

# Understanding the Characteristics of 1996 Extreme Rainfall and Its Association with a Megalandslide in Podi Watershed, Central Sulawesi, Indonesia

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## ABSTRACT

*The 1996 Podi megalandslide in Central Sulawesi, Indonesia, occurred in a remote tropical watershed with limited data, causing severe geomorphic disturbance. Using Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) and post-event Landsat 5 imagery, this study reconstructs the hydrometeorological sequence preceding the event. Rainfall extreme indices from ETCCDI were analyzed to examine intensity, duration, and temporal distribution. Results reveal that September 1996 experienced prolonged dryness (Rx5day: 65 mm; Rx1day: 35–40 mm), which likely desiccated soils and reduced root–soil cohesion in the limestone–ophiolite terrain. In early October, rainfall intensified sharply (Rx5day: 216 mm; Rx1day: 113 mm), persisting until mid-November. The temporal overlap of antecedent dryness, intense rainfall, and fragile geology indicates a compound triggering mechanism. This study highlights how rainfall extremes contributed to slope failure in tropical montane watersheds and emphasizes the need for early warning frameworks integrating satellite-based rainfall and geological susceptibility in remote data-scarce regions.*

**KEYWORDS** : extreme rainfall, megalandslide, tropical watershed, CHIRPS, Central Sulawesi



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## INTRODUCTION

Landslides rank among the most devastating natural hazards worldwide, claiming thousands of lives and causing billions of dollars in economic losses each year. Among their triggers, extreme rainfall is both the most frequent and the most unpredictable, capable of destabilizing slopes within hours through rapid infiltration, increased pore-water pressure, and the sudden loss of shear strength [1]–[3]. In the context of a warming climate, the intensification of the hydrological cycle is driving more frequent, more intense, and more prolonged rainfall events [4], amplifying the risk of catastrophic slope failures even in areas historically considered stable.

From the steep volcanic slopes of Mexico to the coastal mountains of Brazil and the alpine terrain of Slovenia, case studies consistently reveal a critical interplay between rainfall magnitude, antecedent soil moisture, lithology, and human activity. In Mexico, rainfall exceeding 100 mm per day has repeatedly breached empirical thresholds for slope failure, particularly in areas where deforestation and mining have reduced slope resistance [2]. In Brazil, the March 2020 event displaced more than 2,800 people, with climate change estimated to have intensified rainfall totals by up to 42% [5]. In Slovenia, the August 2023 rainfall, among the heaviest in recorded history, triggered nearly 10,000 landslides, illustrating the destructive synergy of saturated soils and prolonged precipitation [3]. Although the expression of these events is site-specific, they share a universal lesson: rainfall alone is rarely sufficient to cause such disasters, as its impacts emerge through the interaction between the physical environment and human activities.

Historical rainfall analysis has proven indispensable in advancing this understanding. By reconstructing past extreme events, researchers have identified seasonal patterns, shifting rainfall regimes, and climatic thresholds that conventional risk assessments often overlook [6]. Yet, methodological challenges persist: localized extremes are frequently underestimated by satellite precipitation products, and seasonal variability is commonly ignored in statistical models [7]. These limitations are most pronounced in remote tropical watersheds, where instrumental records are sparse, terrain is inaccessible, and large-scale events occur so infrequently that each instance represents an irreplaceable opportunity for scientific insight.

One such opportunity lies in the 1996 megalandslide of the Podi Watershed, Central Sulawesi, Indonesia. This isolated upstream catchment, virtually untouched by human activity, experienced a catastrophic slope failure that reshaped the landscape and likely altered downstream hydrological regimes. Despite its scale and uniqueness, no comprehensive climatological and geological reconstruction has ever been conducted. The event thus remains a critical missing piece in our understanding of extreme rainfall and landslide dynamics in minimally disturbed tropical environments.

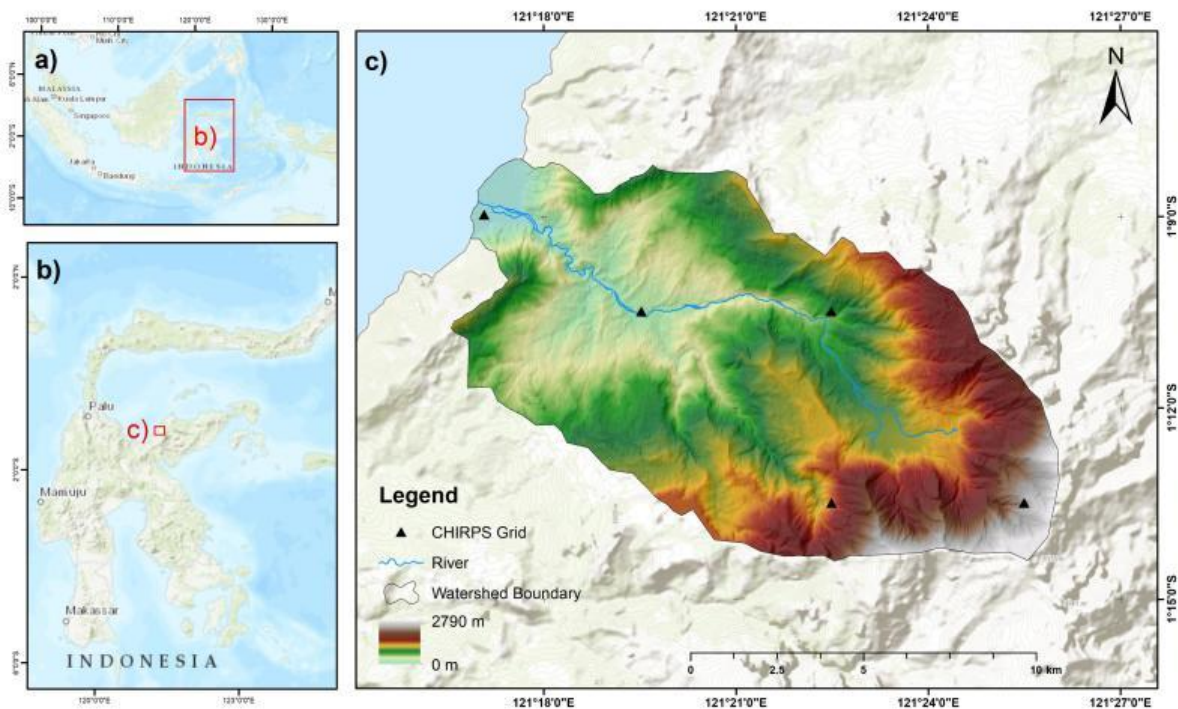
To address this gap, this is the first reconstruction that integrates historical climate data and geological evidence to understand tropical megalandslides occurring in areas with minimal human disturbance. This study aims to: (1) characterize the extreme rainfall conditions preceding the 1996 Podi megalandslide, (2) reconstruct the event sequence through the integration of historical rainfall records and geological evidence, and (3) provide insights to inform hazard management and climate resilience strategies in similarly remote, hazard-prone tropical regions.

## METHODS

### Study Area

The Podi Watershed (DAS Podi) is situated in Tojo Una-Una Regency, Central Sulawesi, Indonesia, draining northward into Tomini Bay (Fig 1). Covering a mountainous and remote tropical catchment, the area is characterized by steep slopes exceeding 40%, dense primary and secondary forest, and minimal anthropogenic disturbance, making it an ideal natural laboratory for studying rainfall-landslide interactions in undisturbed settings. The climate is humid tropical with mean annual rainfall exceeding 2,500 mm, with peaks during transitional monsoon periods that often bring short-duration, high-intensity storms. Geologically, the watershed is underlain by a complex assemblage including the Salodik Formation (limestone), Bongka Formation (conglomerate and sandstone), and an extensive Ultramafic Complex dominated by ophiolite sequences, all of which contribute to varied slope stability conditions. The 1996 megalandslide originated in the upper catchment where fragile lithology, high

slope gradients, and saturated soil conditions from antecedent rainfall created critical instability. This geomorphic and climatic setting, combined with rapid hydrological response during extreme rainfall events, results in high susceptibility to large-scale mass movements, debris flows, and associated downstream sediment hazards. Recent spatial analyses in the broader Tomini Bay watershed region further highlight the relevance of erosion-prone zones in Central Sulawesi, with erosion hotspots concentrated in the mountainous areas and shifting patterns between 2000 and 2020, underscoring the importance of integrating spatial connectivity into hazard and rehabilitation planning [8].



**Figure 1.** Location on (a) Indonesia, in (b) Sulawesi, (c) Podi Watershed

## Datasets

This study employs daily rainfall data from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), a quasi-global rainfall product with a spatial resolution of  $0.05^\circ$  (5 km) and a temporal coverage from 1981 to the present. CHIRPS merges satellite-based infrared precipitation estimates with in-situ station observations, providing bias-corrected rainfall data that is particularly valuable in data-sparse regions such as the Podi Watershed in Central Sulawesi. Previous studies have demonstrated the accuracy and reliability of CHIRPS, showing a strong correlation with ground-based measurements, with correlation coefficients reaching 0.98 in periodic models [9], and adequate performance in reproducing rainfall amounts in various climate zones [10]. Its applicability in hydrological modeling has been validated, including in flood-prone and watershed management contexts [11], [12], and it has proven useful for rainfall mapping and risk assessment in areas with limited monitoring infrastructure [13]. In this research, CHIRPS daily data for grid cells covering the Podi Watershed were extracted to reconstruct the rainfall conditions preceding and during the 1996 megalandslide event, enabling a detailed temporal analysis despite the absence of long-term local rain gauge records. To

complement the rainfall analysis, Landsat 5 Thematic Mapper (TM) imagery in color-infrared composite was utilized to assess pre- and post-event land cover conditions. This imagery enabled the identification of vegetation loss, bare soil exposure, and debris deposition patterns, providing spatial evidence of the geomorphic and environmental changes resulting from the 1996 megalandslide.

### Rainfall Extreme Indices

In this study, extreme rainfall characteristics for the 1996 event in the Podi Watershed were quantified using a set of indices recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI) (see table 1) and computed with the ClimPACT2 software [14]. Daily CHIRPS rainfall data were processed to derive: (1) Simple Daily Intensity Index (SDII), representing the average rainfall intensity on wet days; (2) R99p, the total rainfall from days exceeding the 99th percentile threshold; (3) Consecutive Wet Days (CWD), indicating the longest sequence of days with rainfall  $\geq 1$  mm; (4) Consecutive Dry Days (CDD), indicating the longest sequence of days with rainfall  $< 1$  mm; and (5) Rx1day, Rx3day, and Rx5day, representing the maximum 1-day, 3-day, and 5-day precipitation totals, respectively. These indices capture different aspects of rainfall extremes, from short-duration high-intensity events to prolonged wet spells, both of which can critically influence slope saturation and landslide initiation. The standardized ETCCDI framework ensures that the derived metrics are comparable with other regional and global studies, thereby enhancing the robustness of the analysis and its relevance for disaster risk assessment in remote tropical watersheds.

**Table 1.** Definitions and units of extreme rainfall indices used in this study

Category	Index	Definition	Unit
Intensity	Rx1day	Maximum 1-day precipitation amount in a year	mm/day
	Rx3day	Maximum 3-day precipitation total in a year	mm/3 days
	Rx5day	Maximum 5-day precipitation total in a year	mm/5 days
	SDII (Simple Daily Intensity Index)	Average precipitation on wet days (days with $\geq 1$ mm)	mm/day
	R99p	Total precipitation from days exceeding the 99th percentile threshold	mm/year
Duration	CWD (Consecutive Wet Days)	Maximum number of consecutive days with precipitation $\geq 1$ mm	days
	CDD (Consecutive Dry Days)	Maximum number of consecutive days with precipitation $< 1$ mm	days
Frequency	R99p	Number of days exceeding the 99th percentile threshold (alternative frequency measure)	days/year
	R95p	Number of days exceeding the 95th percentile threshold (alternative frequency measure)	days/year

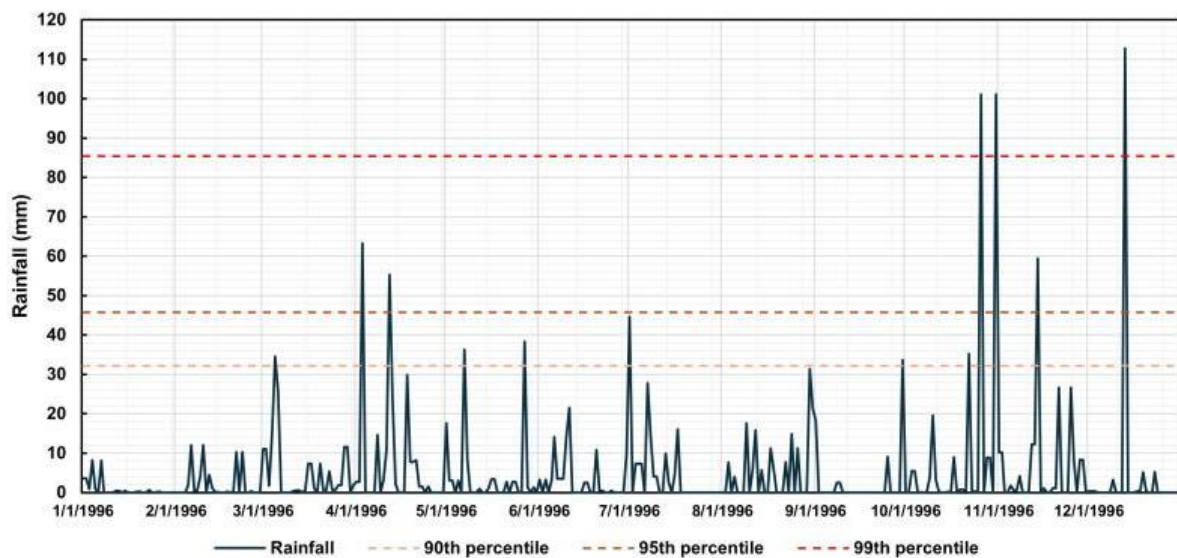
All extreme rainfall indices were computed using ClimPACT2, a software package developed by the Expert Team on Climate Change Detection and Indices (ETCCDI). The procedure consisted of: (1) extracting daily CHIRPS rainfall data for grid cells covering the Podi Watershed, (2) determining percentile-based thresholds (95th and 99th percentiles) using the 1981–2024 climatological reference period, (3) calculating intensity indices (Rx1day, Rx3day, Rx5day, SDII), duration indices (CDD, CWD), and frequency indices (R95p, R99p), and (4) performing data quality checks to ensure no missing or anomalous values. This standardized framework ensures comparability with regional and global studies and enhances the robustness of extreme rainfall characterization in data-scarce tropical watersheds.

## RESULTS AND DISCUSSION

### Results

#### Characteristics of Rainfall Extreme in 1996

Analysis of daily CHIRPS rainfall data for 1996 revealed several notable extreme rainfall events in the Podi Watershed. Throughout the year, three rainfall events exceeded the 95th percentile threshold (55–63 mm/day), occurring twice in April and once in November. More intense extremes were observed for the 99th percentile threshold, with three events recorded: at the end of October, in early



**Figure 2.** Daily Rainfall with extreme threshold in 1996

November, and in mid-December, producing daily totals between 100 and 113 mm. The temporal distribution of these events indicates two distinct periods of heightened rainfall intensity, the first during the transition from the wet to dry season (April) and the second in the late dry to wet season transition (October–December). This pattern suggests the influence of seasonal atmospheric circulation changes, potentially linked to regional monsoon dynamics. The daily rainfall time series with superimposed 95th and 99th percentile thresholds is presented in Figure 2, highlighting the magnitude and timing of these extreme events. Such high-intensity rainfall episodes, particularly those in October–December, are likely to have contributed to soil saturation and the initiation of the 1996 megalandslide in the Podi Watershed.

On a monthly scale, variability in extreme rainfall is clearly illustrated in Figure 3. The highest values of Rx5day, Rx3day, and Rx1day occurred in October, November, and December, while the lowest were recorded in February and September. In September, Rx5day reached only 65 mm, with Rx3day and Rx1day at approximately 35–40 mm, indicating relatively dry conditions. In contrast, October marked the peak extremes of the year, with Rx5day reaching 135 mm, Rx3day 115 mm, and Rx1day 100 mm. This sharp contrast between the dry conditions of September and the intense rainfall extremes of October underscores a rapid shift in hydrometeorological conditions. Such an abrupt increase in multi-day rainfall totals in October 1996 is a strong indicator of the hydrological stress that likely played a critical role in triggering the late-October megalandslide in the Podi Watershed.

Spatial patterns of the extreme rainfall indices SDII, R99p, CWD, and CDD for 1996 are presented in Figure 4. The SDII values show higher rainfall intensity in the downstream area, reaching 12–13

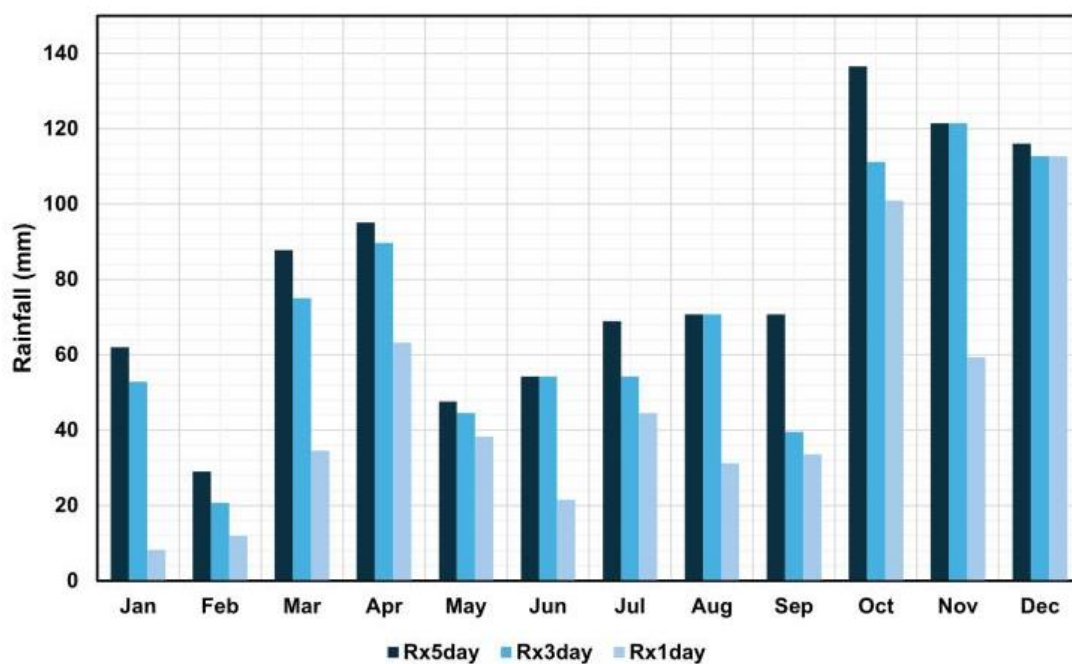
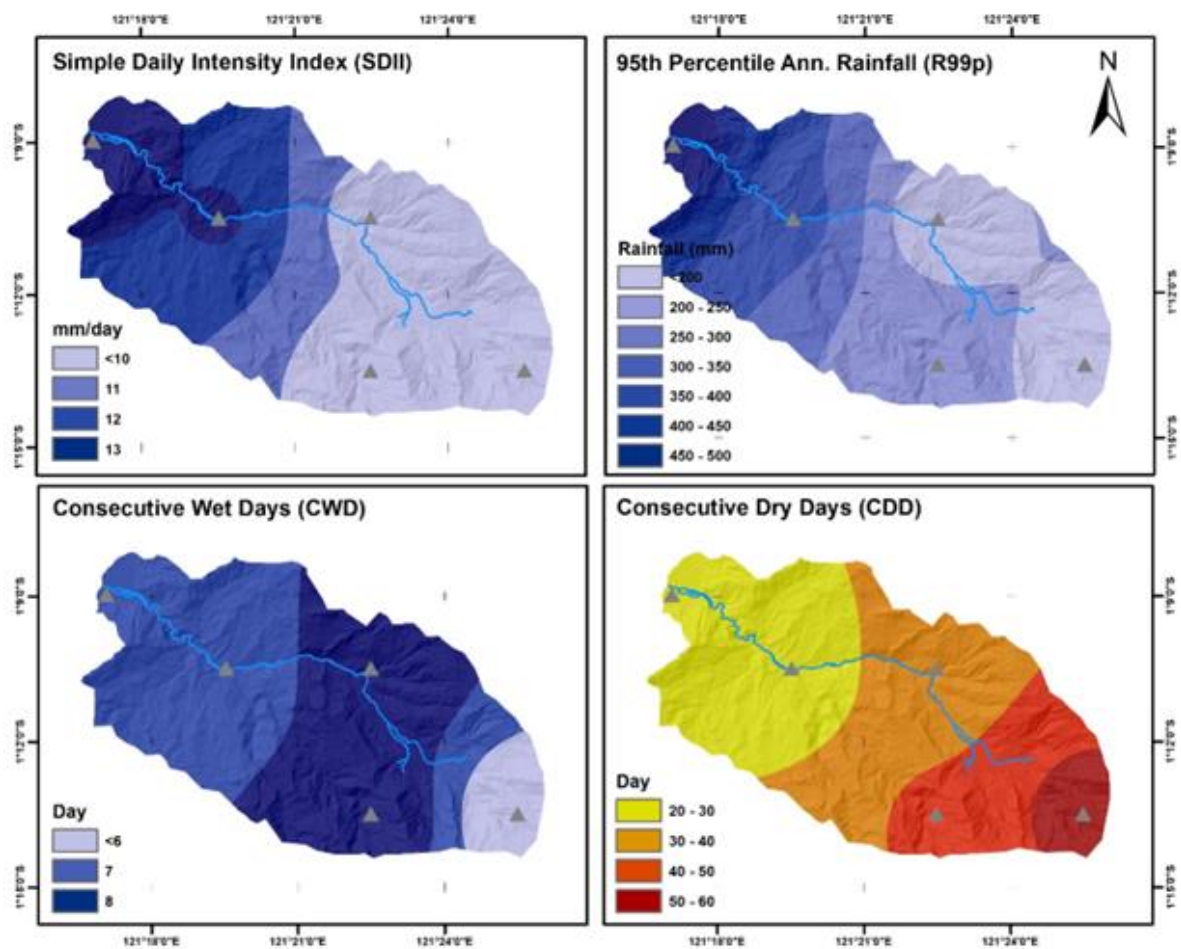


Figure 3. Monthly rainfall extreme with in 1996

mm/day, while the upstream region recorded less than 10 mm/day. Similarly, annual R99p was greater in the downstream section, with totals of approximately 400–500 mm, compared to only 200–300 mm in the upstream area. In terms of CWD, the middle-stream region experienced the longest consecutive wet days, averaging 8 days, followed by 7 days in the downstream and 6 days in the upstream area. Conversely, CDD patterns indicate that the upstream region endured substantially longer consecutive dry periods, ranging from 50–60 days, whereas the downstream experienced only 20–30 days. These spatial contrasts are strongly influenced by the watershed's topography and morphology, where the downstream section is flanked by two mountain ranges that promote more frequent and intense rainfall, while the upstream area lies in a rain shadow zone, receiving less precipitation overall.

### Megalandslide Event based on Imagery

Composite color-infrared imagery from Landsat 5, as shown in Figure 5, clearly illustrates the landscape transformation associated with the 1996 megalandslide event. Prior to the landslide, the



**Figure 4.** Map of extreme rainfall indices with SDII, R99p, CWD, and CDD in 1996

upstream area of the Podi watershed was predominantly covered by dense vegetation, indicated by the strong red tones in the infrared composite, reflecting healthy plant biomass. However, post-event imagery reveals a drastic change in the same area, where extensive vegetation loss has left large patches of bare soil and exposed rock surfaces, signifying the source zone of the landslide. This loss of vegetation cover not only reflects the magnitude of slope failures but also indicates severe disturbance to the local ecosystem. In the downstream section, the imagery shows evidence of widespread debris deposition, which extended into the floodplain and settlement areas. Historical accounts corroborate that this debris flow swept through villages, causing extensive damage to housing and agricultural land, further emphasizing the far-reaching impacts of the megalandslide.

## Discussion

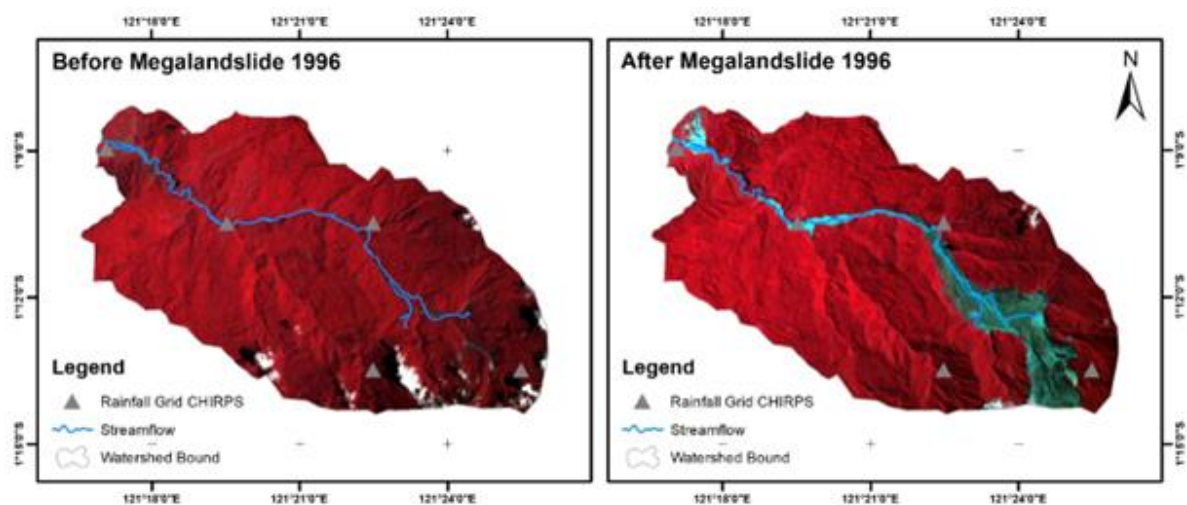
The 1996 Podi megalandslide followed a clear hydrometeorological sequence, captured in CHIRPS-based rainfall records and confirmed by post-event satellite imagery. In September 1996, prolonged dryness (Rx5day: 65 mm; Rx1day: 35–40 mm) likely desiccated soils, weakened root–soil cohesion, and promoted shrinkage cracks. In tropical montane settings, such cracks act as preferential infiltration pathways during subsequent storms, accelerating subsurface wetting [15]. In the lithological context of the Podi Watershed, the mechanism of shrinkage cracks is highly relevant. The landslide

initiation zone is dominated by the Salodik Formation (limestone) and ultramafic–ophiolitic complexes, both of which are characterized by intense weathering, high porosity, and fracture development. In limestone terrain, prolonged dryness such as that observed in September 1996 (Rx5day: 65 mm; Rx1day: 35–40 mm) leads to soil desiccation and the formation of surface desiccation cracks on the carbonate weathering mantle. Meanwhile, in weathered ultramafic materials, extreme drying induces contraction of the serpentinized soil matrix, promoting vertically oriented shrinkage fractures that act as rapid infiltration pathways. These shrinkage cracks significantly accelerate percolation into deeper horizons once intense rainfall occurred in October, increasing pore-water pressures and hastening the reduction in shear strength that contributed to slope failure.

Early to mid-October marked a priming phase with moderate but above-normal rainfall. Several days exceeded the 90th percentile yet remained below local failure thresholds. These events gradually saturated the upper soil profile and allowed infiltration into deeper horizons. This type of sub-threshold conditioning has been observed in Mexico, where moderate storms increased slope susceptibility ahead of more intense rainfall [2]. Such historical analyses are critical for understanding the disaster process, as they help identify temporal patterns, seasonality, and potential thresholds for slope failure [6], [7].

Failure conditions developed in late October when a cluster of storms exceeded the 99th percentile (100–113 mm/day). These short-duration but intense bursts rapidly increased pore-water pressures, driving slopes from partial to full saturation. In colluvial and weathered bedrock, such saturation reduces effective stress and shear strength, triggering rapid collapse. This mechanism is consistent with catastrophic events in Baixada Santista, Brazil, where anthropogenic climate change has been shown to increase the probability and severity of rainfall-triggered landslides [5]. Compared to September, October's Rx5day doubled and Rx1day tripled, indicating a sharp hydrological escalation toward a tipping point.

Spatial patterns of extreme rainfall indices reveal the geomorphic context of the disaster. Downstream sectors received higher totals (SDII: 12–13 mm/day; R99p: 400–500 mm) due to orographic enhancement from flanking mountain ranges, while the upstream initiation zone lies in a relative rain shadow. Under typical conditions, this upstream area remains drier; however, in 1996 even modest increases in intensity exceeded local infiltration and drainage capacities. The short consecutive wet periods (CWD: 6 days) in the initiation zone indicate that intense, short-lived storms were the main



**Figure 5.** Pre and Post megalandslide composite color-infrared imagery from Landsat 5 in 1996

trigger, similar to the August 2023 event in Slovenia, where high antecedent soil moisture preceded widespread landslides [3]. These observations align with broader evidence that extreme rainfall is a primary trigger for landslides in diverse settings, from Puebla, Mexico [2], to Pakistan, where over 50% of recorded landslides are rain-induced [4].

Post-event Landsat 5 imagery confirms these dynamics. Upstream initiation zones show a transition from dense vegetation to extensive bare soil, while downstream floodplains display debris deposition. This multi-phase hazard chain amplified downstream impacts, illustrating the interplay between atmospheric triggers, geomorphic susceptibility, and land cover. Similar interactions have been reported in Mibei Village, China, where vegetation increased infiltration capacity, leading to instability during extreme rainfall [16].

Overall, the Podi case reinforces a global insight: extreme rainfall alone seldom triggers landslides. Instead, outcomes emerge from the compound interaction of antecedent hydrological conditions, storm sequencing, geomorphic setting, geological characteristics, and seasonal atmospheric dynamics [17], [18]. What makes this case distinctive is its documentation in a remote tropical watershed with minimal human disturbance. Combining high-resolution rainfall monitoring, percentile-based extreme indices, and post-event remote sensing proves effective for understanding slope failures in similarly data-scarce environments [19], [20].

Nevertheless, several limitations remain. CHIRPS data provide valuable spatial-temporal coverage but require correction and validation with ground-based observations to improve accuracy, especially for localized extremes [7]. This study also focused primarily on rainfall variability and watershed morphology, without fully integrating geological parameters such as lithology, fault structures, slope material properties, and degree of weathering [21]. A multidisciplinary approach integrating hydrological, geological, and geotechnical analyses would offer a more complete understanding of the 1996 event and strengthen hazard assessments in similar environments.

## CONCLUSION

This study characterized the extreme rainfall conditions preceding the 1996 Podi megalandslide, identifying a sequence of prolonged antecedent dryness, moderate priming rainfall, and short-duration but intense storms exceeding the 99th percentile. The event was marked by a sharp escalation in both  $Rx5day$  and  $Rx1day$  values, with spatial variability showing downstream orographic enhancement and upstream initiation under relatively shorter wet periods. This temporal and spatial pattern strongly correlates with the landslide sequence observed in the Podi Watershed, where antecedent moisture deficits, rapid saturation from extreme rainfall, and the geological setting of colluvial and weathered bedrock combined to reduce slope stability. The findings reinforce that extreme rainfall alone is insufficient to trigger catastrophic slope failures; rather, it is the interaction of hydrometeorological, geomorphic, and geological factors that determines outcomes.

For hazard management in similarly remote and data-scarce watersheds, the results underscore the importance of continuous monitoring using validated extreme rainfall indices, integrating antecedent moisture conditions, and incorporating geological assessments. Such an approach can improve early warning capabilities and strengthen climate resilience strategies for high-risk tropical mountain environments.

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