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Transformations in Exposure to Debris Flows in Post-Earthquake Sichuan, China

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Abstract. Post-earthquake debris flows can exceed volumes of $1 \times 10^6 m^3$ and pose significant challenges to downslope recovery zones. These stochastic hazards form when intense rain remobilises coseismic landslide material. We investigate the relationship between changing exposure and hazard of post-2008 debris flows in three gullies in Sichuan province, China. These were selected based on the number of post-earthquake check dams – Cutou (2), Chediguan (2) and Xiaojia (none). Using high resolution satellite images, we developed a multitemporal building inventory from 2005 to 2019, comparing it to spatial distribution of previous debris flows and future modelled events. Post-earthquake urban development in Cutou and Chediguan increased exposure to a major debris flow in 2019 with inundation impacting 40% and 7% of surveyed structures respectively. We simulated future debris flow runouts using LAHARZ to investigate the role of check dams in mitigating three flow volumes – $10^4 m^3$ (low), $10^5 m^3$ (high) and $10^6 m^3$ (extreme). Our simulations show check dams effectively mitigate exposure to low and high flow events but prove ineffective for extreme events with 59% of buildings in Cutou, 22% in Chediguan and 33% in Xiaojia significantly affected. We verified our analyses through employing a statistical exposure model, adapted from a social vulnerability equation. Cutou's exposure increased by 64% in 2019, Chediguan's by 52% whilst only 2% for Xiaojia in 2011, highlighting that extensive grey infrastructure correlates with higher exposure to extreme debris flows, but less so to smaller events. Our work suggests the presence of check dams increases the perception of exposure reduction downstream, however, ultimately produces a levee effect that raises exposure to large events.

Keywords
Debris Flows, Built Environment, Exposure, Check dams, LAHARZ.

1. Introduction

Major earthquakes such as the 1994 M_w 6.8 event in Northridge, California (Harp and Jibson, 1996) and the 1999 M_w 7.3 earthquake in Chi-Chi, Taiwan (Liu et al., 2008) have triggered chains of hazards, that increase the exposure of local communities to secondary hazards for many years after the initial disaster. Following the 2008 M_w 7.9 Wenchuan earthquake in Sichuan, China, debris flows occurred more frequently and at a higher magnitude ($>1 \times 10^6$ m^3) after the earthquake compared to flows before the earthquake (Cruden and Varnes., 1996; Cui et al., 2008; Huang and Li., 2009; Guo et al., 2016; Thouret et al., 2020). Increased debris flow frequency impacts vulnerable communities and local infrastructure, potentially reshaping the demographic and structural landscape of previously rural regions (Chen et al., 2011). The frequency of post-seismic flows is heavily influenced by sediment availability which is often controlled by coseismic landslide distribution, hydrology, and slope (Horton et al., 2019). The ready transformation and remobilisation of seismically loosened deposits into water-laden sediments leads to a heightened probability of debris flow hazard for extended periods, further exacerbating the potential impacts felt by these areas (Costa et al., 1984; Huang & Li, 2014; Fan et al., 2019b).

Post-seismic debris flows affect the expanding built environment and communities located in the flat land that forms along floodplains and on debris and alluvial fans. In addition to direct loss of life, debris flows repeatedly block and/or destroy rivers, roads, tunnels, and bridges, and damage property and agriculture, and loss of life (Chen, N et al., 2011). Buildings are highly susceptible to the impacts of debris flows (Hu et al., 2012; Zeng et al., 2015), with property damage responsible for nearly all impacts i.e., casualties and fatalities (Wei et al., 2018; Wei et al., 2022). Variations in construction material are a particularly important factor for structural resilience and vulnerability to debris flows (Zhang, S et al., 2018). Despite focus on building resilience and reducing vulnerability, post-earthquake regions are often areas of significant rebuilding and expansion of infrastructure so the exposure to debris flows changes rapidly in these areas. The development of critical infrastructure such as highways and tunnels further encourage the growth of the built environment and subsequent influx of people settling in areas exposed to geological hazards (Cruden and Varnes, 1996; Jiang et al., 2016).

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Check dams are a common form of risk mitigation for debris flows globally (Zeng et al., 2009; Peng et al., 2014; Cucchiaro, S. et al., 2019b), and one that is prevalent in post-earthquake Wenchuan (Chen, X. et al., 2015; Guo et al., 2016). Check dams store debris flow sediment, locally reduce channel slope, and are often permeable to affect debris flow hydrology. However, they have significant disadvantages such as requiring regular maintenance (to reduce sediment inputs) (Kean et al., 2018). The mitigation potential of these structures is contingent on their position along a channel, their height, amount of sediment fill, and their strength (which depends on the materials used for construction) (Dai et al., 2017). These factors evolve through time, meaning that the hazard mitigating factor of check dams varies through time and with unknown sign. The presence of check dams changes the downstream risk, primarily through changing the magnitude and frequency distribution of debris flows within the channel. For well-made check dams of sufficient volume to mitigate the largest debris flows, this can reduce the downstream risk of debris flows to negligible by effectively mitigating the entire hazard. However, in the case of the Wenchuan region, check dams are rarely large enough or regularly cleared of sediment to mitigate the largest debris flows, which can exceed 10^6 m^3-in volume.

The presence of check dams, particularly in drainage basins with a limited history of catastrophic debris flow events may affect the perception of risk downstream. They serve to stabilize, obstruct, drain, and/or halt the movement of flows (Hübl and Fiebiger., 2005; Chen et al., 2015). The perception that check dams have mitigated all hazards may promote the expansion of infrastructure into floodplains and debris fans. The increase of exposure is common on floodplains where the presence of flood control levees can promote building onto floodplains – a process that is called the levee effect (Collenteur et al., 2015). In the flooding example, the presence of levees reduces the frequency of small and medium sized floods, but when large floods occur that cause those levees to fail, heightened floodplain exposure can lead to higher damage, The effect of check dams on risk perception is less well understood. Anecdotal examples from the Wenchuan region (e.g.,, Hongchun, Taoguan gullies) show that large debris flow events in 2010, 2013 and 2019 caused significant damage despite the presence of check dams (Dai et al., 2017). However, it is not clear if the presence of check dams affected exposure relative to the large-scale expansion of infrastructure in the post-earthquake recovery phase.

This study seeks to understand the changing exposure to debris flows in post-earthquake Wenchuan communities. We compare the exposure of buildings to debris flow events in two neighbouring catchments containing check dams (Cutou and Chediguan) using a third, unmitigated gully as a control measure (Xiaojia). We compare post-2008 built environment growth across the 3 catchments and compare the potential exposure of infrastructure in each gully to debris flow events of different sizes.

2. Study Area: Sichuan Province, China

China's mountainous regions, including the Longmenshan, account for 69% of the country's land mass with over a third of the population living in these regions (Chen et al., 2011; He et al., 2022). 72% of this landscape suffers from debris flow activity. Between 2005 and 2018, estimates suggest over 800 debris flow occurrences each year (He et al., 2022; Wei et al., 2021). Of these, landslides dominate provinces in the North and debris flows are generally constrained to provinces in the South (Liu et al., 2018). The 2008 M_w 7.9 Wenchuan earthquake primarily impacted Sichuan province (Fig 1). The epicentre was located near Yinxiu, Wenchuan County, within the seismically active Longmenshan Fault Zone (Li et al., 2019). The shaking triggered around 56,000 landslides and displaced nearly 3 km^3 of loose material (Fan et al., 2018; Luo et al, 2020). In subsequent years, the unstable material has been reactivated as debris flows, many of which exceed -10^6 m^3 in mobilised volume (Frances et al., 2022). The risk from these debris flows has been compounded by increasing exposure due to China's rapid rural development programme, which includes the construction of roads, bridges, and industrial facilities (Tang et al., 2022).

Four significant episodes of debris flows occurred in the post-earthquake Wenchuan region in 2008, 2010, 2013 and 2019 (Tang et al., 2022; Fan et al., 2019b). Each event was associated with monsoon rainfall that occurred in different parts of the range. The largest flow surges, containing millions of cubic meters of sediment were located in the gullies along the Minjiang in Sichuan. Large scale flooding further amplified the impacts, for example in Yingxiu Town, Wenchuan County (Liu et al., 2016b). Debris flow events occurring post-earthquake often exhibit larger material volumes compared to flow events recorded prior to 2008. Horton et al., (2019) attributed the increase in flow volume to the large-scale displacement of sediment during the earthquake. The resulting increase in debris flow hazards necessitated, engineered mitigation measures to reduce risk levels in the basin communities (Tang et al., 2009; Huang et al., 2009; Huang, 2012).

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In this study we focus on three gullies along the Minjiang - Cutou, Chediguan and Xiaojia and debris flow events on August 20th, 2019, and 4th July 2011 (Fig 1). Cumulative rainfall on 20th August 2019 peaked at 83 mm in Cutou and 65 mm in Chediguan resulting in large debris flows measuring over $50\text{x}10^4$ m^3 in each gully. Cutou gully is known for its high frequency of post-seismic debris flows, which has been attributed to the total of $11\text{x}10^6$ m^3 coseismic deposits generated by the earthquake (Yan et al 2014). Although a check dam was built in 2011 to manage debris flow impacts in Chediguan gully a large damaging debris flow of $64\text{x}10^4$ m^3 occurred on 20 August 2019 and destroyed the drainage groove and G213 Taiping Middle Bridge (Li et al., 2021). The debris briefly blocked river flow in the Minjiang causing water levels to rise during flood peak. This led to flooding at the Taipingyi hydropower station located 200 m upstream.

Xiaojia gully, is a moderate debris flow hazard area based on limited past occurrences and has no existing engineered mitigation measures. Following a period of debris flow activity in 2010, and after a period of continuous heavy rainfall approximately 30,000m^3 of deposits were remobilised and transported along the channel to the gully mouth. This event led to a period of disruption on the S303 road from flooding (Liu et al., 2014).

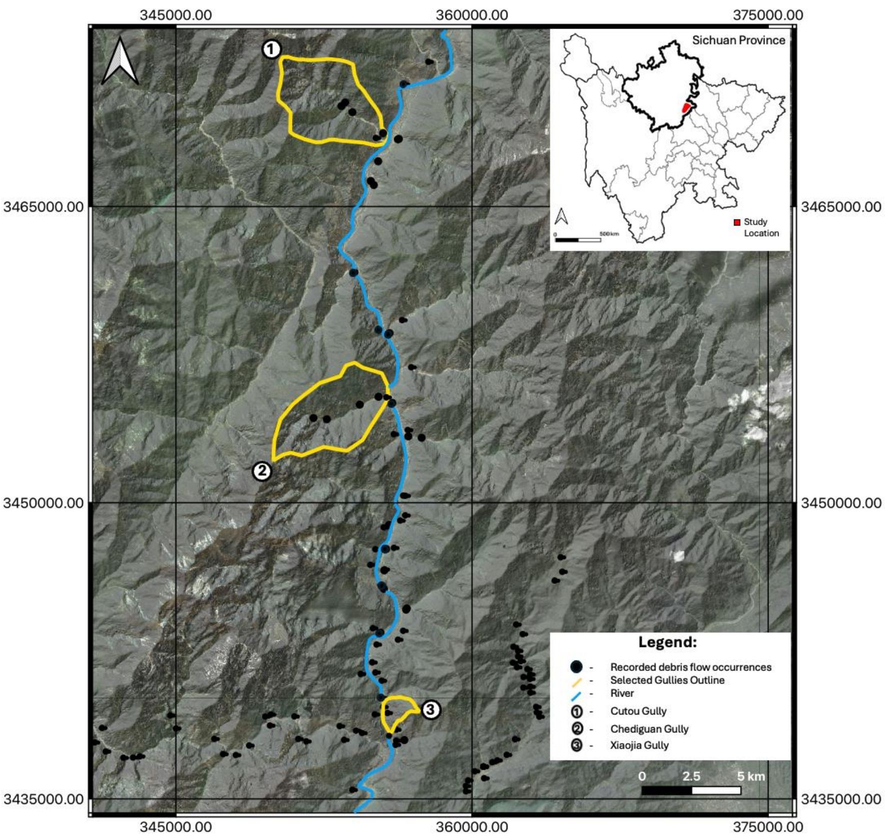

Figure 1: Location of the three gullies that form the focus of this study within Sichuan Province. Recorded post-2008 landslide occurrences are from the Wang et al. (2022) multitemporal datasets (© Google Earth 2019).

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3. Methodology

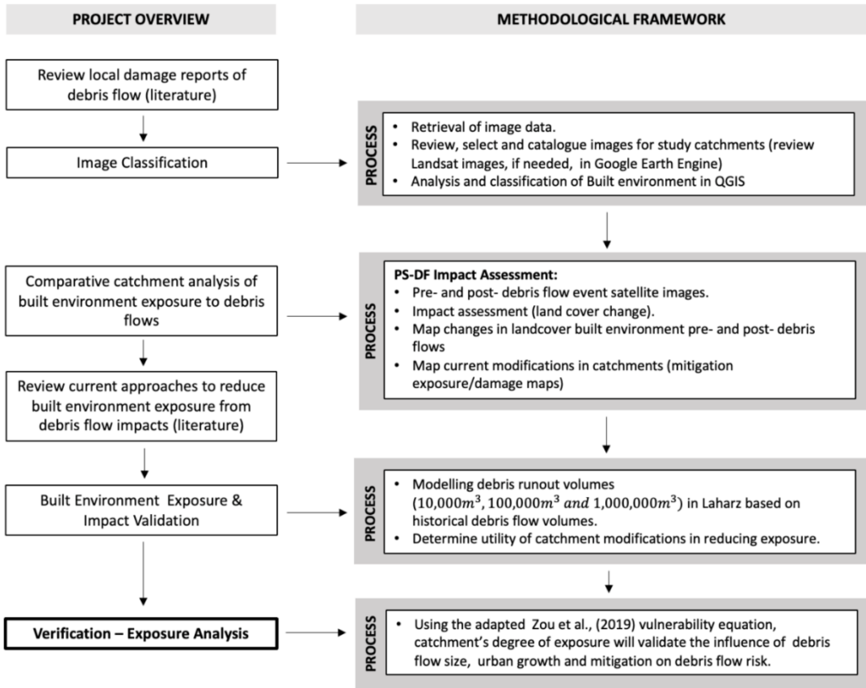

Figure 2: Schematic of our method. The key data sources comprise three multi-temporal datasets, including two from Fan et al. (2019a) covering debris flow and triggering rainfalls, as well as mitigation measures. The third dataset is adapted from Fan et al., (2019a) and highlights gully's with debris flow events post-2008 including information on the flow volume and presence of mitigation. Additional spatial data sources include aerial imagery from OpenStreetMap (OpenStreetMap contributors., 2023), World Settlement Footprint (World Settlement Footprint., 2019) and Shuttle Radar Topography Mission (SRTM) (Farr et al, 2007).

3.1 Data Classification

This study builds on existing multi-temporal debris flow datasets produced by Fan et al., (2019a). Dataset 1 has an aerial extent of 892 km^2 and presents the location and dimensions of debris flow events between 2008 and 2020. Dataset 2 presents a list of mitigative actions e.g., construction of check dams, taken between 2008–2011. We used an SRTM DEM to construct elevation profiles of Cutou, Chediguan and Xiaojia gullies to extract topographic characteristics to understand the mechanism of slope failure in the event of a rainfall-induced debris flow. These profiles facilitate morphological valley changes from debris flows to be identified. Through a comparative analysis of the 20th August 2019 debris flows in Cutou and Chediguan, we investigated the relative difference in land use change in the two gullies from 2008 to 2019, with a focus on changes before and after the 2019 flow event.

Landscape modification from 2005 to 2019 were mapped using high resolution (0.5 to 2.5m) satellite images (Table 1). We selected images with less that than 50% cloud cover and cross-referenced the mapped features with existing data sources in OpenStreetMap (OpenStreetMap contributors., 2023) and Dynamic World (Brown et al., 2022). Where satellite imagery was unavailable, we used aerial photos obtained from Google Earth, OpenStreetMap and World Settlement Footprint (World Settlement Footprint., 2019). It should be acknowledged that platforms like OpenStreetMap offer a regional view of Wenchuan rather than a detailed local-scale with mapping limited to main roads and 150 settlement polygons. However, this study's locations are unaffected by this due to their position next to the G213 national highway and G4217 road.

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Table 1 Satellite and aerial imagery used for data analysis and interpretation of the built environment

Data ID	Data Source	Acquisition Date	Resolution (m)
Aerial Satellite	Worldview (in QGIS – 'Satellite' XYZ tile)	2022	1.0
Satellite	Worldview (in Google Earth Pro., 2023)	10.12.2010 26.04.2011 03.04.2018 29.10.2019	1.0
Satellite	Planet	14.08.2019 24.08.2019	3.0
Satellite	Maxar Technologies (in Google Earth Pro., 2023)	09.09.2005 26.04.2011	3.0
Satellite	CNES/Airbus (in Google Earth Pro., 2023)	15.04.2015	1.0

We mapped features corresponding to human activities such as roads and properties. We highlighted at-risk zones in Cutou, Chediguan, and Xiaojia. We focus on spotlighting areas of high debris flow exposure in Cutou and Chediguan, comparing them with Xiaojia to evaluate the efficacy of check dams in mitigating potential debris flow hazards downstream of the dams.

3.2 Modelling Future Debris Flow Runout and Building Exposure

Both Cutou and Chediguan had check dams installed after the 2008 earthquake. We compared the impacts of 2019 debris flows in Cutou and Chediguan gullies with a 2011 debris flow event in the unmodified Xiaojia gully to identify the effectiveness of artificial dams in mitigating exposure to post-seismic debris flows. By using scenario modelling we identified at which point, does the size of the hazard, outweigh the mitigative capacity of the check dam to prevent overtopping. We mapped debris flows of differing scales within each of our three catchments using LAHARZ a GIS toolkit for lahar hazard mapping and modelling, developed by the USGS to visualise debris flow paths based on an empirical set of equations (Schilling., 2014; Iverson et al., 1998). The model provides an estimate of flow extent from a given initial material volume, and can account for various factors such as topography, slope and mitigative structures which generates more detailed data outputs when simulating future flow behaviour. For each catchment we simulated three flow sizes that represent the range of observed post-2008 earthquake debris flow volumes: $10^4\ m^3, 10^5\ m^3$ and $10^6\ m^3$. These volumes represent low, high, and extreme debris flows respectively based off of recorded post-seismic debris flow occurrences post-2008 documented in the Fan et al., (2019a) datasets. We note that there is not a strong understanding currently of what controls the maximum size of debris flows within Wenchuan catchments, hence we cannot attribute a particular probability to each scenario.

In the analysis of post-seismic debris flow, vulnerability assessment plays a crucial role (Lo et al., 2012). However, adapting traditional vulnerability methods which analyse inherent fragility and the potential loss of elements at risk, both attainable through remote practises, calculating exposure with minimal onsite data, remains a challenge. We adapted a vulnerability model by Zou et al. (2019) to quantify the extent of exposure to the built environment at our three sites, Cutou, Chediguan and Xiaojia.

Utilising satellite and/or aerial imagery and extracting spatial characteristics to identify both elements at risk as well as hazard-affected zones, our analysis facilitates the assessment of regional exposure without relying heavily on data collected onsite. Our model quantifies the susceptibility of the built environment to debris flow damage. The degree of exposure, E_{df}, is expressed as:

$$E_{df} = E_b \times C \pm M \tag{1}$$

E_b is the number of buildings damaged, and C is the fragility index of the elements at risk (Zou et al., 2019). Fragility values range from 0 to +1, with higher values indicating greater susceptibility to damage and/or failure. We assigned fragility values through using a mixture of literature and satellite images; buildings shown to be inundated or damaged in previous events or situated along the channel or gully mouth were given a value of 1, all other buildings were set a value of 0. The key difference between our method and that of Zou et al (2019) is the incorporation a modification factor, M, to account for the effectiveness of engineered measures like check dams in mitigating building damage and subsequent exposure. The addition of this factor brings an evaluative element

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to the exposure assessment, assigning values ranging from -1.0 to +2.0. For instance, gullies will be assigned a value of '+1' if modifications prove unsuccessful, '0' if no modifications are present, or '-1' if protection is offered by the mitigation measures. This approach, based upon the methodology proposed by Zou et al. (2019), allows for an assessment of exposure by considering both the physical resistance of buildings and the efficacy of mitigation efforts.

4. Results

4.1 Assumptions

In constructing the building inventory for Cutou and Chediguan, a comprehensive approach was taken to ensure accuracy and completeness. We used aerial and satellite imagery spanning 14 years, with a focus on mapping changes from 2011 to 2019. This involved careful analysis to delineate individual buildings, considering variations in size, shape, and spatial arrangement. Mapping efforts for Xiaojia were limited to 2010-2011 due to suboptimal image quality. Our approach incorporated assumptions regarding structural categorisation, including residential, industrial, and commercial buildings. These assumptions were informed by existing literature on local building typologies and architectural styles (Hao et al., 2013; Hao et al., 2012) and aerial photograph analysis from platforms such as Google Earth and Dynamic World. By amalgamating diverse information sources, we aimed to create a comprehensive inventory that correctly reflects the built environment of the study area.

Additionally, we used a 30-meter Digital Elevation Model (DEM) obtained from the SRTM dataset (Farr et al., 2007). However, it is necessary to acknowledge the limitations of this data, particularly its poor resolution and subsequent blockiness, which potentially hindered detailed topographical analysis. Despite this, the DEM provided valuable contextual information for understanding the terrain and its influence on building distribution and spatial patterns within the three sites. Furthermore, while using the empirical LAHARZ model for debris flow inundation mapping, we had to account for a degree of approximation in both aerial coverage and debris flow inundation due to the 30m resolution of the DEM file.

4.2 Mapping Post-Earthquake Risk

Analysis of satellite imagery from 2005 to 2019, and topographic profiles, reveals channel widening, deepening, aggradation, and deposition, likely attributed to the mobilisation of coseismic deposits and subsequent debris flow occurrences (Zhang et al., 2015; Wang et al., 2018) (Fig 3). These observations allowed us to determine the zones of erosion, transportation, and deposition for each gully and to track changes over time. Hydrological and geomorphological analysis examines landscape morphology to identify erosional and depositional features i.e., scarring, changes to river channel, sediment buildup (Fig 4). By integrating the above, we delineated erosion-prone areas, which permitted sediment transport routes to be approximated, and identify locations of sediment deposition along the hydrological profile.

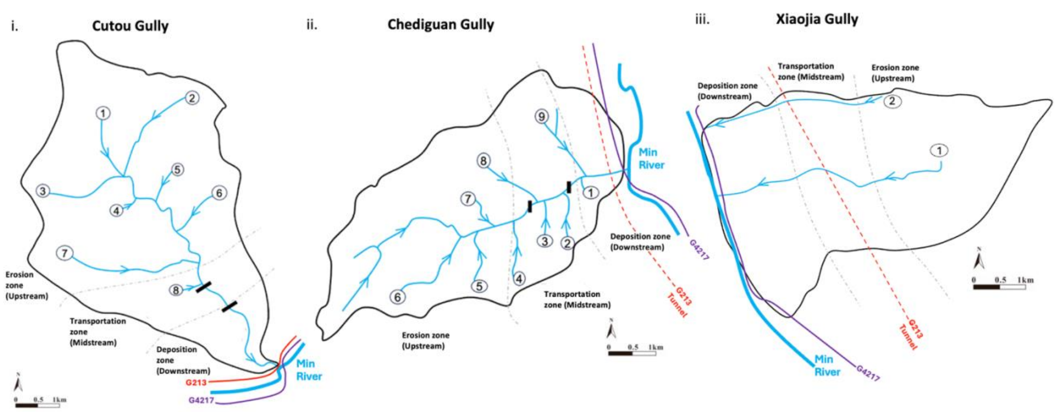

Figure 3: Hydrological profiles for the 3 study sites. Dam locations approximated for Cutou (i) and Chediguan (ii) based on a combination satellite imagery. Streams and main tributaries are numbered. Catchment profiles have been segmented into 3 zones – 'erosion', 'transportation' and 'deposition' and key infrastructure annotated

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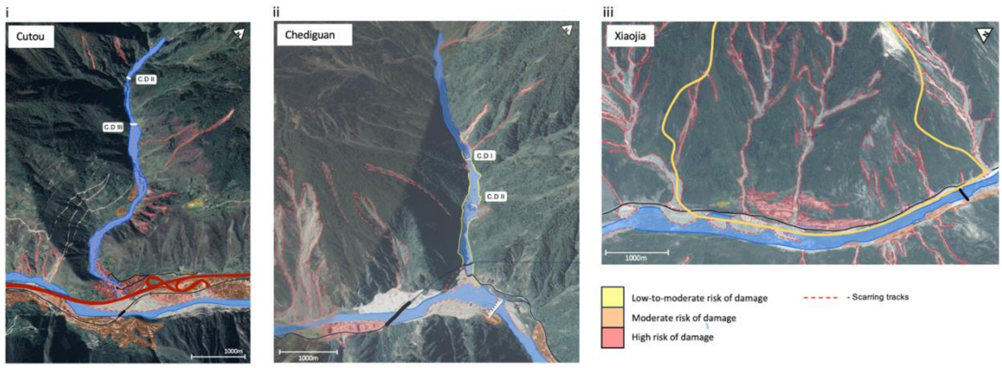

Figure 4: Satellite images of the 3 study locations highlighting areas of scarring from previous debris flow activity and areas of increased erosion (© Google Earth 2019)**.** Dam locations have been approximated for Cutou (i) and Chediguan (ii). The built environment has been shaded based upon risk of damage based upon proximity to areas of high erosion. Critical infrastructure has been added where appropriate: black like represents the G4217 road with the thicker sections representing bridges and the dashed lines, tunnels. The red line in (i) is the G213 Highway

In Cutou and Chediguan, deposition patterns shifted post-earthquake, particularly following the construction of check dams. Increased deposition occurs behind check dams compared to meander bends and basal slopes of the debris fan, demonstrating the effective sediment trapping of the check dams (Wang et al., 2019). Regarding the erosion patterns in Xiaojia, we observed common patterns in the upper gully sections at higher elevations, with deposition occurring at the basal slopes. This is due to the absence of structural alterations to the channel, permitting sediment to be transported to the channel and subsequent river outlet directly. The deposition patterns in Cutou and Chediguan, are strongly controlled by the distribution of check dams, in the middle and downstream portions of the catchment (Wang et al., 2019). The complex interplay between natural and anthropogenic factors demonstrates the dynamic evolution of risk in post-earthquake catchments and highlights the role of check dams in both mitigating and potentially exacerbating risk.

The landscape morphology prior to the 2008 earthquake was marked by extensive vegetation (over 70% of land cover) and minimal permanent engineered features. Cutou gully contained a widespread distribution of buildings along both the mid and lower slopes. Figure 5 shows the growth of the built environment between 2005 and 2019 in Cutou and Chediguan and between 2010 to 2011 in Xiaojia. The built environment in Cutou is concentrated within the transportation and deposition zones on both sides on the stream. In Chediguan by comparison we observed fewer residential structures, mostly industry and some commercial structures. Additionally, buildings in the gully are more spread out than in Cutou highlighted by the isolated settlements to the south of the catchment and single industrial site situated in the basin. Post-2008, noticeable tracks of scarring from debris flows are concentrated downstream of dams 2 and 3 in Cutou (Fig 4(i)), and upstream of dams 1 and 2 in Chediguan (Fig 4(ii)). Deposition patterns are evident downstream of all modifications, forming a depositional zone, encompassing approximately 15% and 20% of the built environment in 2019 within the transportation zone of Cutou and Chediguan, respectively. In contrast, Xiaojia, lacking engineered dam structures, shows a characteristic pattern of erosion upstream and deposition downstream. Notably, between check dam structures in Cutou and Chediguan, deposition predominates on the northern channel flank, while erosion is more pronounced on the southern flank.

Our analysis of Xiaojia unveils no discernible relationship between building development and heightened exposure, particularly to residential and critical infrastructure. This lack of correlation is potentially linked to factors beyond simple urbanisation patterns, like construction quality, building regulations, presence of natural barriers, and effectiveness of mitigation measures. To fully understand this observation, further investigation into the above variables is warranted. Additionally, detailed mapping of past debris flow events and their impacts on the built environment could provide insights into the specific mechanisms influencing vulnerability in Xiaojia. By conducting a more comprehensive analysis that considers these factors, we can gain a better understanding of the complex interactions between building development and exposure to natural hazards in Xiaojia. This, in turn, can inform more effective risk management and mitigation strategies tailored to the unique characteristics of the area. Development in Xiaojia primarily concentrates on the lower slopes (Fig 5(i) and (ii)) at the gully mouth,

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featuring the construction of major roads and highways (G213 and G2417), alongside the expansion of existing residential areas. Chediguan exhibits a less marked land cover transformation, owing to roads being directed through mountain tunnels. Notably, development in Xiaojia mainly surges post-earthquake up to 2010, with only minor construction activities documented thereafter (Fig 5(iii)).

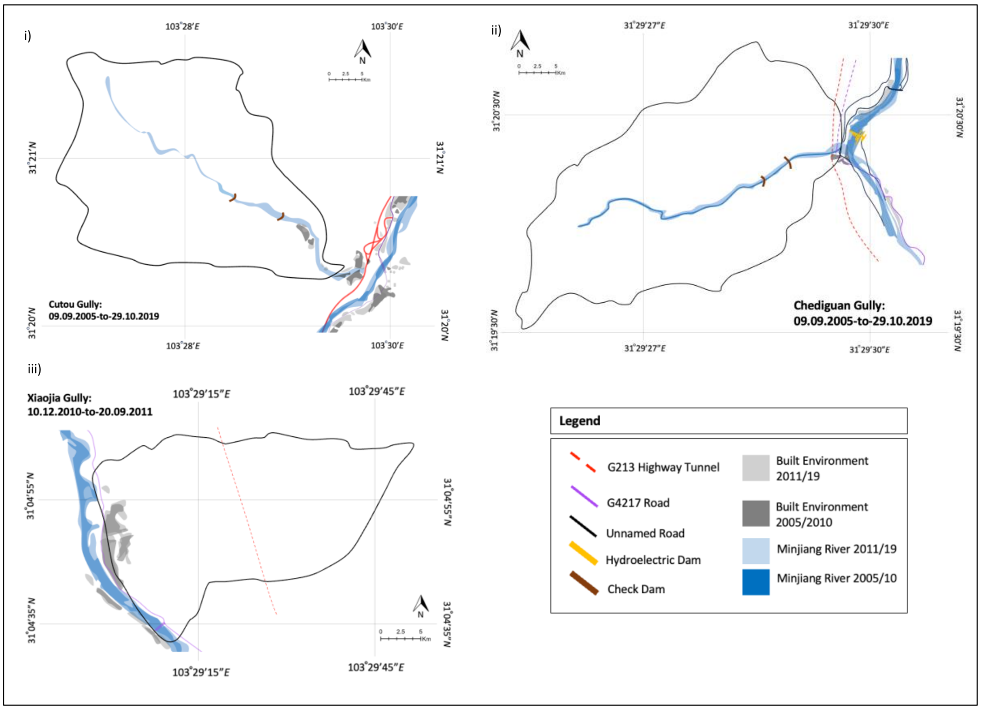

Figure 5: Evolution of the built environment and key infrastructure in (i) Cutou, (ii) Chediguan and (iii) Xiaojia post-earthquake between 2005 and 2019

We mapped the number of buildings impacted by debris flows that occurred within the Chediguan and Cutou gullies. At 02:00 a large-scale debris flows hit Chediguan, impacting numerous structures, at around 05:00 a similar debris flow hit Cutou with significant inundation noted. 79 of the 197 buildings (40%) in Cutou (Fig 5(i)) were impacted by the flow i.e., flooded, damaged, or destroyed. Buildings in Chediguan were less impacted by that event with 7 out of the total 69 (10.1%). We combined the satellite imagery with the datasets produced by Wang (2022) which supported our observations of check dam overtopping in both Cutou and Chediguan during the 2019 event. In 2011 a similar event in Xiaojia impacted approximately 5 of the 43 (11.6%) buildings in the gully (Fig 5(iii)).

4.3 Modelling exposure to post-earthquake debris flows

Our LAHARZ simulations demonstrate a clear correlation between exposure and debris flow runout, revealing a notable increase in building damage as runout volumes escalate from low (10,000m^3) to high (100,000m^3) and extreme (1,000,000m^3) scenarios across all catchments. Despite the presence of check dams, the 2019 debris flows recorded runout volumes significantly larger than the maximum simulated volume, resulting in substantial building and infrastructural loss in Cutou (Fig 6(i)) and Chediguan (Fig 6(ii)).

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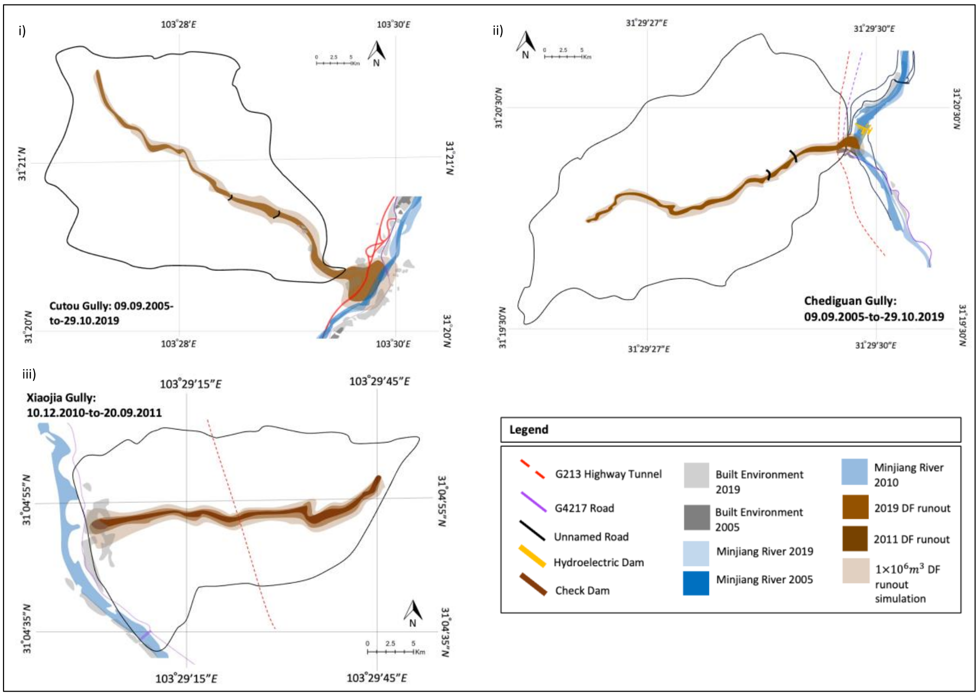

Figure 6: Debris flow runouts for 2019 in Cutou (i) and Chediguan(ii) and 2011 in Xiaojia (iii) underlain by the extreme LAHARZ runout scenario. Low and high runouts are not displayed as they are not easy to visualise at map scale

We examined the temporal dynamics of building changes within the three gullies in response to check dam development, while also considering the implications of the levee effect (fig 6). Our simulations revealed the effectiveness of engineered measures in mitigating exposure to debris flow events. In both Cutou and Chediguan, the presence of check dams led to reduced exposure at low and high debris flow volumes (fig 7(i) and (ii)). However, the mitigative structure provides no discernible protection against extreme debris flows. Notably, Cutou consistently exhibited elevated exposure to debris flow runout compared to Chediguan. The unengineered Xiaojia provided an informative comparison (fig 6(iii)), highlighting the effectiveness of check dams at low and high debris flow volumes. Xiaojia's post-2011 expansion appeared restrained, indicating a potential adaptive response following debris flow events. In contrast, substantial expansion occurred in Cutou and Chediguan between 2011 and 2019, despite experiencing a debris flow event in 2013, suggesting the impact of check dams implemented post-2013.

Furthermore, the incremental increase between high and extreme simulations in Xiaojia paralleled Chediguan's gradual incline, diverging from Cutou's steep escalation. Xiaojia sustained a maximum building damage of 33% under extreme scenarios, compared with 59% in Cutou and 22% in Chediguan. This discrepancy suggests that the optimal efficiency of check dams may be surpassed, urging consideration of additional factors such as the landscape's inherent resilience. Our observations underscore the nuanced variability in the effectiveness of check dams, influenced by contextual factors and landscape characteristics.

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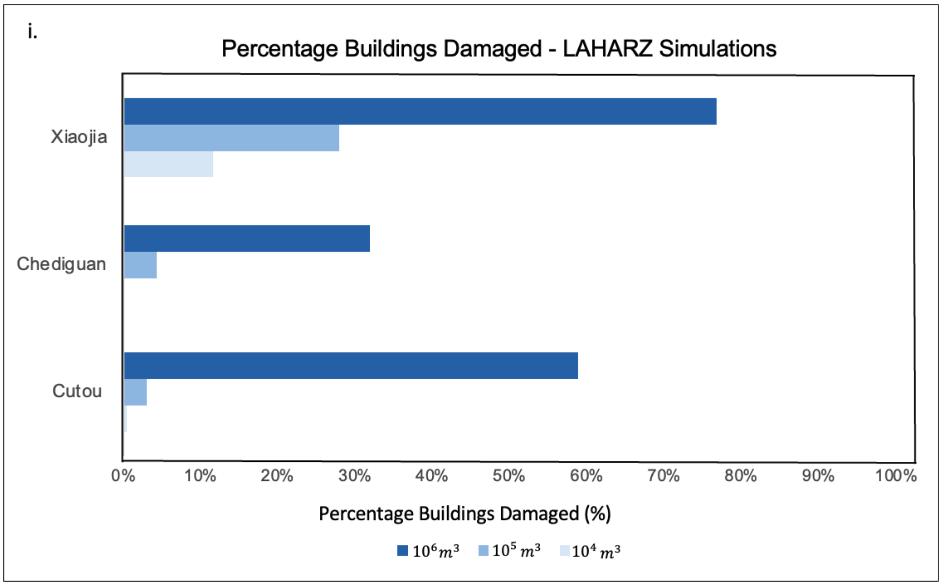

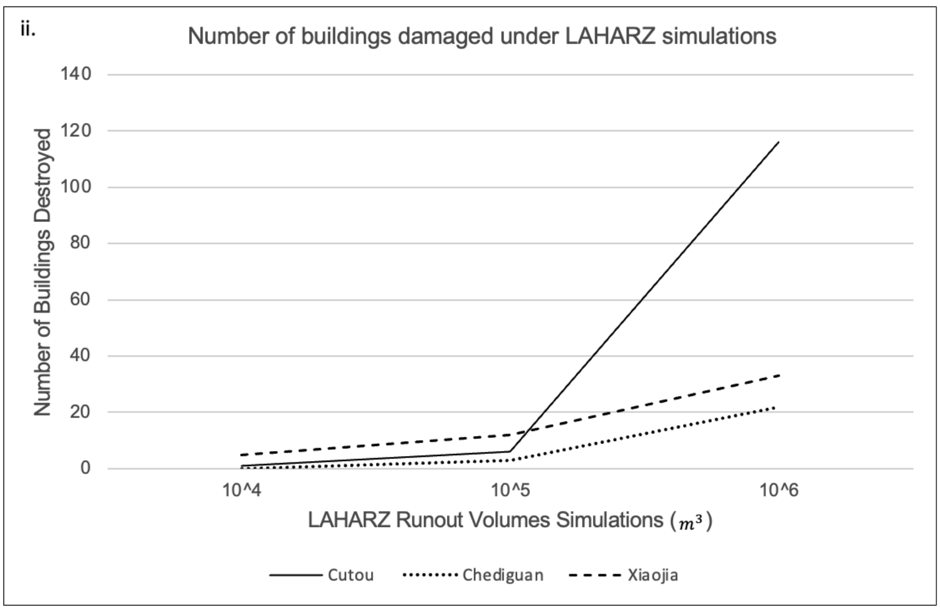

Figure 7: Built environment impacts from three debris flow scenarios modelled using LAHARZ at Cutou, Chediguan and Xiaojia. (i). Percentage of buildings damaged as a proportion of total buildings in each scenario. (ii) Total number of buildings damaged by each simulated debris flow

Figure 7 illustrates how a tenfold increase in runout volume corresponds to building damage, with a discernible rise in impacted building numbers noted between low and high scenarios, and a significant incline between high and extreme scenarios across all catchments. These simulations provide valuable insights into the efficacy of engineered mitigation structures. While check dams in Cutou and Chediguan effectively reduce exposure at low

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and high runout volumes, concerns arise when surpassing the maximum capacity. Urbanization emerges as a significant contributing factor impacting exposure and future risk, with the presence of check dams during the 2019 events significantly contributing to the built environment's exposure. However, to fully understand the effect of check dams and validate our statistical approach, comprehensive numerical analysis of multiple hazard events in each gully is necessary. This sub-section addresses the elements driving hazard-related risk scenarios, including the trigger event, return period, and level of damage, and underscores the importance of considering these factors when suggesting and implementing modifications.

The exposure model is applied to historical events (2019 and 2011) and LAHARZ simulations, showcasing changes in the degree of expacross the catchments with increasing debris flow runout volumes (Fig 8). Consistent with earlier observations in exposure, Cutou exhibits a heightened vulnerability to debris flows at 64% after the 2019 event, followed by Chediguan at 52% and Xiaojia with 2% in 2011. A discernible change in building exposure is observed between the high and extreme scenarios across all catchments. The most influential factor in overall vulnerability remains the number of buildings, highlighting urbanization as a contributing factor impacting both exposure and physical vulnerability. Moreover, the presence of failed check dams in Cutou and Chediguan during the 2019 events significantly contributes to their physical vulnerability.

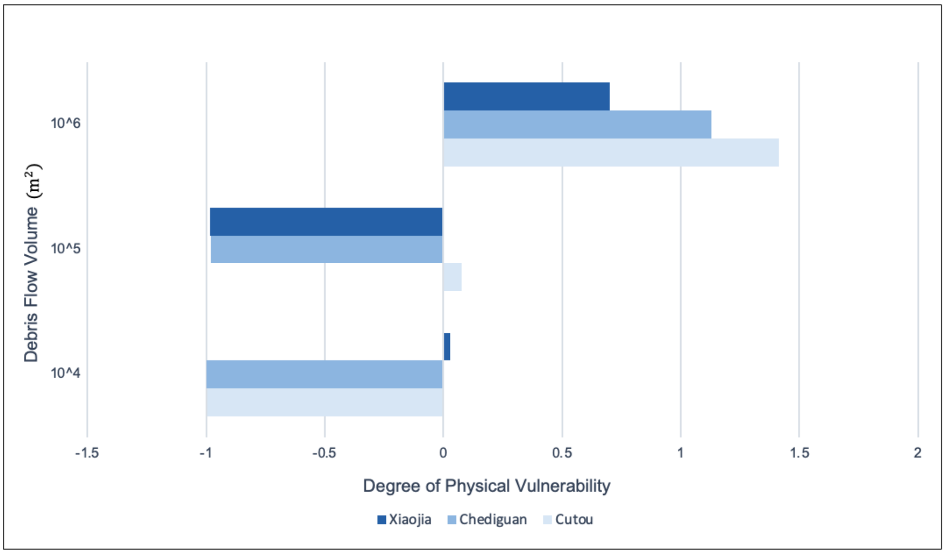

Figure 8: Changes in the degree of exposure with increasing runout volumes using the exposure model developed in equation 1. The 2011 and 2019 debris flows are also noted as a base marker from an observed hazard event

5. Discussion

Post-earthquake structural interventions influence the volume and spatial distribution of sediment within the catchment. Our observations show that check dams act as local depocentres within the catchment, often storing large volumes of sediment upstream of the majority of building development. The choices made about post-earthquake development of the built environment, particularly housing, and mitigative measures like check dams, evolve rapidly without a clear approach to mitigating adverse long-term consequences of sediment retention behind dams (McGuire et al., 2017). Additionally, the processes driving geological disasters in the complex landscape of the Longmenshan occur at different timescales to the rapid socio-economic development in the region (Chen et al., 2022).

Although our analysis focuses on smaller-scale communities, the implications drawn from our findings echo those of broader studies. For instance, Arrogante-Funes et al. (2021)'s extensive investigation into hazard mitigation strategies in larger geographical regions, drew parallels to the effectiveness and limitations of mitigation measures to debris flows. Similarly, Chen et al. (2021) provided insights into the complexities of hazard mitigation, emphasising the necessity of adaptive responses considering local contexts. This aligns with our analysis that each gully must be assessed and mitigated individually rather than collectively to account for local geological and

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hydrological influences on mitigation effectiveness. Moreover, Li et al. (2018) examined the long-term impact of engineering interventions, noting the variability in check dams effectiveness over time. This supports our conclusion that the diminishing effectiveness of check dams is likely the result of sediment accumulation and structural degradation and highlights the necessity for their continued maintenance post-construction in addition to adaptive mitigation strategies. Furthermore, Eidsvig et al. (2014) and Tang et al. (2011) explored the interplay between socio-economic factors and hazard vulnerability, emphasising that community resilience is directly linked to economic resource availability and social cohesion. This corroborates our understanding that debris flow mitigation is a multifaceted issue, and socio-economic conditions are integral to their success. By situating our findings within the broader context delineated by these studies, we accentuate the relevance and applicability of our research beyond the confines of the specific communities under study.

Open check dams, similar to those established in Cutou and Chediguan, play a pivotal role in bed stabilization, slope reduction, and the regulation of sediment transport (Bernard et al., 2019). However, inadequate understanding of post-earthquake debris flow characteristics has led to the failure of many newly constructed engineered structures to mitigate hazards effectively, amplifying damage instead (Chang et al., 2022). During the August 2019 debris flow, Cutou experienced the highest inundation, with 40% of surveyed structures directly affected, including critical infrastructure like the G4217 highway bridge. In Chediguan, despite a declined industrial presence, debris flow impacts affected 7% of structures. The presence of check dams in both locations contributed to raised exposure and hazard impacts during the 2019 event, with overtopping and damage to dam sections recorded.

We conducted LAHARZ scenarios to predict potential exposure to debris flows with volumes that have been observed within the catchments and the region. Our results highlighted a clear correlation between exposure and debris flow runout, showing notable increases in building damage as runout volumes escalated from low to extreme across all catchments. We observed two key elements to the role of check dams in affecting exposure to debris flows. When empty, check dams are effective at mitigating the effects of small and medium volume debris flows. Yet, they are not effective at mitigating the largest of debris flows observed in this region. Large runout volumes in the 2019 debris flows resulted in substantial building and infrastructural loss in both Cutou and Chediguan, suggesting a negative contribution from damaged check dams. Cutou was found to be highly exposed to extreme debris flow volumes, a result of its raised development level situated at the basal slopes. The fact that Xiaojia was found to possess the least exposure to the most extreme debris flow volume suggests that there may be an adaptive component to debris flow mitigation in catchments without significant check dam development. These findings suggest that urban development and debris flow risk co-evolve based on the nature of the structural interventions the studied areas.

Our analysis of erosion, transportation, and deposition zones for each gully revealed significant changes in landscape morphology post-earthquake, likely attributed to mobilised coseismic deposits and subsequent debris flow occurrences. The presence of check dams influenced deposition patterns, with mid-to-downstream trends indicating effective sediment retention in Cutou and Chediguan, while Xiaojia exhibited typical erosion-deposition behaviour. Our findings can be supported by a similar occurrence during the "8.13" debris flow event in Wenjiagou. The damage and subsequent failure of mitigative check dams led to the inundation of 490 houses or more recently, a debris flow in the Miansi and Weizhou townships on 27 June 2023 blocked the valley in the first instance before breaching the dam and causing 7 fatalities (Petley., 2023). Further research is thus imperative to devise appropriate mitigation approaches for post-seismic debris flows. Whilst existing literature has underscored the physical effectiveness of check dams in reducing exposure to debris flow impacts within Alpine terrains (Piton et al., 2016), it should be noted that their primary function extends beyond this to also provide socio- economic and political reassurance (Wu et al., 2012; Chen et al., 2022)

The findings of our paper support the theory of the levee effect by demonstrating how the implementation of mitigative measures, such as check dams, can inadvertently increase exposure levels and risk perception in hazard-prone areas. The interplay between engineering solutions and the built environment as highlighted in our study through analysis of the 2011 and 2019 events as well as the LAHARZ simulations, illustrates the levee effect. Similar to previous studies on flooding and the levee effect, for example Collenteur et al (2015), our paper suggests that the perceived reduction in hazard risk due to mitigative structures can lead to increased levels of exposure due to raised development in debris flow-prone regions. This is particularly evident in the Cutou catchment. This phenomenon reflects the distorted perception of hazard risk, which ultimately drives urbanisation into vulnerable areas (Chen et al., 2015; Ao et al.,2020).

Our LAHARZ simulations further reinforce the limitations of engineered structures as the sole mitigative measure in alpine locations; urbanisation of mountainous terrains further accentuates the balance between technological

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advancements and geological hazards (Zhang, S et al., 2014; Zhang and Li., 2020; Luo et al., 2023). Despite the presence of check dams, our extreme runout volume resulted in significant impacts on the built environment in Cutou and Chediguan, including overtopping and dam failure. The use of these simulations emphasises the challenges of reducing exposure to at-risk structures and highlights the unpredictable nature of debris flow occurrences. Moreover, our findings relating to the altered patterns of erosion and deposition emphasise the relationship between natural topography, engineered interventions, and risk perception in post-seismic debris flows. Urbanisation exacerbates this complexity, influencing exposure and physical vulnerability through deposit remobilisation. Our LAHARZ simulations serve as a practical demonstration of the levee effect, illustrating how engineered structures may not provide adequate protection against runout volumes similar to the extreme simulation, thereby reinforcing the importance of considering the levee effect in debris flow risk management. The unpredictable nature of debris flow occurrences from pinpointing their location and timing to ascertaining their volume and velocity ultimately means that the concept of the 'levee effect' remains core to the issue of debris flows in post-seismic Sichuan (Cucchiaro et al., 2019a; Tang et al., 2022).

Whilst our findings are not able to conclusively determine the prevalence of the levee effect with regards to development in post-seismic environments like Sichuan, we are able to hypothesise this theory. From our study, we are able to posit that the implementation of mitigative check dams may inadvertently increase exposure levels to large-scale debris flow events by creating a false sense of safety. While our investigation does not fully explore this phenomenon, our outcomes highlight the limitations of solely relying on engineered interventions in reducing exposure to at-risk structures under the extreme LAHARZ scenario. Furthermore, we highlighted the complex interplay between engineering solutions and human behaviour, warranting further investigation (Papathoma-Köhle et al., 2011; Gong et al., 2021). By emphasising the challenges and limitations of engineered structures in mitigating debris flow impacts, we underscore the need for comprehensive risk management strategies that consider the complexities of urbanization and flow-based hazards in mountainous terrains.

Despite the presence of these engineered interventions, our analysis demonstrates significant exposure levels and infrastructure damage during extreme debris flow events. This discrepancy between perceived risk reduction and actual hazard exposure underscores the need for a more comprehensive understanding of risk perception in the context of hazard mitigation strategies. Moreover, our study highlights the importance of considering human behaviour and decision-making processes in the design and implementation of risk management measures. Future research should focus on elucidating the mechanisms driving risk perception in hazard-prone areas and developing strategies to bridge the gap between perceived and actual risk to enhance the effectiveness of mitigation efforts.

6. Conclusion

Our study investigated the impact of debris flows in Cutou, Chediguan and Xiaojia since the 2008 Wenchuan earthquake. We used high resolution satellite imagery to build a time series of building inventories between 2005 and 2019. Despite recurrent debris flow occurrences between 2010 to 2013, we found increased urban development across all three gullies until 2015.

We found significant differences between the debris flow events of 2019 and 2011. In the August 2019 debris flow, Cutou experienced the highest inundation, with 40% of surveyed structures directly affected, including critical infrastructure such as the G4217 highway bridge. In contrast, the 2011 event in Xiaojia impacted approximately 11.6% of buildings in the gully, indicating a lower level of damage compared to Cutou. The presence of check dams in Cutou and Chediguan contributed to raised exposure and hazard impacts during the 2019 event, with overtopping and damage to dam sections recorded at both locations. However, despite the presence of these mitigative structures, the impact on the built environment was significant, suggesting limitations in their effectiveness, particularly during extreme runout volumes. Our Laharz simulations demonstrated a clear correlation between exposure and debris flow runout, revealing a notable increase in building damage as runout volumes increased from low to high and finally extreme scenarios across all catchments. Despite the presence of check dams, the simulations indicated that these structures were unable to reduce the impacts on the built environment, especially during extreme events. Moreover, our analysis of building damage and exposure patterns highlighted a heightened level of built environment exposure in Cutou to debris flows compared to Chediguan and Xiaojia. This susceptibility was attributed to factors such as the urbanisation, the presence of critical infrastructure, and the effectiveness of mitigative measures.

Our findings suggest that the presence and location of check dam in gully channels probably facilitated in increasing building exposure and the levee effect in addition to raising concerns about their long-term implications i.e., structural integrity, maintenance and clearing. LAHARZ modelling provides comprehension of check dam efficacy, raising concerns for Cutou and Chediguan in high-to-extreme runout events. Further, the combined use of the LAHARZ GIS toolkit and exposure analysis contributes to a holistic understanding of the risk landscape, informing strategies for enhanced disaster resilience and sustainable development in vulnerable areas.

The assumptions and subsequent considerations highlighted underpin our methodological approach in understanding how the presence of check dams, as a mitigative structure, influences land-use planning and development in hazard-prone areas. They ensure that the data outputs are comprehensive but also reflective of the inherent complexities of the study area and limitations in available data sources and analytical tools. We highlighted a relationship between the presence of engineered measures like check dams alongside the built environment, with increased debris flow impacts post-2008 earthquake in Sichuan provinces along the Minjiang.. Our results emphasise the need for a multi-faceted approach integrating socio-economic development in debris flow prone regions, considering the paradoxical role of mitigative structures on public perception to hazard exposure and vulnerability. Understanding these complexities is vital for informed decision-making and effective debris flow risk management.

Overall, our findings have indicated that the 2019 debris flow events resulted in more significant damage and higher exposure levels compared to the 2011 flow, emphasizing the need for comprehensive risk management strategies in debris flow-prone areas.

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Statements & Declarations

Conflict of Interest

The authors disclose no financial or non-financial interests of competing interest during the preparation of this manuscript.

Author Contribution

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Isabelle Utley, Tristram Hales and Ekbal Hussain. The first draft of the manuscript was written by Isabelle Utley and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript