation of 3 Critical Strips	50	100

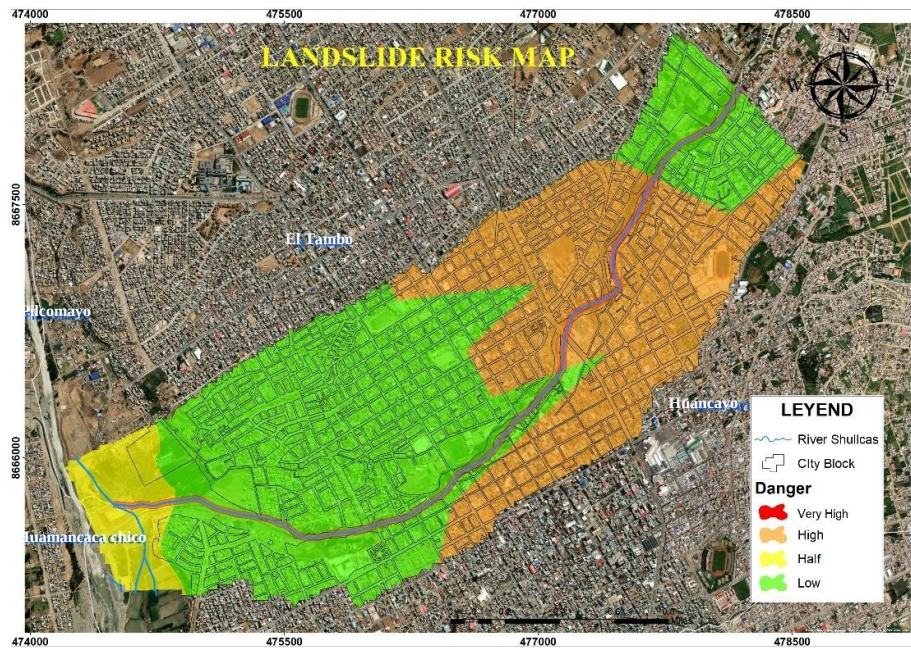
Due to the spatial setting and geographic distribution of the population exposed to hazards along the Shullcas River channel, a sample of 50 residents was selected using spatially based stratified probability sampling. To ensure territorial representativeness and minimize accessibility bias, the 3.2-km-long river section within the study area was geometrically divided into four sectors—San Carlos, Salcedo, Santa Rosa, and La Florida—each covering 800 m. Within each sector, a systematic sampling scheme was applied (Table 5), distributing the resilience assessments transversely across three topographic levels of the slope (crest, hillslope, and riverbank). This design resulted in approximately one sampling unit every 64 m ($3,200 \text{ m}/50 = 64 \text{ m}$) throughout the study area, thereby enabling a reliable assessment of population resilience to risk along the entire river section.

Therefore, the sample of 50 residents provides adequate spatial representation by ensuring that the different risk conditions and sectors along the river margins are included in the assessment.

3. Results

3.1. Soil Management and Landslide Risk Assessment

Risk zones were determined according to the process of identifying triggering factors for landslide risk, mainly climate change through rainfall, and by using geospatial information on conditioning factors such as geomorphology, geology, rivers, slopes, and urbanization. Based on this information, a risk map was prepared and classified by risk level, as shown in Figure 5.

**Fig. 5 Distribution of mass-movement landslide risk in the lower Shullcas river basin**

As shown in Figure 5, the distribution of risk zones is generally at a medium to low level. The San Carlos area,

located in the northeast of the basin, has a low risk because its slopes are minimal, between 2% and 4%. The same occurs

throughout the La Florida area, located in the southwest of the basin. The central zone has a medium to high slope level of 6% to 8%. The area along the Mantaro River, at the far southwest of the basin, has regular slopes of 4% to 6%, while the steepest slopes are found along the Shullcas River, affecting both districts with slopes between 25% and 90%.

Table 6. Risk management rating scale in the basin

Risk Levels	Zone	Homes	Residents
Very high risk	Huancayo	39	141
	El Tambo	30	127
High risk	Huancayo	4608	16594
	El Tambo	3457	11685
Medium risk	Huancayo	18	52
	El Tambo	13	48
Low risk	Huancayo	1943	7785
	El Tambo	6410	24747

Table 6 details the number of households and residents affected across different risk levels in the lower Shullcas River

basin. Within the urban areas of Huancayo and El Tambo, the total population analyzed encompasses approximately 16,518 households and 61,179 residents. A minor fraction—roughly 0.4% of both homes and inhabitants—faces a very high risk, primarily driven by their proximity to the river channel, steep slopes, unplanned urban expansion, and continuous slope erosion. Conversely, the high-risk category accounts for about 49% of households and 46% of residents, rendering them highly vulnerable to climate change triggers, particularly shifting precipitation patterns.

Figure 6 identifies the most critical points of risk related to mass-movement landslides. In total, 15 points show high-risk characteristics. Most of them are located near the river, while others are related to human factors such as road construction, slope leveling, unplanned housing construction, and unplanned urbanization. These points are mainly located in the central and southeastern part of the study basin and coincide with the zones most prone to mass-movement landslides because they have steeper slopes than the rest of the basin.

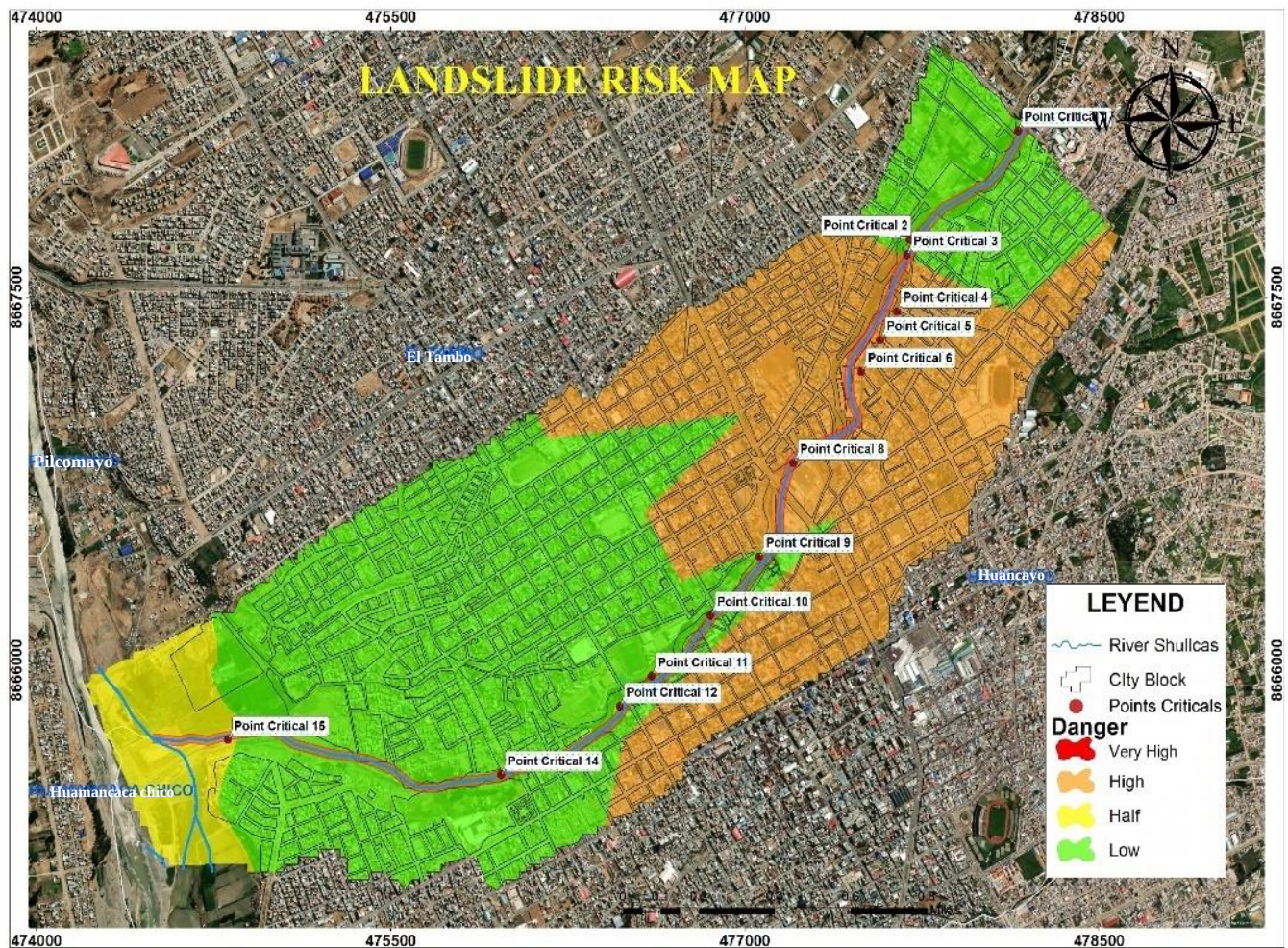


Fig. 6 Critical points prone to mass-movement landslides in the lower Shullcas River basin

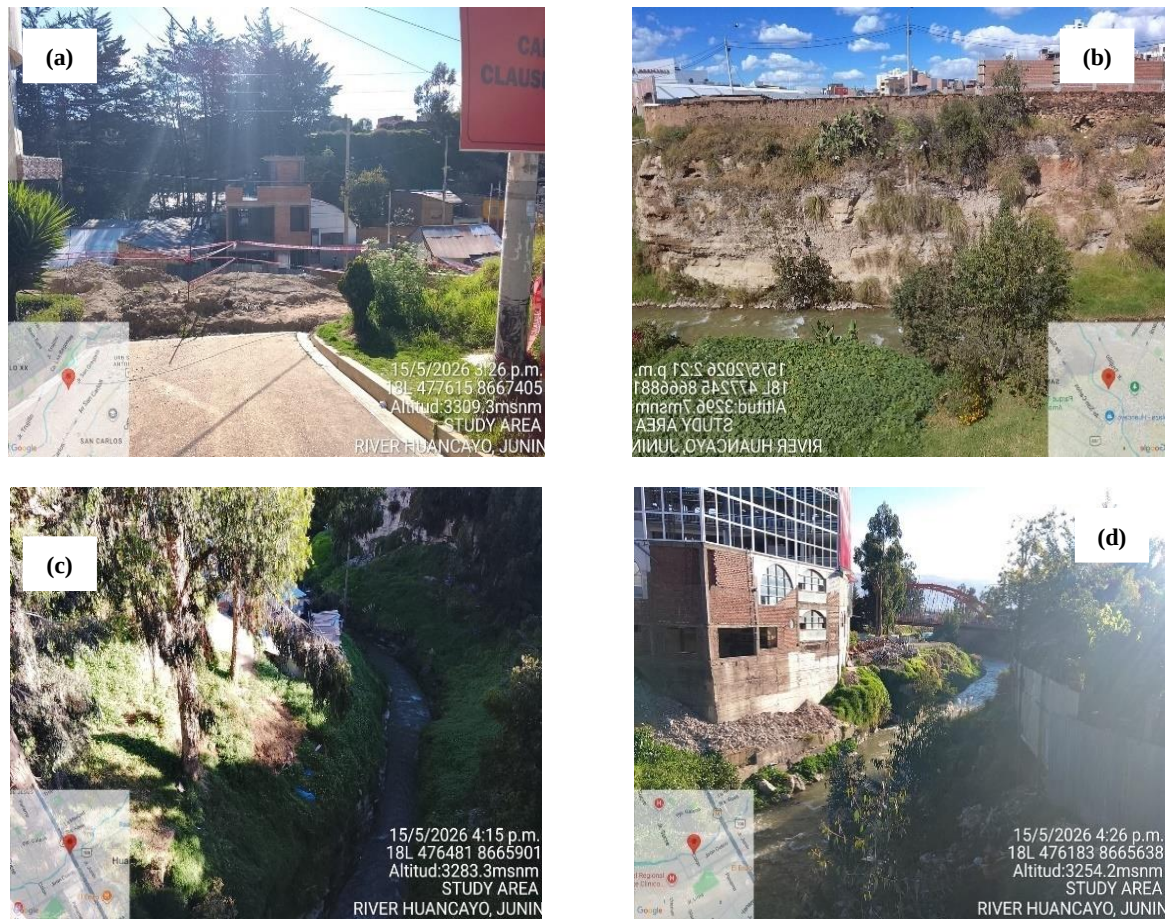


Fig. 7 Photographic panel of the most relevant critical points (a) Point 6, (b) Point 8, (c) Point 12 and (d) Point 14.

Figure 7 shows, through photographs, the most relevant critical points prone to mass-movement landslides in the lower Shullcas River basin. These points have different characteristics: (a) risks caused by human action; (b) high risk because of an almost 90% slope and constant river undercutting; (c) housing built within the marginal strip of the Shullcas River, at a very high level of risk; and (d) very high risk of landslide and even flooding because of its complex location.

3.2. Resilience to Reduce Risks

The population of Huancayo and El Tambo has divided and polarized opinions on this issue. At the same time, the municipalities of both districts have been promoting urban development plans (PDU of the district of Huancayo 2024-2034 and PDU of the district of El Tambo 2017-2034). The Huancayo PDU is still a technical proposal and is in the final approval process. This creates current uncertainty, since the population is growing quickly because the area is a central zone, and the occupation or construction of homes is taking place in an uncertain and irresponsible way. On the other hand, the district of El Tambo has already reached 83.3% progress in the implementation of its PDU, which suggests better urban

planning and risk control, reflected in more modern and sustainable buildings and infrastructure compared with the district of Huancayo.

Regarding the population's resilience to mass-movement landslide events, 74% of the general population shows weaknesses in resilience and prevention because there is no strong prevention culture. The situation is more serious among residents living in the marginal strip of the Shullcas River, where 91% show deficiencies in resilience because they are poorly prepared culturally and economically and, above all, because their homes lack prevention works.

Table 4 shows the evaluation results obtained using the Wagnild and Young Resilience Scale, applied to 50 residents living around the Shullcas River. The results show that in the districts of Huancayo and El Tambo, most of the population exhibits low resilience, accounting for approximately 58% of the residents. Conversely, 32% of the participants show a moderate level of resilience, while only 10% display high resilience among all those evaluated. This shows that there is still a long way to go regarding prevention and reaction to mass-movement landslides.

Table 7. Wagnild and Young Resilience Scale for rating the risk-management component.

District	Residents Evaluated	Score (range)	Evaluated	Resilience Level	Recommended Action
Huancayo	30	14-56 points	18	Low	Psychology workshops and family emergency evacuation plans
		57-81 points	9	Moderate	Create neighborhood committees to strengthen safety and effectiveness against risks.
		82-98 points	3	High	Identify them as brigade members or local risk leaders
El Tambo	20	14-56 points	11	Low	Psychology workshops and family emergency evacuation plans
		57-81 points	7	Moderate	Create neighborhood committees to strengthen safety and effectiveness against risks.
		82-98 points	2	High	Identify them as brigade members or local risk leaders

4. Discussions

The analysis of risk related to mass-movement landslides is a general problem because of constant climate change. For this reason, this research seeks to evaluate the level of risk present in the lower Shullcas River basin, which crosses the districts of Huancayo and El Tambo, cities with strong population growth, because they are a strategic commercial center at the regional level. Together with the identification of critical points and prevention plans and programs, the aim is to increase population resilience to this phenomenon.

The research shows medium-high to low risk levels in the basin, but a very high level near the Shullcas River. These factors have increased the number of homes and residents in high-risk zones. This agrees with the climate change study carried out by SENAMHI, which shows rainfall increases above 45% in the Andes by the year 2050 [17].

In the study area, 12 critical points of risk related to mass-movement landslides were located, most of them near the marginal strip of the Shullcas River. This agrees with research on river risk in Andean communities, where vulnerability levels of 99.15% were reported [3].

Regarding resilience, several studies show that the level of resilience to mass-movement landslides and other natural phenomena in central Peru is low to moderate. This is mainly conditioned by limited response capacity, poor urban expansion, and a culture that is not closely connected to risk prevention and mitigation.

These findings agree with studies carried out in Huancavelica, where an assessment of slope landslide risk found a low to medium degree of resilience, with only 36% response capacity to a risk event [20]. There is also a contrast in resilience levels depending on the study zone. For example, the coastal area of Peru shows moderate to high resilience. This is shown in research on residents exposed to landslide risk in Lima, where a very favorable level of 88.5% was found for risk perception [19].

It is important to acknowledge that the risk mapping and risk levels obtained through Geographic Information Systems (GIS) and the CENEPRED risk assessment methodology involve a certain degree of uncertainty. These uncertainties are associated with factors such as the spatial resolution of the digital elevation data and potential errors in delineating the marginal strip of the Shullcas River [6].

Likewise, the assessment of population resilience focused on a sample of 50 residents distributed across the four study sectors, primarily within the critical areas surrounding the river. Although this sample size provides a valuable and spatially representative preliminary assessment, the observed trends should be interpreted as local and context-specific indicators rather than as findings that can be generalized to the entire urban population of Huancayo and El Tambo.

The sampling design provided approximately one sampling unit every 64 m ($3,200 \text{ m}/50 = 64 \text{ m}$) throughout the study area, enabling an efficient and spatially consistent assessment of population resilience levels. Dividing rivers into spatial sections is an appropriate and feasible approach for obtaining representative samples, as demonstrated in the study conducted on the Caramacate River [16].

At the global level, limited resilience and the increasing risk of rainfall-induced landslides in Huancayo reflect the challenges highlighted by the Intergovernmental Panel on Climate Change (IPCC) and the Sendai Framework for Disaster Risk Reduction [18].

The findings of this study are consistent with global models warning that increasing precipitation, combined with institutional shortcomings and inadequate urban planning in the Global South, may exceed local adaptive capacities. Consequently, urbanized Andean sub-basins are emerging as critical areas of vulnerability, where disaster risk management should shift from predominantly reactive approaches toward preventive strategies based on community resilience and territorial governance.

The methodological limitations of the present study should be acknowledged. First, due to the lack of property titles and updated census records, the 50 dwellings considered represent a conservative estimate (lower bound), and the actual population exposed to risk is likely to be larger. Furthermore, the GIS analysis relied on official static cartographic data, which do not capture in real time the rate of change or anthropogenic modifications to slope morphology. Nevertheless, the incorporation of photographic evidence helped improve the approximation of actual risk levels.

5. Conclusion

The lower Shullcas River basin, which covers a large part of the urban area of the districts of Huancayo and El Tambo, presents a medium-high to low level of risk across much of its area. The very high-risk zones are located near the marginal strip of the Shullcas River, where 69 homes and 268 residents are exposed to this danger. This is mainly due to poor urban planning, socioeconomic factors, and an ineffective prevention culture, as well as recent urban development plans that still have weaknesses and are in the approval process.

The critical points show the areas of greatest danger from mass-movement landslides, mainly because rainfall influenced by climate change causes material dragging and river undercutting. As a result, slope instability increases over time. To prevent disaster situations, riverbank protection works or slope-stabilization works, such as retaining walls or gabions, could be built as a way to mitigate the existing risk.

The evaluations of the resilience level of residents in the most critical zones show unfavorable trends, despite campaigns and events that promote risk awareness. From the tests carried out, it was found that most residents tend to have low resilience, with 29 people in this group. There were 16 residents with moderate resilience and only 5 with high resilience, out of a total sample of 50 residents. It is necessary to speed up the urban development plan of Huancayo and integrate it with the plans of the other districts in order to improve population resilience in disaster-risk matters.

For future research, it is recommended to evaluate risk using other triggering factors, such as earthquakes, geology, and soil erosion, in order to better complement the influence of these factors and define a more accurate course of action for the future. Likewise, the study area should be expanded to other districts in the same zone, such as Chilca, Concepcion, Chupaca, and Pilcomayo. Because of rapid population and urban growth, a comprehensive and multidisciplinary risk-prevention and urban-development plan is needed for this region.

The assessments conducted to determine the resilience levels of residents across the four sectors revealed unfavorable trends despite the implementation of campaigns and programs aimed at raising disaster risk awareness. These findings highlight the need to implement and strengthen measures through educational programs, community activities, emergency drills, and other disaster preparedness initiatives, while extending and integrating these actions across neighboring districts to enhance community resilience to disaster risk.

Recommendations for the relevant authorities, based on the identified risk levels and low community resilience in the lower Shullcas River basin, are as follows:

- Enforcement of the river marginal strip: The Provincial Municipality of Huancayo, in coordination with Peru's National Water Authority (ANA), should prioritize the enforcement and protection of the Shullcas River marginal strip by legally restricting new urban development in identified high-risk areas.
- Implementation of community-based early warning systems: Civil Defense offices should move beyond generic emergency drills toward the implementation of a monitoring and early warning system along the river.
- Implementation of engineering mitigation measures: Structural mitigation projects should include the construction of retaining walls or gabions at the 12 critical scour sites identified, together with slope reforestation using native species, such as *Polylepis* (quinual) and Alder (aliso).

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