Reviewer #1 Comments

The manuscript titled "Dynamics and Impacts of Monsoon-Induced Geological Hazards: A2022 Flood Study along the Swat River in Pakistan" provides a valuable case study on the impact of extreme weather events, specifically focusing on the unprecedented 2022monsoon season in Pakistan. The paper effectively combines field investigations, remote sensing analysis, and numerical simulations to comprehensively understand the factors leading to catastrophic debris flows and floods in the Swat River basin. The authors meticulously analyze the influences of topography, land cover changes, and gully morphology in exacerbating these geological hazards, adding valuable insights to the existing body of literature on climate change and hydro-meteorological hazards.

The authors are to be commended for their thorough, multidisciplinary approach. Using both empirical data and simulation models enhances the robustness of the findings, particularly regarding the dynamics of debris flows. The integration of numerical simulations provides valuable insight into the mechanics of these events, with clear implications for the need to prioritize reforestation and sustainable land management practices. This study makes significant contributions by underscoring the role of deforestation in increasing susceptibility to debris flows and offering practical recommendations for improved disaster mitigation strategies. The emphasis on implementing early warning systems and enforcing rigorous land use planning also adds to the paper's relevance, especially given the escalating threats posed by climate change.

While the manuscript is well-prepared and makes a compelling case for the urgent need to address climate-induced hazards, Minor Revisions have been recommended, and a few additional clarifications could enhance its impact and accessibility.

Reply: We thank Reviewer #1 for their insightful comments and positive evaluation of our manuscript. We are pleased that the multidisciplinary approach, combining field investigations, remote sensing, and numerical simulations, was well-received and that the study's contributions to understanding climate change-induced hazards and practical mitigation strategies were appreciated. We have carefully addressed the suggested clarifications and implemented all necessary revisions to enhance the manuscript's impact and accessibility. The reviewer's concerns have been addressed point by point below, and we are very thankful for recommending a minor revision.

General Comments

G-1. The methodology section would benefit from additional context on the specific remote sensing techniques. Although the overall approach is well-explained, more detail would help readers understand how the data were collected and interpreted.

Reply: Thank you for your insightful comment. We have added further details on the specific remote sensing techniques and clarified how the data were collected and interpreted. (Please see lines: 168-170)

"The satellite data include Land Use Land Cover (LUC) and a Geographic Information System derived Digital Elevation Model (DEM) were obtained from sites such as NASA's Earth Explorer and other trusted sources like the US Geological Survey (USGS) and Sentinel-2. To enhance spatial comparability all the datasets were resampled at a 30-meter grid cell size"

G-2. The simulations are a strong point of this study, but expanding on the parameters chosen for these models would be beneficial. For instance, detailing how initial conditions were set and how simulation results compare with field data could strengthen the readers' confidence in the validity of the findings.

Reply: The simulations in this study are based on carefully selected parameters that aim to replicate real-world debris flow dynamics as closely as possible. Initial conditions for each debris flow simulation were established using field measurements from source zones, incorporating the observed flow depth and velocity data as baseline input. These initial settings were calibrated to match known debris flow characteristics in the Swat River basin. Additionally, parameters such as channel slope, sediment concentration, and water flow rates were fine-tuned based on local hydrological data to improve accuracy.

The simulation results were validated against field observations and data from previous debris flow events in the basin. For example, observed flow velocities and depths during peak flood periods closely aligned with those produced in the simulations, indicating strong model reliability. This alignment between simulated and observed data strengthens confidence in the model's accuracy and ensures the findings are representative of actual debris flow behavior

G-3. The study touches on the socioeconomic impacts of the 2022 floods, mentioning financial instability and widespread infrastructure damage. Additional quantitative or qualitative data (if available) would be beneficial to further illustrate the implications for local communities and resilience efforts.

Reply: Thank you for this point. The 2022 floods severely disrupted local communities, displacing thousands of residents and causing significant damage to infrastructure. This led to the displacement of local populations and disrupted access to essential services such as healthcare and education. The cost of rebuilding has been high, impacting local economies, especially those reliant on agriculture and tourism. The information has been added in the section 4.8.

G-4. The discussion and conclusion sections provide valuable recommendations for immediate mitigation strategies. Including a brief discussion on potential long-term strategies, such as reforestation or climate-resilient infrastructure, would broaden the paper's relevance and align with the findings on the critical role of deforestation and climate adaptation

Reply: Thank you for this valuable suggestion. We have expanded the discussion and conclusion sections to include potential long-term strategies, such as reforestation and the development of climate-resilient infrastructure. (Please see lines 581-592.) The modified text of the main draft is as follows.

"In addition to short-term mitigation measures, long-term strategies are essential to build resilience against these hazards. Reforestation, especially with native or drought-resistant species, emerges as a critical solution for stabilizing soil, reducing runoff, and enhancing ecosystem health in landslide-prone areas. Integrating climate-resilient infrastructure—such as permeable pavements, bio-retention systems, and strategically placed vegetation—into land use plans can complement traditional engineering methods, providing additional stability and reducing the strain on infrastructure during extreme weather events.

The study also underscores the importance of policy initiatives that support sustainable land use practices, particularly in vulnerable regions. These could include policies that incentivize reforestation, restrict deforestation in high-risk areas, and promote green infrastructure investments. By aligning practical, evidence-based recommendations with broader climate adaptation strategies, this study reinforces the need for holistic and proactive approaches in disaster management. Together, these measures can address the complex challenges posed by geological hazards in the face of climate change and ensure a more resilient future for affected communities."

Specific Comments

The introduction is well-organized and effectively presents the relevant literature. However, the final paragraph could benefit from greater specificity and focus to better frame the study's objectives.

Reply: Thank you for your constructive feedback. We have revised the final paragraph of the introduction to provide greater specificity and a clearer focus on the study's objectives. This adjustment enhances the framing of the research and establishes a stronger context for the study. (Please see lines: 98-109)

"The different factors contributing to geological hazards have been well identified, but current studies have primarily focused on isolated factors and their potential consequences. However, there remains a gap in research for a comprehensive approach that considers the interplay between extreme climate events and geological hazards, incorporating various triggering factors, the intensity of debris flow, and their resulting consequences. This study addresses this gap by examining the combined effects of multiple triggering factors on the frequency and intensity of debris flows, their role in triggering secondary events such as floods, and the subsequent infrastructural damage. Additionally, it considers how human activities worsen vulnerability, heightening both economic and life risks. To frame the study's objectives, this focused on understanding the conditions under which debris flows occur, particularly in relation to rainfall thresholds, and the effects of deforestation as identified through both field observations and numerical modelling. Lastly, this study offers recommendations for mitigation strategies, aiming to support government authorities in implementing proactive measures to prevent future hazards. This comprehensive approach offers insights that could enhance hazard prediction, early warning systems, and resilience planning in affected regions."

Sections 3.3 and 3.4 need to be explained well, including how they analyze and elaborate on the field data.

Reply: In Section 3.3, the study investigates Land Use and Land Cover (LUC) changes over a 20-year period (2002–2022) through the analysis of MODIS MCD12Q1 V6.1 data. Using ArcGIS, land cover classifications were made for four years: 2002, 2009, 2016, and 2022. The analysis involves comparing these classifications to detect and quantify changes in land cover types, focusing on vegetation, croplands, barren land, built-up areas, and others. By doing this, we highlight trends in LUC shifts, especially in response to human activities and environmental processes, providing valuable insight into how these changes impact slope stability and debris flow susceptibility. This temporal analysis helps assess the dynamic relationship between land use practices and natural hazards, illustrating the influence of LUC on hydrological processes, infiltration, and runoff.

In Section 3.4, the study uses a 2D debris flow movement model based on the depth-integrated continuum method, which simplifies the Navier-Stokes equations to analyze the debris flow dynamics triggered by heavy rainfall and landslides in the study area. The model incorporates the Bingham fluid model to simulate viscous debris flows. The initial conditions for simulations are derived from field data collected in source zones, including flow depths and velocities, ensuring realistic boundary conditions. The simulations are calibrated with local hydrological data, and model outputs are validated against observed debris flow events to ensure accuracy. The numerical simulations are performed using the Massflow software, which employs a custom secondary development for the Bingham fluid model, verified through experimental benchmarks. This robust approach strengthens the reliability of the model results, enabling an accurate representation of debris flow dynamics. The changes in the main text have follow

" Considering the impact of changing LUC, the model accounted for variable soil cohesion and friction factors, which might differ depending on the land cover type (e.g., forested vs. urbanized areas). Initial conditions for the debris flow simulations were defined based on field data from source zones, including measured flow depth and velocity at t = 0 min to ensure that the starting parameters accurately reflected real conditions. Parameters such as channel slope, sediment concentration, and water flow rates were calibrated using local hydrological data to enhance simulation fidelity. Furthermore, the simulation outputs were validated against field observations and past debris flow events, ensuring a close alignment between observed and simulated values for flow velocities and depths. This model calibration and validation approach strengthens confidence in the simulations' accuracy and reliability, effectively capturing the dynamics of the debris flows observed in the Swat River basin."

In Section 4.4, it would be helpful if the authors could provide more details on how historical land use data was integrated into the analysis. Were land-use change trends considered in the numerical simulations to account for potential future scenarios?

Reply: In Section 4.4, historical land use data were integrated into the analysis by employing land cover classification and change detection methodologies. Land-use trends, including shifts in vegetation, built-up areas, and croplands, were evaluated across multiple time periods (2002, 2009, 2016, and 2022) using satellite imagery. These temporal trends were analyzed to assess the potential implications of LUC changes on future debris flow susceptibility. Although this study did not directly incorporate future land-use change trends into numerical simulations, the trends identified provide a basis for considering potential land-use modifications in future hazard assessments. Future simulations could consider these trends by integrating them into updated land cover classifications to model potential scenarios of increased development or changes in agricultural practices, which could further exacerbate the impacts of landslides and debris flows.

By providing a detailed account of LUC patterns, this study contributes to a better understanding of how future land-use changes might influence the stability of slopes and the dynamics of debris flows. This can inform the design of more resilient infrastructure and risk mitigation strategies. The main changes in the main draft are as follows

"The analysis of Land Use and Land Cover (LUC) reveals an ongoing and pronounced decline in vegetation cover, accompanied by a notable increase in barren land. Grassland, an essential protective biome against erosion, declined from 42% in 2001 to 35% in 2022 (Fig. 03). Similarly, broadleaf forest cover dwindled from 12% to 8%, with other vegetation categories following a downward trend, indicating a persistent loss of vegetation across the landscape. In contrast, the cropland category displayed fluctuations, potentially indicating changing agricultural practices or land management strategies. Barren land witnessed a notable expansion, escalating from 15% in 2001 to 24% in 2022. This increase in barren land has significant implications for the region's susceptibility to debris flow events, as the lack of vegetation contributes to increased surface runoff and soil erosion. This transformation highlights increased land degradation and shifts in land utilization. The built-up areas category displayed a parallel increase, emphasizing urbanization's encroachment on natural habitats. These changes in LUC are critical in understanding how land use influences the dynamics of debris flow events, with urban areas and barren land offering less resistance to flow, thereby increasing flow velocity and damage potential."

Section 4.6 discusses rainfall intensity and duration as key triggers for debris flows. Could the authors elaborate on whether these thresholds vary across different areas within the Swat River basin? This additional detail would enhance the understanding of how localized environmental conditions influence debris flow risks.

Reply: In Section 4.6, rainfall intensity and duration are recognized as critical factors in triggering debris flows, especially in the Swat River basin, where localized conditions impact the threshold levels. Based on observed events, the intensity and cumulative rainfall required to initiate debris flows varies across regions within the basin. For instance, in areas like Kalam Valley, a cumulative rainfall threshold exceeding 100 mm over 48 hours has historically triggered debris flows, while regions with more vegetation cover or stable terrain typically require prolonged rainfall

or higher intensities to reach similar outcomes. This variance highlights how localized environmental conditions, such as topography, soil type, and land cover, directly influence debris flow susceptibility.
Our findings provide these rainfall thresholds, enabling better risk assessments and the identification of high-risk periods based on meteorological forecasts. This detail also reinforces the need for area-specific thresholds in debris flow management, which could significantly improve early warning systems and adaptive strategies tailored to different zones within the Swat River basin.

The discussion section is insightful but could be further refined. Focusing and streamlining the points presented would improve its impact and readability. Also included more references to the broader body of literature, linking findings from the study to established work on climate change, deforestation, and geological hazards.
Reply: Thank you for your constructive feedback. We have carefully revised the discussion section to address your concerns. We streamlined the presentation of the main points, ensuring clarity and focus. Additionally, we have integrated more references to the broader body of literature, linking our findings with established research on climate change, deforestation, and geological hazards.
For example, we have incorporated studies that explore how climate change is influencing the frequency and intensity of extreme weather events (IPCC, 2021), and how deforestation exacerbates the risk of geological hazards such as debris flows (Choi & Liang, 2024). We also reference work on how landscape modifications can trigger debris flows (Petley, 2012), reinforcing the relevance of our findings to ongoing discussions about environmental change and disaster risk management.
These revisions should provide better context for our findings and highlight their contribution to the broader scientific discourse. Thank you again for your valuable input, which has strengthened the manuscript.

In Section 5.4, since the findings emphasize the importance of early warning systems, the authors should discuss ways to enhance current warning systems to address the specific hazards highlighted in this study. Additionally, are there specific technological advancements or practices that could improve the accuracy and responsiveness of these systems?
Reply: Thank you for this thoughtful suggestion. In response, we have expanded Section 5.4 to include a discussion on enhancing current early warning systems, specifically targeting the hazards identified in our study. We also explore recent technological advancements and best practices that could improve the accuracy and responsiveness of these systems (please see lines 553-558).
"Integrating real-time satellite precipitation products and radar-based rainfall monitoring, such as data from NASA's Global Precipitation Measurement (GPM), could significantly enhance the accuracy of rainfall forecasts and early warnings. Additionally, machine learning models could analyze historical data on precipitation, land cover, and debris flow incidents, enabling more predictive, location-specific alerts. These predictive models could refine warnings by incorporating specific thresholds for rainfall and runoff, thus reducing false alarms and enhancing local responsiveness."

Technical corrections:
L32: change "discouraging construction activities in flood-prone and debris flow-prone regions" to "flood-prone and debris-flow-prone regions."
Reply: Changed. (Please see line: 29).
L37: degree to extent
Reply: Changed. (Please see line: 34).
L44: drought to droughts and "on human use system" to "on human systems."
Reply: Changed. (Please see line: 41).
L49: catastrophe events to catastrophic events
Reply: Corrected. (Please see line: 47).
L56 to L58, please make it clear the sentence is confusing
Reply: Revised. (Please see lines: 58-61).
L77: flood to Floods
Reply: Changed. (Please see line: 81).
L105: Changed "district Swat" to "the district of Swat" and "River Swat" to "the Swat River" and "River Swat is nourished all year round" to "The Swat River is nourished year-round."
Reply: Changed
L106 to L108 make the line clear; it is confusing.
Reply: Changed

L111: removed "In the extreme southern end of the Swat Valley, the river enters a narrow gorge and joins the Panjkora River at Bosaq before entering the Peshawar Valley," as it was repeated.
Reply: Removed.
L121: "has experienced a significant history of geological hazards" to "has experienced a significant number of geological hazards."
Reply: Corrected. (Please see line: 136).
L123: "in the monsoon season of 2022" to "In the 2022 monsoon season" for smoother flow.
Reply: corrected. (Please see line: 138).
L127: "physically visited" with "physically inspected."
Reply: Changed. (Please see line: 143).
L130: "The positions of each debris flow dam and meticulously measured the dimensions" to "The dimensions of each debris flow dam were also measured and documented comprehensively."
Reply: modified. (Please see line: 158).
L136: conducted to performed
Reply: Changed. (Please see line: 158).
L140: "near Kalam Swat" to "near Kalam, Swat"
Reply: Changed. (Please see line: 162).
L151: misplaced parenthesis
Reply: Changed
L163: for "Land Use and Land Cover (LUC)" throughout the section using consistent terminology and format.
Reply: Change and the authors have ensured to make it consistent throughout the manuscript.
L177: please make it clear the line
Reply: Changed
L185: please rephrase the sentence and check the reference
Reply: Changed
L193: rain to rainfall
Reply: Changed. (Please see line: 220).
L202: please rephrase it
Reply: Changed
L217: replace it with "The most extreme and high-magnitude floods were recorded at Bodai Kamar Khwar, with levels reaching 70 to 80 feet."
Reply: Changed. (Please see line: 245).
L226: replace it with "As shown in Table 2, the average slope angles within the debris flow initiation zones ranged from 30° to 45°."
Reply: Changed. (Please see line: 255).
L230: replace to "This occurs primarily because most debris flows begin as shallow landslides or as rill or gully erosion on large landslide deposits."
AR: Changed. (Please see line: 259).
L248: replace it with "These debris flows deposited debris, mud, and rock along National Highway N-95 (Fig. 1), which runs parallel to the River Swat."
Reply: Changed. (Please see line: 299).
L275: replace to "Individual landslides and erosive processes are responsible for exposing bare areas on the mountainsides (Figs. 5-7)."
Reply: Replaced. (Please see line: 325).
L325 and 326: the lines should need to be rephrased
Reply: Rephrased. (Please see line: 375).
L334 and 335: replace to "The debris flow depth reaches its peak between 45 and 60 minutes, ranging from 36 to 40 m, while the velocity reaches a maximum of 17 to 18 m/s, as shown in panels d-e and i-j, respectively."
Reply: Corrected. (Please see line: 385).
L402: add "which offers" after "Swat River basin,"
Reply: Added. (Please see line: 458).
L445: add "a" after "permeability"
Reply: Added. (Please see line: 501).
L482: change "with infrastructural damage totaling $30 billion."
Reply: Changed. (Please see line: 539).
L522: change was observed to was recorded

Reply: Changed. (Please see line: 595).
L524: change “catalyzed” to triggered
Reply: Changed. (Please see line: 597).
L527: change “reveal” to revealed
Reply: Changed. (Please see line: 600).
L537: change “Had” to reach
Reply: Changed. (Please see line: 610).
L541: change “events” to event
Reply: Changed.
L549: replaced to "This paper pinpoints the most vulnerable regions in Pakistan."
Reply: Replaced. (Please see line: 620).