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MULTI-HAZARD ASSESSMENT OF THE EASTERN SLOPE OF THE SISTEMA DE FAMATINA, LA RIOJA PROVINCE (ARGENTINA)

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Abstract

In the eastern sector of the Sistema de Famatina, both natural processes and anthropogenic activities pose considerable risks to the landscape and its inhabitants. This study investigates the geohazards and environmental agents that have historically affected the region, with a focus on their implications for local communities and territories. The analysis integrates case studies of documented natural events, identification of mitigation strategies, satellite imagery interpretation, landform recognition, and direct field observations. In addition, meteorological, hydrological, seismic, and demographic data were compiled to identify previously undocumented events with the potential to generate significant socio-environmental impacts.

The study area is subject to a range of natural hazards, including those originated by meteorological events (e.g., intense precipitation and strong winds), fluvial processes (e.g., avulsion, gully erosion, and flooding), mass movement processes (e.g., landslides and rockfalls),

and seismic activity. Our results reveal the recurrent nature of these hazards; in general, their consequences are compounded by anthropogenic pressures, including land-use changes, variations in land cover, and environmental pollution. Collectively, these factors intensify existing socio-environmental issues.

This research contributes to sustainable environmental management by considering plausible future scenarios and hazard interactions. Our findings are intended to inform local and regional socio-economic development strategies and to serve as a scientific resource for policymakers and planners. Furthermore, by enhancing awareness of ongoing and recurring hazards, the study supports community resilience building and the reduction of adverse impacts at the local level.

Keywords: Sistema de Famatina; Hazard assessment; Environmental consequences; Socio-economic development

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Author Contributions

All authors contributed to the study conception. Data collection during field campaigns and analysis of geological and geomorphological aspects were performed by María Cecilia Corbat, Oscar Juárez and Enrique Fucks. Remote sensing, hydrology and climatic data procedures were carried out by María Cecilia Corbat. Seismic material collection, preparation and analysis were performed by José Augusto Casas and María Cecilia Corbat. The literature review and interpretation of results were carried out by María Cecilia Corbat. The first draft of the manuscript was written by María Cecilia Corbat. All authors contributed to final version of the manuscript.

MULTI-HAZARD ASSESSMENT OF THE EASTERN SLOPE OF THE SISTEMA DE FAMATINA, LA RIOJA PROVINCE (ARGENTINA)

1. Introduction

At a global scale, geodynamic processes can produce direct or indirect adverse effects on territories and their populations, thereby constituting geological hazards. While these events reflect the dynamic behavior of the environment and the evolution of the Earth's relief, they may also be triggered or exacerbated by anthropogenic activities due to the complex interactions between human actions and natural processes (González de Vallejo and Ferrer 2011). Regardless of the physical origin of a hazard, its capacity to cause damage can be substantial, impacting both the physical environment and social structures, which may lead to increased casualties and significant economic losses. Notably, numerous studies identify floods as among the most severe and impactful natural hazards worldwide (Revilla-Romero et al. 2015; Pulvirenti et al. 2016; Amitrano et al. 2018; Alexandre et al. 2020; Amitrano et al. 2024).

In Argentina, the *Sistema Nacional de Alerta y Monitoreo de Emergencias* (SINAME) program monitors selected natural hazards and evaluates potential adverse scenarios to generate information that supports a timely and effective governmental response (SINAME 2025). The regional-scale analyses of hazards and vulnerabilities (Ministerio de Planificación Federal, Inversión Pública y Servicios 2010; Instituto Regional de Planificación, Control y Servicios Ambientales 2024) provide a general framework for the contributions presented in this article. Within this framework, particular emphasis is placed on the study conducted in Chilecito city (La Rioja province), which addresses the dynamic environmental components of the area, their interrelations, and the proposed strategies aimed at promoting socio-economic development and preserving the environmental setting (Instituto de Geociencias y Medio Ambiente 1988). Due to the limited availability of scientific data in the study area, the local population may underestimate the risks associated with the occurrence of hazardous processes. The information presented in this article contributes to a more comprehensive understanding of these events and supports improved decisions by authorities as well as risk awareness among local inhabitants.

In this article, we identify and characterize the hazards present in the eastern area of the Sistema de Famatina—those capable of producing significant negative impacts on the environment. To achieve this objective, we analyze a set of selected parameters that are sensitive to the natural processes present in the region. These include climatic variables related to precipitation and snow/ice melt, the dynamics of fluvial systems, the characteristics of the surface materials, regional geomorphological features, and seismic activity. Particular attention is given to geomorphological processes with implications both on the environment and the anthropogenic activities and a potential for recurrence. Additionally, we examine existing environmental issues that influence the socio-environmental system and may contribute to future adverse scenarios.

This article holds both scientific and societal relevance. It provides evidence of the occurrence of the natural processes active in the study area, contributes to the prevention of future events with potentially adverse impacts on local human activities, and provides an updated framework to support subsequent research—such as quantitative risk assessments. Additionally, our findings contribute to the development of regional and local multi-hazard databases, offering

valuable input for territorial management and land-use planning in cities and towns across the region (i.e., Famatina, Chilecito, Guanchín, Nonogasta and Sañogasta).

Risk assessment necessitates a prior evaluation of the associated hazards. A comprehensive understanding of the underlying natural physical processes, their environmental implications, and the resulting socio-environmental conflicts is essential for the development of accurate and effective risk models. In this context, the present study represents a significant step toward advancing that objective.

2. Study area

The Sistema de Famatina is a morphostructural unit oriented in a NNW–SSE direction, located between latitudes 27°00'S and 30°10'S and longitudes 67°00'W and 68°00'W. The unit extends across two Argentine provinces—Catamarca and La Rioja—and is bounded by the Western Sierras Pampeanas and by the Puna region to the north (Ramos 1999)(Fig. 1).

The study area is situated within the central sector of the Sistema de Famatina, specifically encompassing the eastern flank of the Sierra de Famatina and the adjacent Antinaco-Los Colorados valley. This region is bounded by the cities of Famatina to the north and Nonogasta to the south (Fig. 1C). It concentrates the majority of the local population and hosts the principal productive ventures in the area.

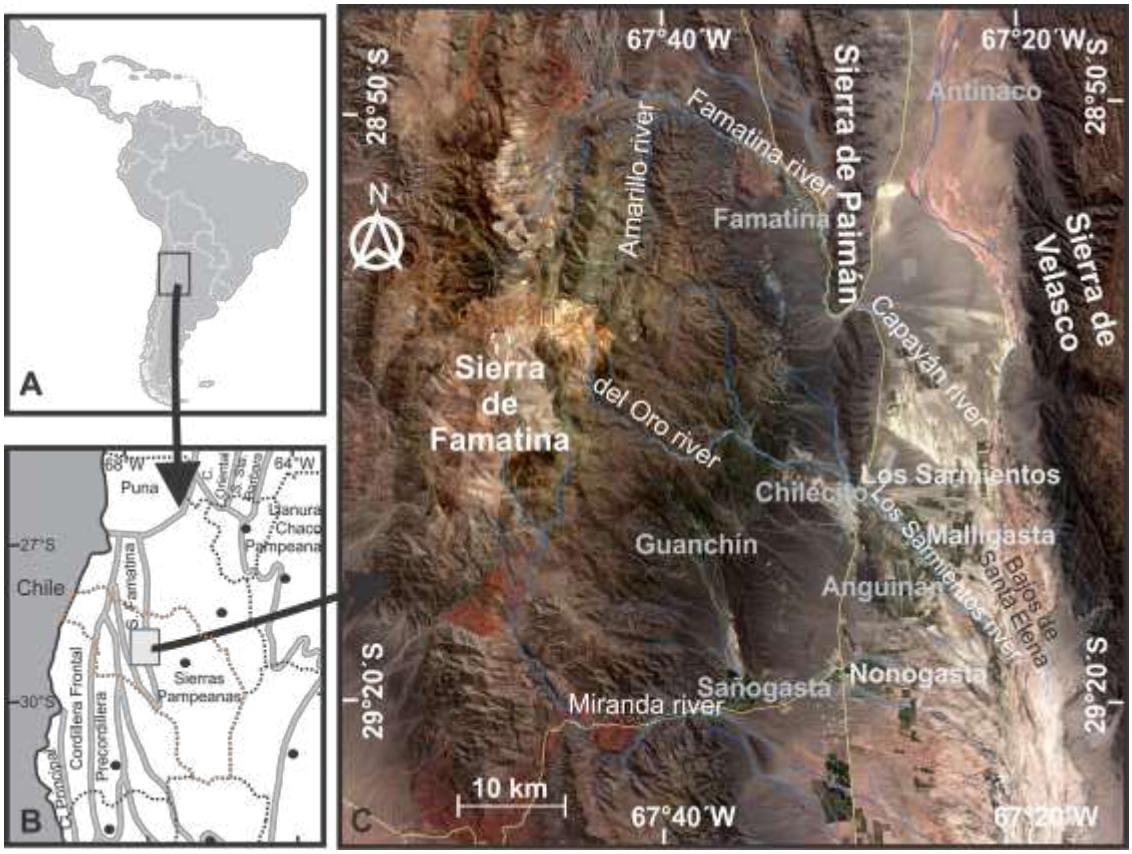


Fig. 1 Location of the study area. A) At continental scale. B) In a regional context of morphostructural units. The province of La Rioja is delineated with an orange dashed line. C) Mountain ranges, main roads (in yellow), and localities are superimposed on Sentinel imagery from Instituto Geográfico Nacional (2019). In the eastern sector of the Sierra de Famatina, perennial fluvial courses are represented by solid blue lines, while ephemeral or temporary courses are shown with dashed blue lines. G.M.B.hill refers to General Manuel Belgrano hill.

In the study area, the occurrence of events with adverse impacts on both the population and/or territory is strongly influenced by geological and environmental variables, particularly, the lithostratigraphic characteristics of the Sistema de Famatina, its structural configuration, and the prevailing meteorological dynamics. These controlling factors are detailed below.

2.1. Lithological characterization

The Sistema de Famatina comprises igneous-metamorphic basement units associated with a Lower Ordovician volcano-sedimentary sequence (Pankhurst et al. 1998; Candiani et al. 2011), overlain by a sedimentary cover.

The oldest basement rocks correspond to the Negro Peinado (Turner 1960), Achavil (Collo and Astini 2008), Paimán and Ñuñorco (Turner 1962) formations. The basement comprises granitic bodies associated with quartz-mica schists, phyllites, quartzites, and hornfels, among others, which constitute the mountain ranges in the region. The Lower Ordovician volcano-sedimentary sequence is sparsely exposed within the study area. The sedimentary cover consists of lithologies ranging from the Carboniferous to the Cenozoic, exhibiting varied grain sizes and encompassing multiple stratigraphic units (detailed in Candiani et al. 2011). The last-formed deposits, located in topographic depressions, are characteristic of piedmont and fluvio-aeolian depositional environments.

2.2. Structural characterization - Geomorphology

The regional structural geology is characterized by the presence of Precambrian to Early Paleozoic basement blocks uplifted during the Andean orogeny in the Late Cenozoic and subsequently rotated along inverse listric faults (González Bonorino 1950; Jordan and Allmendinger 1986; Jordan et al. 1989; Strecker et al. 1989; Fauqué and Caminos 2006). Throughout the Cenozoic, uplift of the western sector occurred, accompanied by a migration of the deformation front toward the foreland. Consequently, the present-day landscape is defined by mountain ranges separated by subparallel valleys. In each one of these predominant morphostructural features linked to the study area, structural lineaments have been distinguished (Corbat et al. 2018a, 2018b, 2024; Servicio Geológico Minero Argentino [SEGEMAR] n.d.). The structural lineaments associated with deformation processes affecting both the basement and sedimentary cover evidence ongoing tectonic, including neotectonic, activity.

The mountain systems analyzed in this study comprise the Sierra de Famatina, Sierra de Guanchín, and Sierra de Paimán ranges, along with the associated tectonic valleys surrounding them, namely the Guanchín, Famatina-Chilecito, and Antinaco-Los Colorados valleys. These geomorphological units exhibit a predominant north–south structural orientation.

The mountainous sectors exhibit a diversity of morphologies, controlled by topographic relief, lithological composition, and structural framework. The exposed units are subject to exogenous processes—primarily fluvial and gravitational—that contribute to the formation of Quaternary deposits along mountain slopes and within valley infill sequences. In intermontane areas, prominent mountain-related landforms include both isolated features such as alluvial fans and coalescent forms, such as bajadas. In particular, the central sector of the Antinaco–Los Colorados Valley displays a transition to a fluvio-aeolian plain characterized by fluvial channels, playa lake deposits, and aeolian dunes (Corbat et al. 2024). In spatially restricted zones, covered

pediments are observed. These are defined by gently sloping, low-relief surfaces developed on pre-Quaternary bedrock, shaped by erosion and sediment transport, and mantled by a thin layer of gravel.

2.3. Climate

The study area is situated within the arid belt that extends across South America in a northwest–southeast direction, from northwestern Peru to Argentine Patagonia (De Martonne 1935; Bruniard 1982; Abraham et al. 2020). This region is characterized by low precipitation and a predominance of dry climatic conditions (Vich et al. 2014).

The study area is characterized by a continental climate, ranging from temperate to warm and from semiarid to arid conditions (Sosic 1971). It exhibits low atmospheric humidity, high solar radiation, strong evaporative demand, and the presence of warm, dry winds. Precipitation is generally scarce but may occur as intense rainfall events during the summer. In particular, the Sierra de Famatina exhibits a high-Andean climate (term used by Martínez Carretero 2013), due to its elevated altitude. This zone experiences sub-zero temperatures and frequent snowfall during winter, while summers are cool, with frequent condensation of atmospheric moisture. At the highest elevations, the area is subject to pronounced diurnal temperature fluctuations.

According to climatological data compiled by the Servicio Meteorológico Nacional ([SMN], 2015a, 2015b, 2023b) from measurements at the Chilecito-Aero meteorological station, the study area presents an annual mean temperature of 18.6 °C and a concentration of precipitations during the summer months. Therefore, the study area is classified as BWh under the Köppen–Geiger climate classification system (Peel et al. 2007). Furthermore, prevailing winds are predominant from the south.

3. Methodology and source data

The selected methodology involved the analysis and integration of bibliographic sources, cartographic materials, satellite imagery, and field data. This integrated approach enabled the development of a framework for describing potential hazards and recognizing impact-reduction strategies, providing information on key elements of the risk assessment.

A lithological, structural, and geomorphological characterization was conducted based on geological maps at scales of 1:200,000 (15d-Famatina and 16d-Chilecito; Turner 1971, De Alba 1979) and 1:100,000 (2969-18 and 2969-24, Candiani et al. 2011). The studies by Fucks et al. (2018), Corbat et al. (2018a, 2018b, 2018c, 2020, 2022, 2024), and Juárez et al. (2018, 2022a, 2022b) form the foundational framework of this analysis, offering detailed geological characterizations derived from systematic field observations.

For the meteorological characterization, we used climatological statistics derived from precipitation, temperature, and wind data recorded by the Chilecito-Aero station, operated by the SMN (2015a, 2015b, 2023b). This station, the only official meteorological station in the study area, serves as the primary reference point. The climatic classification was determined through the processing and statistical analysis of its long-term records.

Our analysis focused on identifying geodynamic processes, morphological features, risk mitigation components, and anthropogenic factors. This was based on a comprehensive review

of documented hazardous events, the analysis of satellite imagery (primarily from Google Earth Pro), and field-based observations. For each dataset or imagery set, we conducted a preliminary assessment to determine the most appropriate processing methodology, selecting those approaches that minimized potential limitations and ensured robust results.

Hydrological data for the study area were obtained from governmental databases, i.e., the *Base de Datos Hidrológica Integrada* of the Subsecretaria de Recursos Hídricos de la Nación (2018) and the *Base de Datos del Sistema Nacional de Información Hídrica* of the Secretaría de Infraestructura y Política Hídrica de la Nación (2022). Specifically, the annual mean discharge and the maximum daily mean discharge recorded at the Famatina and Miranda gauging stations were utilized for comparative analysis. These data provide insight into the hydrological behavior and variability of each river over their respective observation periods. Additionally, daily mean river stage data from the active gauging station at Chilecito were analyzed and compared with precipitation records (SMN 2018a, 2021, 2023a) from the same locality to explore potential correlations between rainfall and river response.

Based on the compiled documentary and instrumental data, we identified and georeferenced significant events that have occurred in the study area. Each event was characterized through the analysis of its conditioning factors and triggering mechanisms, providing a foundation for future vulnerability assessments and risk zonation. In addition, we documented the corrective interventions and preventive strategies implemented in the region to mitigate potential impacts, several of which were recorded photographically during fieldwork.

To estimate the spatial extent of the areas affected by the identified events, we used satellite imagery acquired from the Landsat and Sentinel-2 missions. Based on these datasets we generated products that reveal the impacts within the study area through the visualization of various spectral band combinations (e.g., true color and false color composites), using the EO-Browser platform provided by Sentinel Hub (https://apps.sentinel-hub.com/eo-browser/). In the case of wildfires, for instance, we assessed changes in surface reflectance (Chuvieco et al. 2019, 2020) by comparing pre- and post-event images, which enables both the identification and confirmation of fire occurrence. This approach is commonly employed in conventional remote sensing analyses (Scheip and Wegmann 2021). The visual interpretation of the obtained optical imagery is inherently influenced by atmospheric conditions. Table S1 summarizes the specifications of the satellite images used in this study.

We characterized the seismicity of the area using publicly available seismic catalogs from the Instituto Nacional de Prevención Sísmica ([INPRES], https://www.inpres.gob.ar/desktop/), the Incorporated Research Institutions for Seismology ([IRIS], https://ds.iris.edu/ieb/) and the United States Geological Survey ([USGS], https://earthquake.usgs.gov/earthquakes/map/), as well as information extracted from journalistic sources. The seismic catalogs provide standardized information, including the exact date of occurrence, event location, magnitude, and additional details such as whether the earthquake was felt by the local population. These databases were used to analyze the spatial distribution of all recorded and located seismic events. In parallel, news articles were reviewed to assess the reported impacts of events occurred on the study area. Particular attention was given to events located in proximity to the study region, specifically within the coordinates 28°–30°S latitude and 66.5°–68.5°W longitude. Additionally, we include information about events classified by INPRES as felt by the population, even when no structural damage was reported.

We evaluated both evidenced and potential impacts pertinent to socio-environmental conflicts. Given the clear influence of population dynamics and anthropogenic activities, we analyzed census data from 1991, 2001, 2010, and 2022 to characterize the temporal evolution of population. To complement the demographic data from Instituto Nacional de Estadística y Censos de la Republica Argentina (INDEC, 1991, 2001, 2010, 2022), we utilized Landsat satellite imagery (4-5 TM, 7 ETM+, and 8 OLI) to assess urban expansion within the study area. Specifically, we selected true-color images processed via Sentinel Hub, choosing those with less than 20% cloud cover and temporally corresponding to the months of each evaluated census. Additionally, high-resolution imagery from Google Earth Pro was employed to examine specific localized cases.

For the spatial analysis of agricultural expansion, we used Landsat 8 imagery from Sentinel Hub and ASTER satellite data from the Land Processes Distributed Active Archive Center (https://lpdaac.usgs.gov/, NASA), covering various relevant dates. ASTER images were processed using the open-source QGIS platform. We applied band combination 3-2-1 (infrared-color composite) and enhanced image quality, primarily through standard deviation adjustments to improve contrast, facilitating more accurate delineation of cultivated areas. Both ASTER and Landsat datasets were further visualized using false-color (infrared) composites to accentuate vegetation in reddish tones.

To evaluate the dynamics of meteorological parameters, we analyzed data provided by the SMN for the study area. Precipitation was assessed using monthly records from 1989 to 2018 (SMN 2018b) and daily records from 2010 to 2022 (SMN 2018a, 2021, 2023a). These datasets were integrated to generate a continuous monthly precipitation series spanning 1989 to 2022. Using this series, we examined the temporal evolution of precipitation during contrasting seasons (i.e., winter and summer).

Temperature analysis was based on daily data from 2010 to 2022. From daily maximum and minimum temperatures, we derived daily, monthly, seasonal, and annual mean temperatures for each year within the analyzed period. The high-resolution temperature dataset enabled detailed analyses. Temperature values are presented as both raw measurements and calculated anomalies, given that the latter lead to more accurate interpretations of temperature variations (Farmer and Cooke 2013). We calculated the anomalies as deviations from the long-term average temperature baseline (1991–2010). We evaluated annual and seasonal temperature anomalies, whose deviations above or below the reference baseline indicate warming, cooling, or stable trends in the study area over the 2010–2022 interval. Additionally, we assessed the potential environmental and societal impacts arising from variations in these meteorological parameters, considering both current conditions and projected future climate change scenarios.

4. Results, interpretation and discussion

In order to complement existing information and integrate it with newly acquired data, we aim to enhance the understanding of potentially destructive geodynamic processes that pose risks to the socio-environmental system. Within this framework, we identify the principal hazards present in the study area and analyze both their underlying driving factors and associated consequences. To illustrate the occurrence and recurrence of specific events that have impacted the territory or its population, we also present the mitigation strategies implemented for hazard management and reduction of potential impacts.

4.1. Meteorological hazards

Based on the meteorological characteristics of the study area, we emphasize the significant influence of precipitation and wind on adverse environmental impacts. The primary negative consequence of precipitation is associated with runoff events, which are detailed in the subsequent section. Precipitation constitutes the most important and recurrent triggering mechanism for the events discussed in this article. Notable examples include documented cases reported in news articles (El Independiente 2017, 2018a, 2018b; Diario Chilecito 2022a; Nueva Rioja 2022a, 2022b), such as the rainfall event on May 5, 2018, in Chilecito. This event was characterized by a continuous four-hour rainfall that generated substantial surface water flow through streets, seepages in buildings and displacement of objects along roadways. The adverse effects of runoff in residential areas can be mitigated by appropriate infrastructure, particularly channeling systems designed to direct flow along the slope, as well as the implementation of sewerage networks. However, these mitigation strategies can transfer the impact downstream.

Based on the daily precipitation records from 2010 to 2022 obtained at the active meteorological station, we observe the discontinuous nature of rainfall and its increased frequency during the summer months. The highest daily precipitation recorded during this period was 45 mm, on April 1, 2019. Precipitation in the region exhibits marked spatial and temporal variability, which limits the representativeness of single-station measurements to a relatively confined area surrounding the station. Consequently, the data from this station are used solely for localized inferences within its immediate vicinity.

The meteorological event that occurred on December 17, 2013, exemplifies the potential adverse impacts of such phenomena on the study area. This event was characterized by rainfall, wind, and hail, which caused damage across multiple settlements as El Nevado, Pomán Norte, Centro, La Puntilla and Tilimuqui (La Rioja es noticia 2013). A comparable event resulted in infrastructure disruptions in Nonogasta on February 20, 2018 (El Independiente 2018c). More recently, on December 16, 2022, severe weather conditions led to the falling of tree limbs, trees, and electrical poles in Chilecito Department; no casualties were reported (Nueva Rioja 2022c). Although information regarding the consequences of these events remains limited, it is essential to analyze historical pluviometric records (Consejo Federal de Inversiones [CFI] 1974) that document extreme daily precipitation values. For Chilecito, the records indicate 115 mm on January 2, 1939; 90 mm on February 4, 1952; 124 mm on January 25, 1953; 97.5 mm on February 23, 1955; and 68.4 mm on March 2, 1959. Additionally, daily precipitation data from CFI (1974) indicate exceptional values at several stations: 52 mm in March 1963 at Carrizal station (active 1938–1964), 55 mm in February 1955 at Famatina station (1933–1961), 120 mm in November 1956 at Guanchín station (1938–1959), 124 mm and 117 mm in January 1953 at Chilecito Met. and Chilecito F.C. stations (1933–1964), 136 mm in February 1952 at Malligasta station (1949–1964), 135 mm in February 1952 at Anguinán station (1949–1964), 60 mm in February 1952 at Nonogasta station (1933–1964), 80 mm in December 1962 at Sañogasta station (1944–1964), and 58 mm in October 1956 at Miranda station (1952–1961). In all these instances, recorded precipitation values substantially exceeded the maximum levels observed during the analyzed period (2010–2022), yet no documented adverse impacts were reported.

The request for a declaration of an agricultural emergency to the local government (Instituto Nacional de Tecnología Agropecuaria [INTA], 2017) and its subsequent approval in 2017 (Ministerio de Agroindustria 2017), the declaration of an agricultural emergency due to a hailstorm in 1998 (Ministerio de Economía, Obras y Servicios Públicos, y Ministerio del Interior 1998), and the issuance of a climatic emergency in 2019 for the Famatina Department (Nueva Rioja 2019a) all underscore the significant impacts of meteorological phenomena on both society and the environment.

Meteorological data provided by the SMN for the period 2011–2020 (SMN, 2023b) indicate hailstorms occurring in February, with snowfall predominantly in July and August. Data from 2001–2010 (SMN, 2015b) indicate hail events in November, January, and February, while snowfall is most frequent in June, July, and September. For the decade 1991–2000 (SMN, 2015a), hail events were mostly observed in January, August, October, and December, with snowfall mainly occurring in June, July, and August. A meteorological event lasting approximately 20 minutes on February 3, 2017, resulted in considerable damage to cultivated lands (INTA 2017) and electrical infrastructure, as well as short-term road obstructions due to hail affection in Famatina (Agritotal 2017; Agrolink 2017; Ámbito 2017; Clarín 2017; Infobae 2017; Infocampo 2017; La Nación 2017). Additionally, several hailstorms caused substantial damage to crops, notably on December 29, 1999, in San Nicolás; January 29, 2000, in San Nicolás, Anguinán and Malligasta; and February 2, 2000, in Guanchín (Ministerio de Producción y Desarrollo Económico de la Provincia de La Rioja 2019).

The low rainfall and sparce vegetation cover in the piedmont areas, combined with the groundwater extraction for industrial, productive, and social activities carried out there, influence variations in soil moisture and wind-driven soil dynamics. Consequently, surface materials become susceptible to aeolian erosion and deflation, facilitating the removal and displacement of local sediments. This phenomenon decreases visibility and poses health risks by introducing airborne particles that impact the human respiratory system (Supplementary, Fig. S1). De Alba (1979) mentioned the persistence of suspended particulate matter following transient episodes of warm, intense, dry winds, which significantly reduce visibility. Additionally, the role of wind in wildfire propagation is emphasized, with notable detrimental effects on the biological components of the environment. Among the most severe wildfire events, the episode from November 17 to at least November 21, 2017, significantly impacted stall-holder, flora, and fauna (Opina La Rioja 2017; Resumen de Actualidad 2017). Other notable wildfires include occurrences in July 2016 between two cable-car stations (Clarín 2016; Jornada 2016); June 2020 in Argañaraz -west of Chilecito- and around Famatina (Garay 2021); August 2020 in Los Manzanos, west of Chilecito (Garay 2021); November 2020 in El Potrerillo and Guanchín (Garay 2021); December 2020 near Agua Negra (Garay 2021); August 2021 in Bajo Carrizal and Plaza Vieja (La Radio FM 103.3 2021; Prensa Chilecito 2021); October 2021 east of Chilecito (Garay and Agüero 2021); August 2022 in Sierra de Famatina (Garay and Agüero 2023); and November 2022 near Guanchín (Diario Chilecito 2022b; El Independiente 2022; Nueva Rioja 2022d; Prensa Chilecito 2022; Garay and Agüero 2023). The November 2022 fire, which ignited on November 23 and was extinguished on November 28 (Servicio Nacional de Manejo del Fuego [SNMF], 2022), posed significant challenges to firefighting efforts due to elevated temperatures and smoke-induced reduced visibility. Fig. 2 and Fig. S2 present burned areas through satellite images captured before and after selected wildfire events within the study area. In this change detection analysis, false-color composites—specifically the RGB 12,8,4 composite for Sentinel-2 and its Landsat 8 equivalent, the RGB 7,5,4 composite—enhance the identification of burned regions. Notably, Fig. 2B reveals a larger affected area than previously reported. Based on documented wildfire occurrences, primarily sourced from local news reports, we infer that the wildfire season spans from June to November, corroborating the data provided by SNMF (n.d.).

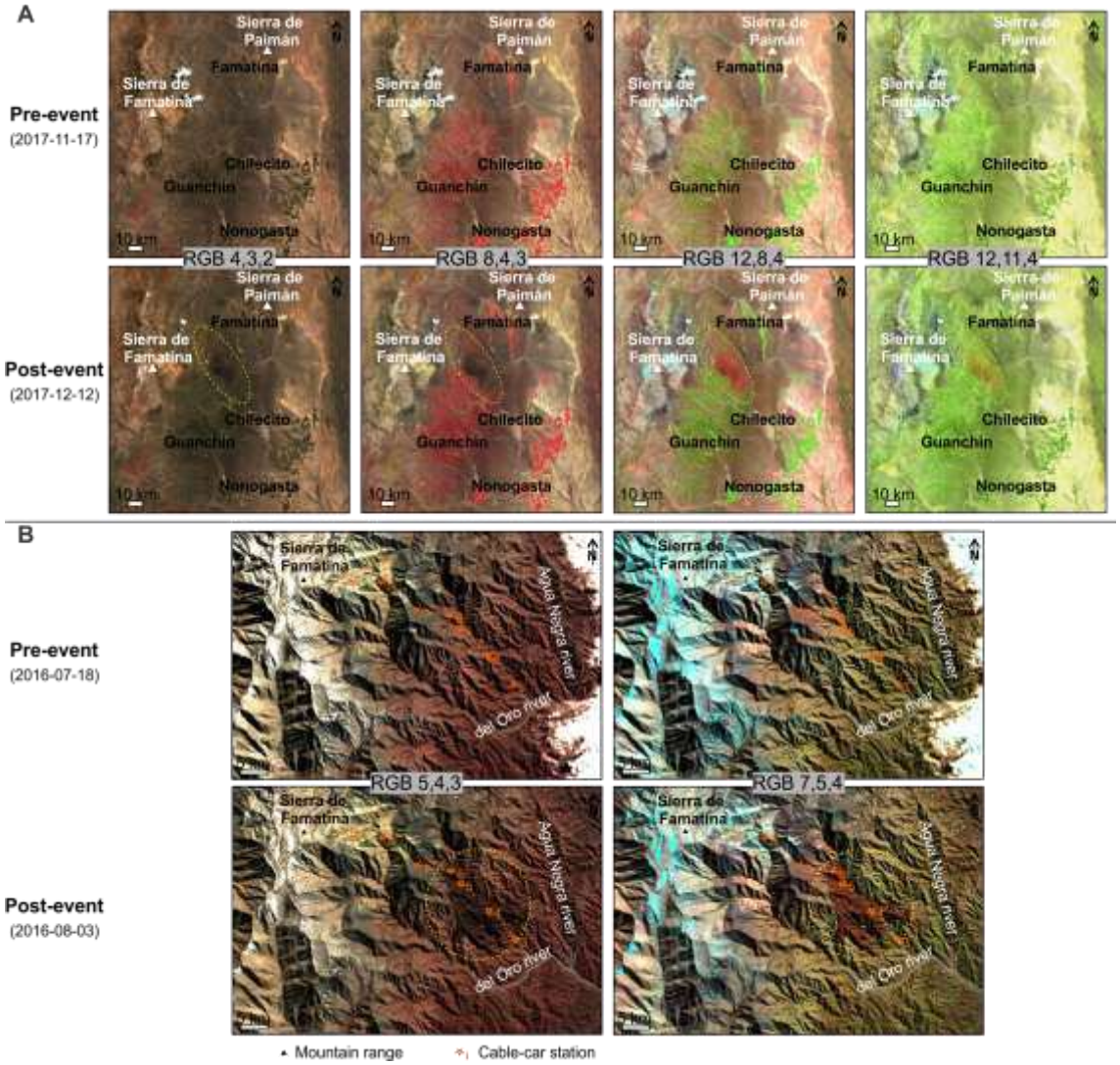


Fig. 2 Areas affected by wildfires (dashed lines) detected through analysis of satellite imagery employing various RGB band combinations. Top: pre-event images. Bottom: post-event images. A) Sentinel-2 images; B) Landsat 8 images.

In relation to the impacts associated with strong winds, notable events include the toppling of trees and utility poles in Chilecito, although no casualties were reported on October 14, 2021 (Nueva Rioja 2021). According to reports from the SMN (2015a, 2015b, 2023b), SE winds can be particularly intense in the region, with recorded gusts reaching up to 96 km/h on February 18, 2015; even though no severe consequences were documented during that event.

4.2. Fluvial action

Despite the arid to semi-arid climatic conditions of the region, fluvial processes represent key contributors to landscape modification (Corbat et al. 2024). The characteristic high-intensity short-duration precipitations in these environments induce flash floods (Instituto de Geociencias y Medio Ambiente 1988; Lin 1999; Rosa and Mamaní 2000; Foody et al. 2004), which lead to rapid increases in streamflow and sediment delivery within stream channels. These hydrological events have the potential to cause significant damage to infrastructure, disrupt agricultural productivity, and adversely impact human activities, which are predominantly concentrated along riversides.

The Amarillo-Famatina, Oro-Durazno-Los Sarmientos, and Miranda Rivers serve as the principal collector streams on the eastern flank of the Sierra de Famatina region. Originating from their headwaters near the summit of General Manuel Belgrano hill (6097 m a.s.l), these rivers descend through the piedmont zone, traversing the localities of Famatina and Chilecito in the first cases (Fig. 1C).

The development of streams—components of the drainage network that sustain perennial or temporary flow—depends primarily on water input, which is influenced by climatic and geological conditions. Climatic factors exhibit temporal variability, limiting streamflow to periods of precipitation and snowmelt occurring at high elevations. Hail and snowfall, frequently intense in the summit region of the Sierra de Famatina, represent important contributors to the hydrological system. Although it is generally assumed that streamflow in this system is largely controlled by the magnitude and intensity of precipitation events, as well as the melting of snow and ice, there is a lack of meteorological and hydrological data from high-altitude zones to quantitatively assess these inputs or their temporal variability.

The final report of the *Programa de Readecuación de los Sistemas de Riego Superficiales y de Intensificación Productiva* (Programa de Servicios Agrícolas Provinciales, 2008) highlights the occurrence of high-intensity, short-duration river rises, as well as the significant presence of suspended sediment and bedload material in the fluvial system. These observations are consistent with Bassi (1953), who indicated that the mountainous segment of the del Oro River between La Mesada and the El Oro mine experiences frequent summer river rises that severely impact channel stability. Although such events are documented in prior studies (Baldi 1970; CFI 1974; Juárez et al. 2022a, 2025), recent news articles (Cadena 3 2018; Diario Chilecito 2019) and field observations, there is a lack of quantitative streamflow data during peak discharge events to validate these findings.

The influence of geological and geomorphological factors on hydrological dynamics is evident in the contrast between the mountainous and piedmont sectors. The mountainous region is predominantly composed of impermeable crystalline rocks, and is associated with steep topographic gradients, narrow and deeply incised valleys. These characteristics promote rapid surface runoff and increase the likelihood of flash flooding during intense precipitation events. In contrast, the piedmont sector is characterized by alluvial deposits, lower topographic gradients, and channel divergence, which collectively enhance infiltration. In this zone, surface runoff occurs during storm events when rainfall intensity exceeds the soil's infiltration capacity.

In the piedmont areas, the drainage configuration of alluvial fans typically results in the concentration of hydrological activity within a primary channel, while most of the other fluvial channels remain inactive under normal conditions (Schumm 1968). However, during storm events or episodes of significant water discharge, multiple channels may become active, and even the spatial distribution of flow can be altered due to avulsion processes (Beaty 1970; Kesel 1985; North and Warwick 2007; Karamitopoulos et al. 2022; Martin and Edmonds 2022). The frequent fluvial inactivity across large portions of these areas has encouraged their use for agricultural purposes and urban development (e.g. Chilecito, Los Sarmientos, Malligasta, Tilimuqui, Anguinán, Nonogasta), often without adequate consideration of the associated hydrological risks. As a result, a key hazard in the study area is the potential for runoff migration to alternate channels through variable or abrupt processes, which can lead to significant geomorphic and infrastructural impacts.

Regarding hydrological erosion processes, based on Burian et al. (2015), we highlight the hazard associated with the presence of gullies in the piedmont zone of the study area. These erosional landforms develop in low-slope terrains composed predominantly of fine sediments and are characterized by incised drainage channels with steep lateral walls, typically from centimeters to meters in both vertical and horizontal dimensions. They exhibit a distinct break in slope relative to the surrounding land surface. The identification of these gullies was carried out through satellite imagery or field observations, depending on their scale and site accessibility. Fig. 3 illustrates examples of these features, their morphology and the exposed sedimentary materials. These depressed landforms are marked by rapid geomorphological evolution, as they enhance surface runoff concentration and promote intense localized erosion. This often results in the collapse of overlying material, lateral expansion of gully margins, and headward retreat due to upstream erosion. Consequently, such processes contribute to widespread land dissection and significant topographic degradation. Gully erosion is thus recognized as a severe and visually striking form of land degradation (e.g., Castillo and Gomez 2016; Thwaites et al. 2022; Majhi et al. 2024), with the potential to negatively impact both infrastructure (Fig. 3A; Supplementary, Fig. S3) and adjacent agricultural areas.



Fig. 3 Gullies. (A) Airbus satellite image on July 4, 2023, obtained via Google Earth Pro. The orange star marks the location of cable-car station 1. Yellow circles and corresponding labels indicate the locations at which the associated photographs (A.1–A.4) were taken. (A.2) Detail of sedimentary materials exposed along the gully margin; a yellow circle highlights a 20 cm-long notebook used as a scale reference. (A.3) A yellow circle indicates a truck, serving as a scale reference. (A.4) Gullies observed in proximity to inhabited structures, with a person of 165 cm in height used for scale. (B) Satellite image showing the main drainage channel of the Antinaco-Los Colorados valley (along the north–south direction) and associated gullies in the Malligasta area. Yellow circles indicate the locations of the photographs shown in panels B.1 and B.2.

We infer that variations in the longitudinal profiles of the channels are driven by the combined influence of meteorological and tectonic factors, along with changes in channel base level, flow discharge, and sediment supply. These influences are reflected in the dynamic behavior of the fluvial system. Additionally, topographic and geological conditions—particularly relief, slope gradients, lithology, and tectonic structures—exert a significant control on fluvial activity.

Based on the temporal analysis of satellite imagery from Google Earth Pro, we identify significant variations in both the streamflow dynamics and spatial configuration of the del Oro River

(Supplementary, Fig. S4). These observations reflect ongoing modifications in the fluvial landscape within the study area. Notably, the migration of the active river course has resulted in alterations to channel morphology (as proposed by Schumm 1981; Ashworth 1987; Rosgen 1994) and the repositioning of sedimentary bars within the channel system. Similarly, we document morphological changes associated with the Miranda River, further illustrating the dynamic nature of fluvial action in the region (Supplementary, Fig. S5).

Based on the analysis of available hydrological data for the main watercourses within the study area (Secretaría de Infraestructura y Política Hídrica de la Nación 2022), we infer that fluvial activity constitutes a potential hazard, despite the limited information on its associated impacts. For the Famatina River, the maximum daily discharge recorded during the 1944–1945 hydrological year indicates that streamflow within a single day can significantly exceed the annual average. Although the mean annual discharges for the years immediately before and after differ, this event is interpreted as hydrologically significant, with possible implications for the area (Fig. 4A). Moreover, as shown in Fig. 4A, streamflow values exhibit a low variability from 1956 onward. In the case of the Miranda River, the maximum daily discharge recorded during the 1969–1970 hydrological year is comparable in magnitude to that observed in the Famatina River (Fig. 4B). Additionally, the Miranda River discharge records indicate marked variability between 1967 and 1981. The assessment of the physical parameters driving these processes is constrained by the scarcity of hydrometeorological data available for the region.

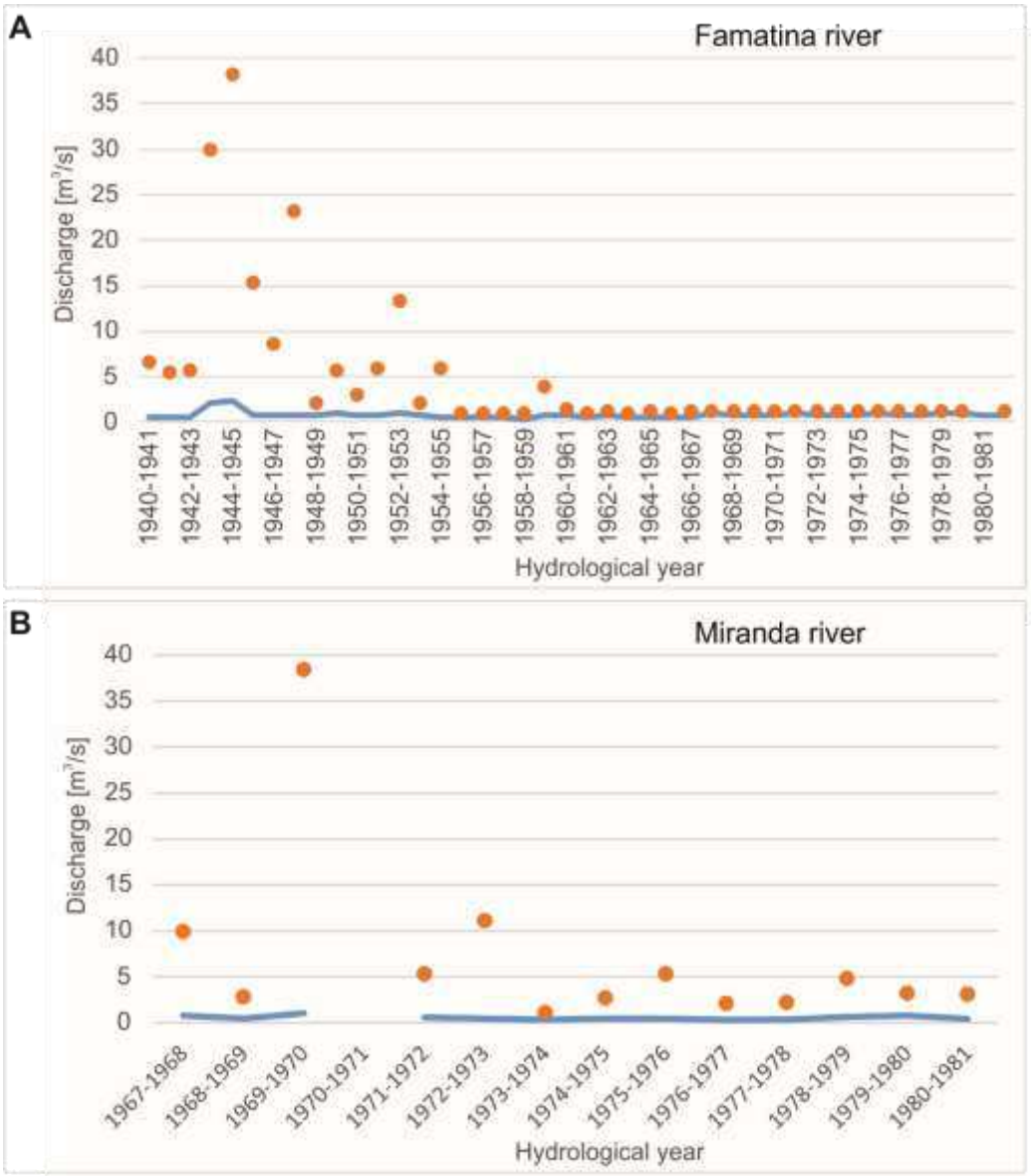


Fig. 4 Mean annual discharge (blue lines) and maximum daily mean discharge (orange circles), expressed in m^3/s, for the Famatina River (A) and the Miranda River (B).

Despite the limited information about hazardous events in the study area and their impacts, several sources indicate that intense precipitation events have triggered flooding in Guanchín, Chilecito, and surrounding regions (La Prensa 2011). On December 31, 1998, an extreme rise in the water level of the Los Sarmientos River caused damage to water pipelines, public lighting poles, and a campsite in Chilecito (El Independiente 1999). In February 2013, the rising water level of the Miranda River led to the closure of National Route 40 (Casas and Albarracín 2015). An event on January 31, 2018 (SEGEMAR n.d.; La Nación 2018), is associated with reported rescues of individuals traveling toward Anguinán and nearby Guanchín. During the same period, the rising of the Pismanta River resulted in a van —with a person inside— being dragged by the current. Although the *Sistema Nacional de Información Hídrica* database records high hydrological values for the river impacting Chilecito on the same date, these values do not reach the peak river levels and precipitations reported in the SMN databases (arrow in Supplementary, Fig. S6). Furthermore, the overflow of the Nonogasta River on February 21, 2018, caused the collapse of utility poles and columns, and flooding affected a power plant, leaving many

residents without electricity (El Independiente 2018c). On January 26, 2019, heavy rainfall caused river levels to rise in the Famatina Department, leading to fallen trees, street flooding, and restricted traffic circulation (El Independiente 2019). Likewise, the evidence suggests that the precipitation event of December 28, 2019, was extreme. Reports include assistance to a driver stranded due to the rising of Los Sarmientos River, fallen trees in the Pomán neighborhood (Chilecito Department), and widespread urban flooding (Nueva Rioja 2019b). However, as shown in Fig. S6, the values of the hydrometeorological parameters recorded in the *Sistema Nacional de Información Hídrica* and SMN databases for this event do not coincide with their peak values. Therefore, these obtained maximum records warn of their potential.

As a result of the spatial distribution of the main runoff channels, the torrential nature of precipitation events, and the potential impact on both urban and rural areas—particularly those located near fluvial channels in the piedmont sector—the principal watercourses are equipped with containment and/or erosion-control structures. These structures are designed to regulate water flow and mitigate the adverse effects of flooding on adjacent areas (Supplementary, Fig. S7). They typically consist of simple concrete lateral walls of varying lengths (ranging from tens to hundreds of meters), depending on their location. Standard dimensions for these walls are approximately 2 meters in height and 1 meter in width (Giaconi et al. 2017). They are oriented either obliquely or parallel to the direction of streamflow. However, due to undercutting and lateral erosion driven by fluvial dynamics, many of these structures have experienced structural damage or complete failure (Supplementary, Fig. S7A.5), resulting in reduced effectiveness. In recent years, some of the damaged structures have been replaced by semi-permeable gabion walls, which are easier to repair.

Erosion-control structures are distributed along the Amarillo River, particularly within the segment corresponding to the Famatina locality. These structures are designed to mitigate fluvial erosion, enhance the stability of channel margins, and reduce the potential impacts of extreme hydrological events on both human settlements and economic activities (Supplementary, Fig. S8A). Similar infrastructure is also present along the Los Sarmientos River, specifically within the alluvial fan—approximately 180 km² in extent— (Corbat et al. 2020, 2024) located east of the Sierra de Paimán and Chilecito locality (Supplementary, Fig. S8B; Supplementary, Fig. S7A). In this sector, the main channel features structures aimed at reducing the likelihood of avulsion-related impacts, particularly in the neighborhoods of Los Sarmientos, La Puntilla, and Malligasta. Notably, a significant portion of this alluvial fan is occupied by urban developments or areas of intensive productive use.

Another major drainage pathway impacting the urban and peri-urban areas of the Chilecito locality originates in the vicinity of Santa Florentina and exhibits surface runoff in a northwest–southeast direction. Its natural flow is intercepted by a containment structure that redirects the discharge southward, thereby preventing inundation of the urban area (Supplementary, Fig. S8B.1). Additionally, this watercourse was altered toward the end of 2011 during the construction of the pathway that currently connects cable-car stations 1 and 2.

The Miranda River is a perennial watercourse characterized by pronounced seasonal variability. It flows initially towards the southeast and subsequently turns eastward, approximately following a path parallel to National Route 40. Along this latter segment, the river receives surface runoff contributions from the Sierra de Sañogasta and continues toward the Miranda and Sañogasta localities, marking the transition from the mountainous region. In this transitional zone, structural interventions were implemented to redirect the main channel and its tributaries to mitigate river flooding (Supplementary, Fig. S9). Further downstream, within the piedmont zone, the main channel resumes a southeastward trajectory toward the Bajos de Santa Elena.

In the section of the Trinidad River between the Sañogasta and Nonogasta localities, a series of gabion structures oriented along a northwest–southeast axis has been built. These installations serve to divert the natural west–east surface runoff toward the southeast (Supplementary, Fig. S9B), thereby preventing the direct flow of water through the Nonogasta locality. This hydrological diversion redirects both water and sediment load to areas south of Nonogasta, significantly reducing the potential damages associated with extreme events. Furthermore, in the vicinity of Nonogasta and surrounding the agricultural lands, there are elevated linear structures to intercept and redirect runoff away from cultivated areas. These strategies are intended to safeguard agricultural productivity and are commonly observed throughout the broader study region.

4.3. Mass movement processes

The morpho-climatic characteristics of the study area promote the downslope mobilization of materials driven by gravitational forces -mass movement processes- and the development of associated morphological features.

The occurrence of these gravitational processes is strongly influenced by structural factors (represented by Turner 1971; de Alba 1979; Durand et al. 1987; Collo et al. 2006; Candiani et al. 2011) that shape the initial topography of the area, the steepness of the slopes, the lithological characteristics of the affected rocks, their structures, and the degree and type of weathering, which increases the availability of unconsolidated materials prone to remobilization. Additionally, limited vegetation cover reduces slope stability, while the presence of water within the slope materials further promotes instability. Evidence of mass movement processes triggered by anthropogenic activities (Supplementary, Fig. S10) has also been identified in the area. Secondary sources emphasize the challenges posed by these slope instabilities for infrastructure development, particularly in relation to the construction and maintenance of National Route 40 (Paolini Hnos. 2022). Although the occurrence of gravitational processes is facilitated by the aforementioned factors, they tend to be spatially sporadic and do not exhibit a systematic or regional distribution pattern.

Based on the analysis of satellite imagery and field observations, we identified a variety of landforms indicative of mass movement processes in the mountainous sector. These include talus slopes, debris cones, and debris flows (Supplementary, Fig. S11A-C), as well as landslide scarps (Supplementary, Fig. S11D-E), jointed rock masses suggesting toppling failure (Supplementary, Fig. S11F), and granitic blocks separated by discontinuities, forming unstable units susceptible to rockfalls. The structurally weakened and weathered basement rocks (Fig. 5), typically exposed in steep mountainous terrains, enhance the likelihood of rockfall events, which are common in the study area (Fig. 5F, J). These mass movement processes are of particular concern due to the proximity of transportation routes and inhabited areas to the mountainous zone. Their significance is underscored by documented incidents (Rioja Virtual 2018; Nueva Rioja 2020), such as the fatal rockfall in February 2011 near the Cuesta de Miranda sector, where a 3-meter-long boulder struck a vehicle, resulting in four fatalities (Petric 2011; Clarín 2011; La Capital 2011; La Voz 2011; SEGEMAR n.d.). In response to such hazards, various mitigation strategies have been implemented along several routes, especially in the Cuesta de Miranda sector, including the installation of protective structures (Supplementary, Fig. S12; Supplementary, Fig. S13) and warning signage at critical points (Supplementary, Fig. S12G; Supplementary, Fig. S13E).

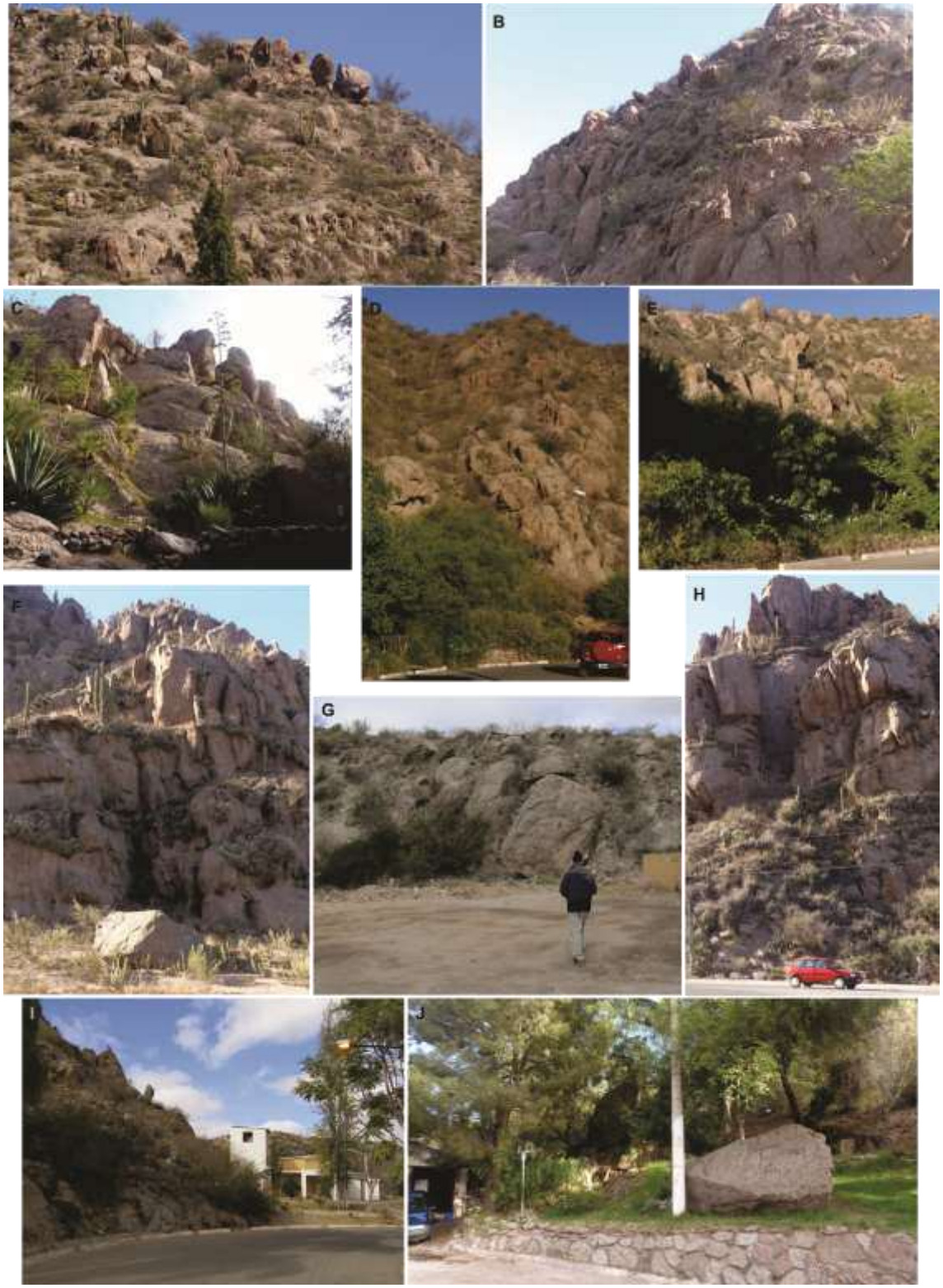


Fig. 5 Weathering features observed in granitoid rocks at Sierra de Paimán (A-B: 29°10´02"S/ 67°29´09"W; C: 29°10´01"S/ 67°29´14"W; D-E: 29°09´13"S/ 67°29´28"W; F: 29°09´43"S/ 67°29´04"W; G: 29°09´08"S/ 67°29´33"W; H: 29°09´39"S/ 67°29´06"W; I: 29°09´31"S/ 67°29´25"W; J: 29°10´17"S/ 67°29´10"W), highlighting blocks prone to rockfall.

Additional features related to mass movement processes were identified in the study area, particularly in association with fluvial systems (Supplementary, Fig. S14) including unstable rock masses prone to these processes (Supplementary, Fig. S14F), as well as evidence of a past landslide event along the Amarillo River (Limarino et al. 1994; Juárez et al. 2022b), and geomorphic expressions in periglacial environments. In the latter, the high elevations, sparse vegetation, and significant temperature fluctuations define a freeze–thaw dynamics (Gutiérrez Elorza 2001; Matsuoka and Murton 2008) developing solifluction and gelifluction features commonly in conjunction with rock glaciers (Fucks et al. 2018; Corbat et al. 2020, 2022; Juárez et al. 2022a, 2022b; Supplementary, Fig. S15), contributing to slope instability in periglacial terrains.

The evidence gathered regarding mass movement processes indicate that they constitute significant natural hazards within the study area. Such events can directly impact critical infrastructure —including roads, shelters, and urban developments— or indirectly impact human activities —for example, by obstructing watercourses and altering hydrological dynamics. A notable example occurred on December 7, 2021, in the mountainous sector along the del Oro River, where a destructive event was recorded for the third consecutive year. This event, triggered by intense rainfall (Alanis 2021) -as in previous occurrences (Aguirre 2019)- and increased sediment transport, disrupted access to the Las Placetas outpost, highlighting the recurrent nature and infrastructural implications of this type of events in the region.

It is assumed that mass movement processes in the study area require specific triggering factors for their activation. These include intense precipitation events, rapid snow melt, seismic shaking, and slope undercutting (Glade and Crozier 2005), as well as anthropogenic activities (such as road construction and mining). Based on documented cases, the presence of water appears to play a key role in initiating these processes, establishing a strong link with summer-season conditions. Nevertheless, the occurrence of mass movement events during other seasons or triggered by seismic activity cannot be ruled out, given the current lack of detailed information on meteorological conditions, mass movement occurrences, and the influence of seismic events.

4.4. Seismic activity

One of the key geotectonic consequences of the subhorizontal subduction of the Nazca Plate beneath the South American Plate (Isacks et al. 1982; Jordan et al. 1983a, 1983b; Jordan and Allmendinger 1986; Ramos 1997; Ramos et al. 2002; Anderson et al. 2007; Perucca and Moreiras 2009; Costa et al. 2018; Rodriguez Piceda et al. 2022) is the generation of increased seismic activity (Pereyra 2018). The study area is situated within this tectonic context and falls within a zone of moderate seismic hazard, according to the official national seismic zonation (INPRES 2021). Moreover, the spatial distribution of earthquakes, as reported by international reference institutions (specifically, USGS and IRIS, as of June 2025), classified by magnitude and focal depth, reflects the regional seismotectonic regime (Fig. 6). The high density of seismic events is consistent with the dynamics of subhorizontal subduction and suggests a significant degree of interplate coupling along this segment of the convergent margin (Fig. 6C).

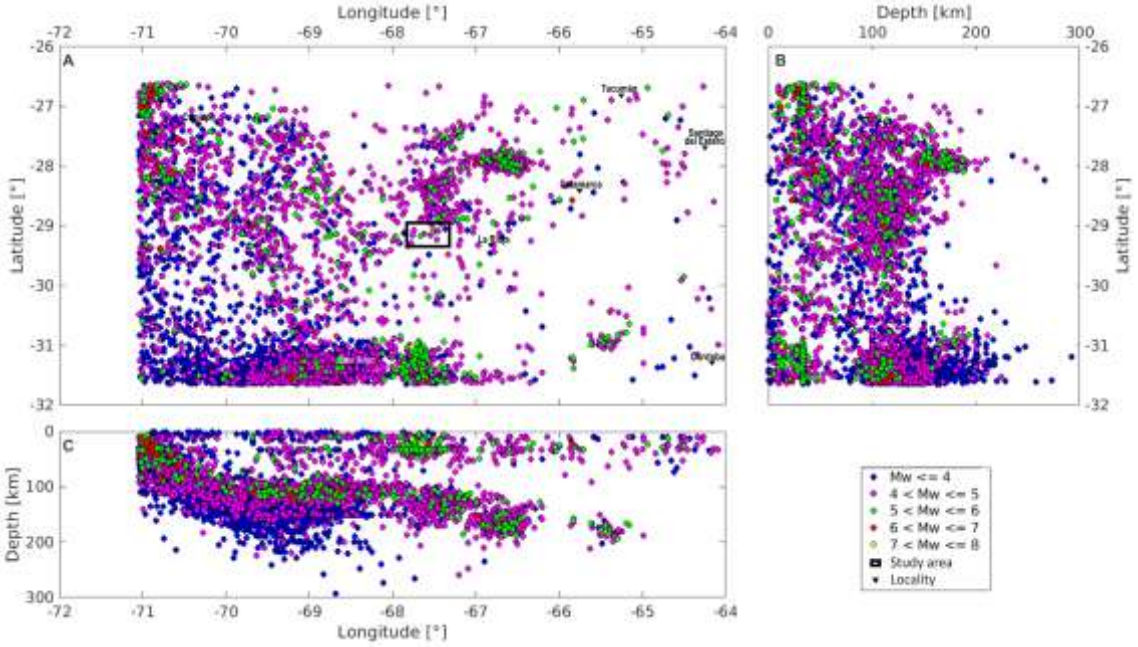


Fig. 6 Spatial distribution of earthquakes reported by USGS and IRIS, categorized by magnitude (Mw). (A) Map view. (B) Depth versus latitude cross-section. (C) Depth versus longitude cross-section. The black rectangle delineates the location of the study area.

Seismic energy propagation generates ground vibrations that can weaken or damage the rocks through which it travels. This effect is dependent on the physical and mechanical properties of the host rocks, including density, stiffness, and the presence of structural discontinuities. Among the most prominent morphological manifestations of seismic events are tectonic deformations, surface rupture features, and features related to mass movement (Keefer 1984, 1994, 2002; Costa et al. 1999; Rodríguez et al. 1999; Perucca and Paredes 2003; Costa 2004; Tello and Pérez 2004; Meunier et al. 2007; Owen et al. 2008; Perucca and Moreiras 2009; Zavala et al. 2009; Mardones Flores and Rojas Hernández 2012; Gunawan et al. 2016; Huang et al. 2017; Winocur et al. 2021; Hu et al. 2021; Ginesta Torcivia et al. 2022).

The earthquake that occurred on October 27, 1894, is the earliest documented seismic event in the region (Bodenbender 1894 in Tello and Pérez 2004). Despite being felt in a relevant portion of the country, it resulted in significant structural damage and few fatalities in the capital of La Rioja province, none of those in the locality of Chilecito (Revisionistas n.d.; Tello and Pérez 2004). Within the study area, this event was assigned a Modified Mercalli Intensity of VIII according to the map in Castano (1993, in Tello and Pérez 2004).

Several other historically significant earthquakes have also affected the region, particularly the study area and its surroundings. Among these, the event that occurred in Chilecito on May 20, 1909 (Viteau 1910), is noted as locally felt (INPRES n.d.). Both the earthquake of February 5, 1898, located in Catamarca and the April 12, 1899, event in La Rioja reached an intensity of VIII; the latter caused structural damage in the localities of Jagüe and Vinchina, resulting in 11 fatalities and numerous injuries. Two notable events with an intensity of VII occurred in Córdoba on September 22, 1908, and in La Rioja on October 24, 1957; the latter reported damage along the western portion of the province. In more recent decades, events such as the earthquake in San Juan on September 26, 1972 (intensity VI), and in La Rioja on June 7, 1977 (intensity VII), have also impacted the region. The earthquake of May 28, 2002, in La Rioja, assigned an intensity of VIII, caused extensive damage to hundreds of dwellings and resulted in 27 injuries in the

northeastern sector of the La Rioja province. It also led to the obstruction of National Route 40 in the vicinity of Cuesta de Miranda (La Nación 2002; Río Negro 2002) and is the only event with confirmed earthquake-induced landslides in the historical record. Further seismic activity includes the event in Catamarca on September 7, 2004, with an intensity of VII, and the earthquake of January 18, 2021, in San Juan, which reached intensities of VI–VII near the epicenter and IV in the city of La Rioja.

Although earthquake-induced landslides have only been formally recorded during the 2002 event, it is plausible that similar processes were triggered by earlier earthquakes of comparable intensity, though they remain undocumented due to historical limitations in monitoring and reporting. Most recently, on May 1, 2025, a magnitude 5.5 earthquake occurred within the study area. This event was felt by the local population, who reported structural damage—particularly in Campanas, located right to the north of the study area—as well as the occurrence of mass movements in the surrounding mountainous terrain (Infobae 2025; Nueva Rioja 2025).

According to the official list of felt earthquakes provided by INPRES, recorded magnitudes range from 2.5 to 6.0, with the highest instrumental value corresponding to the previously mentioned 2002 seismic event. These magnitudes indicate the potential for significant impacts within the study area, as evidenced by the occurrence of earthquakes with magnitudes up to 5.0 within the upper 70 km of the lithosphere (Fig. 7). Multiple seismic events are expected to trigger the mobilization of surface and near-surface materials due to the propagation of seismic energy. Even though the minimum magnitude required to induce such material displacement remains a subject of ongoing scientific debate (Keefer 1984, 1994; Rodríguez et al. 1999; Owen et al. 2008), those minimum values are exceeded by some of the magnitudes in the utilized catalog.

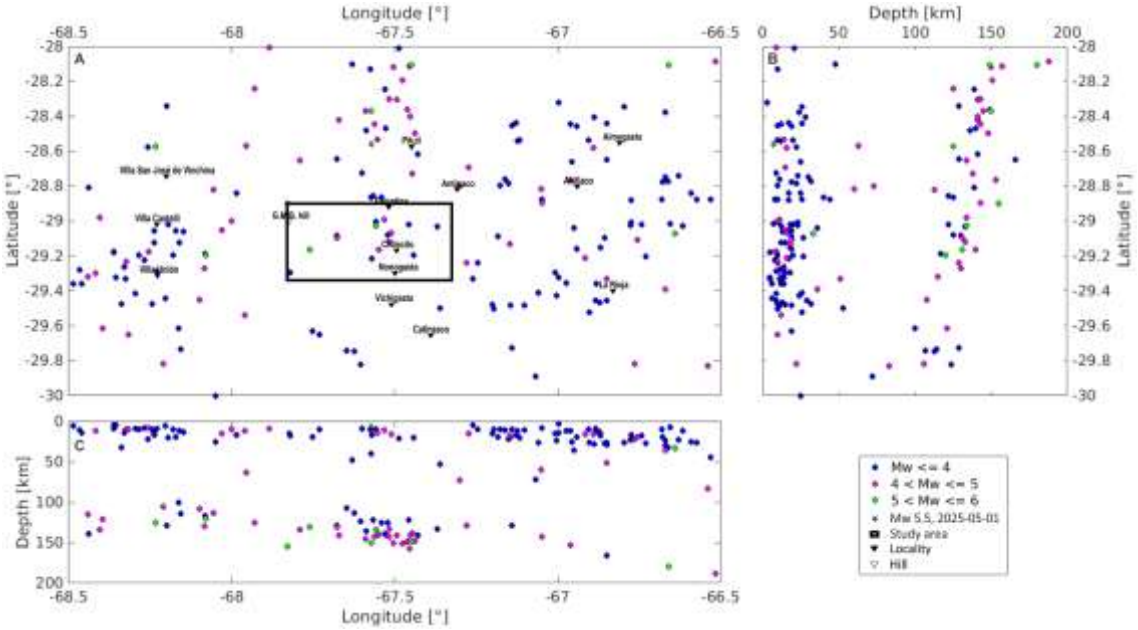


Fig. 7 Spatial distribution of earthquakes reported by INPRES as felt by the population, categorized by magnitude (Mw). (A) Map view. (B) Depth versus latitude cross-section. (C) Depth versus longitude cross-section. The black rectangle delineates the location of the study area. G.M.B. stands for General Manuel Belgrano.

Historical records indicate a limited number of casualties and structural damage associated with earthquakes in the region. However, documented cases demonstrate that seismic events represent a relevant natural hazard. Notably, a high-magnitude earthquake (Mw 7.4) occurred

approximately 200 km from the study area on November 23, 1977, highlighting the potential for the occurrence of large-magnitude events within or near the region.

4.5. Socio-environmental problems

The growing population and expansion of productive activities have led to an increasing demand for environmental resources, prompting studies on their availability, use, and the interaction between society and the natural environment. Consequently, the study area exhibits both current and potential environmental conflicts. The expansion of road and building infrastructure in urbanized zones has intensified surface impermeabilization (Supplementary, Fig. S16; Fig. 8A), altering the effective runoff dynamics on paved surfaces and overloading stormwater drainage systems. These changes shift hydrological impacts downstream and exacerbate the severity of flood events. The natural hydrographic network has been extensively modified and channelized to optimize land use and accommodate human settlements, thereby transforming the original environmental conditions (Fig. 8). Additionally, the unregulated establishment of settlements along riversides—often driven by local decisions made without adequate risk awareness—exposes these populations to heightened vulnerability during both rainfall-induced and fluvial flood events. Many settlements are distributed on vulnerable areas (Supplementary, Fig. S17), reflecting the insufficient regulation of settlement patterns and the lack of comprehensive land-use planning to guide population growth toward safer areas.



Fig. 8 Temporal evolution of urbanization and associated changes in surface drainage in areas A and B. Satellite images were obtained from Google Earth Pro. 1) Maxar Technologies imagery dated April 17, 2004. A.2) Airbus imagery dated March 30, 2019. B.2) Airbus imagery dated September 23, 2013. 3) Airbus imagery dated April 7, 2023.

On the other hand, changes in land cover and land use—primarily associated with the expansion of olive cultivation and its byproducts (Levembach 2012; Bárbaro et al. 2015; Hadad and Palmisano 2017; Montilla et al. 2018; Secretaría de Agroindustria 2019; Moreira et al. 2020a; Montilla 2022)—have become increasingly significant in recent years in the valley located at the eastern foothills of the Sistema de Famatina. Additionally, viticulture has emerged as a notable productive activity over the past few decades (Instituto Nacional de Vitivinicultura 2014, 2018a, 2018b, 2019). Fig. S18 illustrates the expansion of cultivated land within the study region. This large-scale transformation in agricultural activity has led to several environmentally detrimental changes, including the loss of native vegetation (Luna Toledo and Figuerola 2010), a decline in groundwater levels (González Ribot et al. 2015; Miguel et al. 2015; Miguel and González Ribot,

2016; Miguel et al. 2017a, 2018; Falcón et al. 2019), and soil degradation. These changes have, in turn, contributed to the acceleration of both water and wind erosion processes in the area, consistent with trends observed in other regions (Sujatha et al. 2000; Keller and Blodgett 2004). Furthermore, it is important to highlight the routine use of nutrients, fertilizers, and pesticides in extensive agricultural production at the national scale (Vigglizo and Frank 2015; Andrade et al. 2017).

The implementation, persistence, and expansion of anthropogenic activities over time in the region have led to the degradation of the environment and the loss of natural assets. This is particularly evident in the reduction of native forest cover (Rojas 2013; Rojas et al. 2014a, 2014b; Bárbaro et al. 2015; Biurrun et al. 2015; Dirección Nacional de Bosques 2017, 2022), which now persists only as remnants associated with fluvial channels (Laudecina et al. 2023). Several studies (e.g., Barrera et al. 2019) suggest that the decline in woody vegetation due to deforestation and logging was particularly significant between 1990 and 2010 in the vicinity of the Antinaco locality. Additionally, various forms of potential environmental pollution represent important concerns in the area.

Two major sources of environmental pollution have been identified in the study area: one associated with tanneries in Nonogasta locality, and the other with wastewater treatment plants in the Chilecito area (sites 1 and 2 in Fig. 9A, and Fig. 9B), both with a strong odor emitted from the effluents. While no official records of effluent discharge or its environmental and social impacts are reported for Chilecito, some studies have reported soil contamination with chromium (a heavy metal used in leather processing) for Nonogasta (Behrends Kraemer et al. 2019). Public concern and dissemination of information regarding the environmental and health impacts of the chemicals used in tanning activities in Nonogasta have been primarily driven by affected residents, through the El Retamo Assembly, social media, and local news outlets (Tamashiro 2017; Maidana 2019; Moreira et al. 2020a). Among the reported data, it is noteworthy that the Nonogasta tannery operates large effluent discharge basins (containing untreated, highly toxic wastewater), which lack protective barriers to prevent infiltration and environmental contamination (Tamashiro 2017; Moreira et al. 2020b). Estimated discharge volumes range between approximately 90 million (Maidana 2019) and 200 million liters per month (Olmedo and Ceberio de León 2016; Rovina 2017). Moreover, the chemicals present in these effluents can be redistributed through rainfall or airborne dispersion when dried, potentially posing risks to surrounding populations (Asamblea el Retamo de Nonogasta 2015; Olmedo and Ceberio De León 2021).



878

879 **Fig. 9** A) Location of treatment basins and agro-industrial facilities shown on an Airbus satellite image (September 7,
880 2023) obtained from Google Earth Pro. 1: tannery effluent basin, 2: domestic wastewater treatment basin. The figure
881 shows industries related to walnut (yellow circle), olive (green circle), tomato (red diamond), and grapevine (purple
882 hexagon) processing, as documented by Vuksinick (2022). B) Photograph of the treatment basins, taken from Sierra
883 de Paimán (29°09´33"S/67°29´09"W) looking toward Sierra de Velasco. C) Photograph of a fluvial channel exhibiting
884 a black coloration, likely associated with agro-industrial effluent discharge (29°14´35"S/67°23´58"W).

885 As an indicator of the potential contamination hazard in the area, both qualitative and
886 quantitative data on agro-industrial effluents, as well as their discharge into dry riverbeds or
887 direct disposal onto soil (Vuksinic 2022), are of particular concern—an issue that had been
888 previously reported (Poblete and Guimaraes 2006). The results reveal that the physicochemical
889 properties of these effluents exceed the regulatory thresholds established by La Rioja legislation
890 (Law 4.741). Observations of spills and overflows from sedimentation basins further support
891 concerns regarding the potential negative impacts on water resources, with consequent effects
892 on the environment and regional development. As an illustrative example, Fig. 9C shows a black-
893 colored fluvial channel, which was identified during fieldwork by its strong odor. Furthermore,
894 the ongoing expansion of cultivated land and agro-industrial activity contributes to an increase
895 in associated waste production, with significant environmental implications.

896 Simultaneously, the agro-industrial activities conducted in the area, along with the treatment
897 basins located in close proximity to populated centers, also impact air quality. These conditions
898 may adversely affect the health of individuals exposed to unpleasant odors, as discussed in the
899 studies by Fortt Zunzunegui (2012), Capelli et al. (2013), Sáenz et al. (2016), Bermúdez et al.
900 (2018), which were used to establish the contextual framework for this analysis.

These issues related to productive enterprises also involve underlying socio-political dimensions, and it is necessary to account for their environmental impacts and/or potential remediation strategies in order to assess and manage a balanced integration of the interests at stake.

The presence of chemical elements and compounds in the waters of the Amarillo-Famatina and del Oro-Durazno-Los Sarmientos Rivers must be highlighted, as it is primarily attributed to the lithological composition at the headwaters of their drainage basins and to dissolution–oxidation processes occurring during surface runoff (Maza et al. 2014; Lecomte et al. 2016; Bernardelli et al. 2021). These concentrations affect water quality, influence soil characteristics, and impact crop development. For instance, Miguel et al. (2016) reported concentrations of Fe, Cu, and Zn (in mg/L) in the Amarillo and del Oro Rivers during November of 2014 and 2015 that exceed guideline values established for irrigation water quality. Furthermore, analyses of water samples collected in September 2016 near the headwaters of the del Oro River (Corbat et al. 2020) revealed $SO_4^{=}$ and F^{-} concentrations (mg/L) above the reference limits set by the Argentine Food Code. Additionally, previous studies in the region have documented elevated levels of sulfates, fluoride (Sosic 1964), arsenic, and nitrates (Miguel et al. 2017b) in groundwater from specific wells, which limit its suitability for irrigation and pose potential health risks for human consumption.

Although some authors (Maza et al. 2014; Maza 2015; Lecomte et al. 2016) argue that the acidity of the Amarillo-Famatina River has been intensified by mining activities at La Mejicana, the presence and oxidation of sulfide minerals—particularly pyrite—in that area represent the natural source of the low pH characteristic of acid rock drainage (Nordstrom et al. 2015; Oyarzún 2022). The abundance of sulfides exposed to weathering in former mining zones within the Sierra de Famatina has a detrimental effect on water, soil, and air quality (as similarly documented by other researchers in northwestern Argentina; Kirschbaum et al. 2012). In addition to decreasing the pH of the system, these processes release heavy metals and promote the formation of secondary minerals, thereby degrading environmental conditions. These impacts are consistent with those observed in other regions globally (Nordstrom 1982; Jambor 1994; Nordstrom and Alpers 1999; Dold and Fontboté 2001). Consequently, the environmental risks associated with legacy mining waste in the Sierra de Famatina remain a source of concern for local communities (Supplementary, Fig. S19). Public mobilization and social activism have played a key role in raising awareness of this conflict and have successfully halted the advancement of mining projects in the region (Job 2012; Sola Álvarez 2016; Wagner 2018; Frente Social por el Agua y la Vida 2018; No a la mina 2018; Orche 2020; Bottaro and Sola Álvarez 2024), in defense of environmental integrity and in opposition to the negative impacts associated with this industry (Taillant 2012; Leguizamón and Moreno 2013; Mohle 2021).

Additionally, in the context of mining excavations and groundwater extraction, land subsidence must be considered as a potential concern that has not yet been analyzed in the study area. There are documented cases worldwide in which excessive groundwater pumping has induced significant subsidence (Bull 1974; Coplin and Galloway 1999), highlighting the need to evaluate this process in regions undergoing similar extractive activities.

Considering the intensive use of water resources, deforestation, intensive agriculture, and the compaction of surface materials—which collectively contribute to the occurrence of erosive processes—desertification also emerges as a critical process requiring attention. Additionally, the concentration of soluble salts near the surface in low-relief areas further exacerbates land

946 degradation. Although the area analyzed falls within zones identified as having a high average
947 global vulnerability index to desertification (Huang et al. 2020; Isla and Espinosa 2021), there
948 are currently no detailed reports on the specific contributing or driving factors in this region.
949
950 Regarding current environmental challenges, the widespread presence of solid waste in various
951 plots, drainage channels, and gullies contributes significantly to pollution and land degradation
952 within the study area (Supplementary, Fig. S20). During episodes of intense local precipitation
953 or rapid surface runoff, this waste obstructs drainage systems, preventing proper water
954 evacuation and exacerbating flood risks. The visible accumulation of waste, along with other
955 anthropogenic interventions (Supplementary, Fig. S20F), negatively affects both the
956 environmental quality and aesthetic value of the landscape, leading to its degradation.
957 Nevertheless, efforts have been made to improve local conditions, including the establishment
958 of the Centro Ambiental in Chilecito and the closure of open-air dumpsites, aimed at enhancing
959 the well-being of the local population (Ministerio de Turismo de la Nación 2016).

960 One of the environmental issues that has received increasing attention in recent years is climate
961 variability and its associated impacts, which have been exacerbated by human activities. In light
962 of the complex relationship between society and the natural environment, the temporal analysis
963 of both observed and projected climatic variables is essential. Such analysis, along with the
964 identification of their effects on socio-environmental system, provides a foundational approach
965 to understanding the dynamics of climate change.

966 Precipitation records for the period 1989–2022 reveal a marked concentration of rainfall during
967 the austral summer months, with a high degree of summer variability. Furthermore, the data
968 indicate a decreasing trend in summer precipitation over the observed time span
969 (Supplementary, Fig. S21).

970 Temperature records for the period 2010–2022 indicate that annual mean temperatures
971 fluctuated between 18.7°C and 19.8°C, reaching a maximum in 2020 (Supplementary, Fig. S22).
972 While no clear trends were observed when analyzing contrasting seasonal temperatures, it is
973 important to note that the relatively short duration of the analyzed period may limit the
974 identification of robust trends. However, the data show a greater thermal amplitude in winter
975 temperatures compared to summer temperatures. Changes in mean annual and seasonal
976 temperatures were also analyzed in relation to the 1991–2010 climatological baseline. Despite
977 interannual variability, the mean temperature anomalies show a warming trend, evidenced both
978 by values exceeding the reference baseline (zero in Fig. S23) and by an overall upward trajectory
979 during the 2010–2022 period. Notably, the deviation in 2020 exceeded +1°C. Seasonal anomalies
980 (Supplementary, Fig. S24) reveal a predominance of positive anomalies during the studied
981 period, with the highest value recorded in autumn 2020. Summer anomalies suggest a shift
982 toward positive deviations from the reference values, indicating persistent, though not uniform,
983 warming throughout the short study period (i.e., values always above 0°C). Regarding extreme
984 temperature events between 2010 and 2022, the absolute maximum temperature was 43°C
985 (recorded on December 24, 2019), and the absolute minimum was -7.6°C (on July 23, 2013)
986 (SMN 2018a, 2021, 2023a). Furthermore, the SMN (2020) reported the occurrence of heatwaves
987 in Chilecito at the end of January 2020. Based on the criteria defined by Ministerio de Salud
988 (n.d.), similar conditions suggest that heatwaves likely occurred in January 2022 as well (e.g.,
989 January 1–3: minimum temperatures 22.6–23.5°C, maximum 39.1–40.8°C; January 9–16:
990 minimums 21.6–26°C, maximums 36.7–41.5°C), although these were not officially reported by

991 the SMN. During these periods, the temperature thresholds used by SMN (2020) to define the
992 2020 heatwave were simultaneously exceeded. These observations underscore the relevance of
993 continued climate and meteorological analysis in the region, a line of inquiry that extends
994 beyond the scope of this study. Nevertheless, the data presented herein provide a valuable
995 baseline for understanding climatic and meteorological conditions in the study area.

996 Among the major global changes currently underway (IPCC 2007; Farmer and Cooke 2013; IPCC
997 2021; NASA 2024; World Bank Group 2024), several are particularly relevant to the region
998 analyzed in this study: increasing temperatures, the rising frequency and intensity of extreme
999 weather events, and the reduction of both snow cover and mountain glaciers. Numerous studies
1000 have documented glacial recession across South America as a consequence of climate change
1001 (e.g., Francou et al. 2003; Vuille et al. 2003, 2008; Bradley et al. 2006; Vergara et al. 2007; Mark
1002 et al. 2010; Dussaillant et al. 2019; Abdel Jaber et al. 2019; Masiokas et al. 2020), although the
1003 specific manifestations and rates of change may vary by region. Other research highlights the
1004 influence of climate change on wildfires (e.g., Tolmé 2004; Fried et al. 2004; Keller and Blodgett
1005 2004). These climatic shifts may lead to serious, challenging, and potentially irreversible
1006 consequences for both ecosystems and human populations, with global-scale implications
1007 (Heinzenknecht et al. 2018; Armstrong McKay et al. 2022)—for example, impacts on agricultural
1008 productivity, water availability, and public health (Raju and Kumar 2018; FAO 2021; IPCC 2021,
1009 2022; World Bank Group 2024). Accordingly, these issues require detailed investigation,
1010 continuous monitoring, and comprehensive understanding, enabling society to prepare for and
1011 adapt to possible future changes and even climate-related disasters.

1012 Climate change projections for various timeframes and emission scenarios (Secretaría de
1013 Ambiente y Desarrollo Sustentable de la Nación 2015; Copernicus Climate Change Service 2024;
1014 World Bank Group 2024) indicate an increase in surface temperatures in the study area,
1015 corresponding to different levels of global warming. These projected temperature changes are
1016 expected to significantly impact both cryospheric components—such as seasonal snow cover,
1017 permanent ice masses, and numerous mountain permafrost landforms (Taillant 2012; Instituto
1018 Argentino de Nivología, Glaciología y Ciencias Ambientales 2018; Fucks et al. 2018; Corbat et al.
1019 2020; Juárez et al. 2022b)—and the frequency and intensity of extreme heat events. The
1020 cryospheric features mentioned are particularly relevant to the region, as they function as
1021 critical sources and natural reservoirs of water (Taillant 2012). Consequently, they must be
1022 considered within the broader context of declining snow and ice in mountain environments
1023 (Huss et al. 2017; Slaymaker and Embleton-Hamann 2018; Abbott 2020) and the growing
1024 competition for water resources. However, it is essential to acknowledge the inherent
1025 uncertainties associated with climate projections, as they involve complex interactions among
1026 multiple variables over time.

1027 Another area of particular relevance in the context of socio-environmental interactions is the
1028 section of the so-called “Qhapaq Ñan” (Main Andean Road) located within the province of La
1029 Rioja, which was designated a UNESCO World Heritage Site in 2014 (Lumbreras Salcedo et al.
1030 2020; Sosa et al. 2020; Revuelta 2023). In addition, near the northeastern sector of the locality
1031 of Chilecito lies the “Tambería del Inca” archaeological site, which currently exhibits a significant
1032 degree of deterioration, despite having been declared a National Historic Monument in 1970
1033 (Ruarte 2015; Decree No. 1373/1970). The preservation of these culturally significant sites is
1034 increasingly threatened by various environmental and anthropogenic pressures that affect, or
1035 could potentially affect, the integrity of the surrounding landscape. Effective conservation

strategies should therefore consider these threats to ensure the long-term protection of this cultural heritage.

5. Integrated approach

The availability of information regarding the location, frequency, and effects of past and ongoing processes with destructive potential is essential for understanding their dynamics, evaluating their behavior, mitigating their impacts, and establishing strategies that promote human adaptation to the natural environment, ultimately reducing its degradation. However, the available data on this subject remain limited. As noted by Stallings (2017) in a broader context, even obtaining a description of baseline conditions or patterns for comparative purposes is difficult, which hinders the identification of anomalous behaviors. Further coordinated and sustained research is required to address these environmental challenges with greater precision. This includes the development of longer and more consistent data series, the enhancement of monitoring efforts, the integration of surface and subsurface survey techniques, and the application of remote sensing tools—such as synthetic aperture radar—to assess surface roughness and ground deformation. Equally important is the regular updating of information and its broad dissemination to ensure effective environmental assessment and informed decision-making.

The multi-instrumental and integrated approach implemented in this study—including the review and assessment of scientific literature, technical reports, legal documents, newsletters, direct field observations, hydrological and meteorological gauge data, and remote sensing-based methodologies—represents a significant advancement in the detection and analysis of natural hazards and socio-environmental conflicts in the study area. This analysis demonstrates that the region is exposed to various types of hazardous phenomena—meteorological, fluvial, mass movement, and seismic—with differing characteristics and variable socio-environmental impacts. The consequences of such events depend on several factors, including their magnitude and intensity, the nature of the affected materials, the location of occurrence, the surrounding morphological conditions, and the proximity to populated areas, settlements, or critical infrastructure such as transportation routes. Although recorded instances of damage or disruption within the study area are limited, the identified hazards and the associated potential risk are considerable and warrant close attention.

Most of the natural hazards identified in the study area—such as wildfires, mass movement processes, floods, and gully formation—are closely linked to climatic variables, vegetation cover, and topography. These phenomena are further exacerbated by anthropogenic activities that alter the physical environment and intensify the complexity of the human–nature relationship. Changes in land cover and land use driven by human action, alongside the spatial expansion of productive activities over recent decades, have contributed to an increased incidence of land degradation processes. Consequently, and in light of projected climate change scenarios, environmental resources are expected to become increasingly constrained. This will likely intensify not only the existing environmental challenges identified both in the study area and globally, but also the future difficulties associated with achieving a balanced interaction between society and nature, particularly under the framework of sustainable development. As an illustrative example, the rising demand for water—driven by population growth and industrial expansion—has further deepened the imbalance between limited water availability and its increasing consumption. This dynamic not only deteriorates water quality and reduces its

supply, but also has broader environmental repercussions and implications for socio-economic development.

Although certain control and mitigation strategies have been implemented to reduce the potential negative impacts on the socio-environmental system within the study area—such as rigid concrete walls, gabions, and wire mesh structures—, these actions serve primarily as warnings rather than complete solutions. The inherent unpredictability of interacting endogenous and exogenous processes significantly limits the ability to anticipate their timing and precise location. The spatial and temporal variability that characterizes these processes, along with their capacity to trigger cascading events, reflects the dynamic nature of the environment. This dynamic not only influences landscape evolution but also affects the vulnerability and adaptive responses of exposed populations. For instance, since the highest rainfall volumes are concentrated during the summer and typically occur as torrential rains, a substantial increase in the discharge of permanent rivers is expected during this season. Furthermore, also ephemeral streams and dry riverbeds, which remain inactive for most of the year, may experience significant surface runoff, leading to processes such as fluvial erosion, channel avulsion, and sediment-laden flash floods. Similar dynamics have been documented by Perucca and Paredes (2005) and Esper Angillieri (2007) in the province of San Juan. Consequently, infrastructure and activities located on floodplains are susceptible to damage from such events, particularly when these areas are reoccupied by active watercourses—as also emphasized by Abbott (2020), among others. Although the available data for the study area do not permit the identification of direct hydrometeorological correlations, the critical role of water input in triggering hazardous exogenous processes is evident. This analysis underscores the importance of understanding both natural and anthropogenic drivers of landscape change, recognizing their potential interrelationships, and prioritizing long-term monitoring to inform a comprehensive and adaptive risk management strategy. Furthermore, it must be acknowledged that multiple hazards may occur simultaneously, giving rise to complex and compounding scenarios.

This analysis contributes to understanding the current situation and identifying priority topics that require further attention in light of future scenarios, with potential implications for both socio-economic activities and the environment. A growing understanding of hazardous processes, their regional impacts, and the socio-environmental conflicts within the area is paramount for improving future risk assessments. These assessments are inherently complex due to the challenge of evaluating the three core components of risk—vulnerability, exposure, and hazard. Moreover, the integration of these components involves intricate and often interactive dynamics. This complexity can be mitigated through the systematic collection and critical analysis of comprehensive evidence within the study area. Overall, this research represents a significant advancement in hazard identification and assessment. In this regard, it aligns with and supports current international priorities for disaster risk reduction and sustainable development planning (e.g., United Nations Office for Disaster Risk Reduction 2005; Banco Interamericano de Desarrollo 2015).

The findings of this analysis underscore its value as a foundational information for event documentation and database generation, a strategic instrument for territorial planning, and a vital tool for community alert and awareness-raising regarding the significant impacts posed by hazards and conflict-prone situations within the region. Accordingly, this study facilitates the effective utilization and management of generated information at the nexus of academic, social, and policy-making spheres, guided by principles of environmental sustainability. Furthermore, the employed methodologies—contingent upon the availability of data—demonstrate robust efficacy in detecting and elucidating individual events and their associated impacts (e.g., through

the integration of documented information, instrumental records, remote sensing data, change detection approach, and the identification of diagnostic features). Owing to their methodological reproducibility and operational simplicity, these approaches are well-suited for adaptation and application in other regions facing analogous environmental challenges.

6. Conclusions

Based on the analysis of meteorological, hydrological, seismic, and demographic data; review of journalistic reports and scientific studies documenting past events within the study area; as well as field surveys and interpretation of satellite imagery, various events and processes with adverse socio-environmental impacts were identified, alongside potential alert situations. Among the most significant environmental challenges, which this study brings to light, are flooding, wildfires, channel avulsions, gullying, mass movement processes (including soli-gelifluction, rockfall, toppling, landslides, and debris flows), seismic activity, land cover and land use changes, the presence of unmanaged waste disposal sites, and inefficient management of urban and industrial waste contributing to soil, air, and water pollution. While many of these issues are primarily governed by the natural characteristics of the region—such as geological, geomorphological, biological, and hydrometeorological factors—in certain cases, anthropogenic influences emerge as critical drivers. Indeed, the growth of the local population and expansion of human activities have intensified pressures on natural resources, giving rise to complex socio-environmental conflicts that warrant focused attention and management.

Therefore, this study—primarily analytical and awareness-oriented—represents a valuable contribution to the understanding of the region. It not only highlights critical fields that require further attention, but also supports evidence-based decision-making for the development of strategies aimed at reducing vulnerability to potential future impacts and scenarios. By providing an integrated and updated analysis of one of the key components for risk assessment, it reinforces the importance of accessible and evidence-based knowledge.

In this context, the study makes available relevant information to the broader community, emphasizing the role of both exogenous and endogenous geodynamic processes—often random and unpredictable—that may have socio-economic consequences. It also sheds light on current and emerging socio-environmental conflicts, which must not be underestimated. Furthermore, the research offers guidance for future environmental investigations and territorial planning efforts that contribute to the protection of the region and promote a sustainable interaction between society and its specific environmental characteristics, ultimately supporting regional socio-economic development.

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Data and material availability
The meteorological data used in this study are available from Servicio Meteorológico Nacional upon request. The data relevant to gauging stations are publicly available through the “Base de Datos del Sistema Nacional de Información Hídrica” (https://www.argentina.gob.ar/interior/secretaria-de-infraestructura-y-politica-hidrica/base-de-datos-hidrologica-integrada). The data that support the findings of this paper are freely available in “Mosaico de imágenes satelitales ópticas-Provincia de La Rioja" at https://www.ign.gob.ar/NuestrasActividades/SensoresRomotos/MosaicosSatelitalesOpticos (Instituto Geográfico Nacional [IGN], 2019), in Google Earth Pro®, in NASA data distribution hubs

and in Sentinel Hub EO Browser (https://apps.sentinel-hub.com/eo-browser/). The seismic data used are publicly available at Instituto Nacional de Prevención Sísmica ([INPRES], https://www.inpres.gob.ar/desktop/), Incorporated Research Institutions for Seismology ([IRIS], https://ds.iris.edu/ieb/) and United States Geological Survey ([USGS], https://earthquake.usgs.gov/earthquakes/map/) databases and was accessed on June 2025. Demographic data are available at Instituto Nacional de Estadística y Censos de la Republica Argentina ([INDEC], https://www.indec.gob.ar/indec/web) databases. Moreover, data of particular events or situations used for the study were obtained from news portals and local reports, all of which were cited in the text.

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