Al-imad Journal of Humanities and Applied Sciences (AJHAS)
مجلة العماد للعلوم الإنسانية والتطبيقية
ISSN: 3106-0323
Volume 2 – Issue 2 – 2026
Pages 680-701

Satellite-Based Assessment of Flood Inundation, Vegetation Damage, Channel Change and Environmental Impacts of the August 2026 Rasuwa Flood, Nepal Himalaya

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تقييم بالأقمار الصناعية لغمر الفيضانات وتضرر الغطاء النباتي وتغيرات مجرى النهر والآثار البيئية لفيضان راسووا في أغسطس 2026 بمنطقة جبال الهيمالايا في نيبال

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Received: 20-07-2026; Accepted: 20-08-2026; Published: 29-08-2026

Abstract:

The devastating flood event in northern Nepal that occurred in August 2026 brought significant modifications to the river channels, valley floors, vegetation, and sediments of the Bhotekoshi/Lhende Khola and Trishuli river corridors. The present study integrates a remote sensing, geographic information system (GIS), terrain, and hydrometeorological analysis to understand the event in the Rasuwa region of the Central Nepal Himalaya. An optical and radar satellite remote sensing approaches were used to assess impact on the study area's surface-water extent and flood-affected regions respectively. In addition, the study made use of Sentinel-2's multispectral imagery to describe the environmental disturbance, vegetation condition, exposed sediments, debris, and river-channel modifications. The normalized difference vegetation index (NDVI) and normalized difference water index (NDWI)/modified normalized difference water index (MNDWI) were applied to assess impacts on vegetation and surface-water conditions. A digital elevation model (DEM) was evaluated to determine the influence of elevation, slope, drainage, and valley morphological control, on flood and debris-flow paths. In addition, pre- and post-event imagery comparisons were made to identify riverbank erosion, channel widening, sedimentation, and debris accumulation. The Department of Hydrology and Meteorology hydrometeorological records were used to assess rainfall-temporal relationships, river level, and satellite flood extent correlations. Finally, flood extend, vegetation loss, erosion, sedimentation, topography, drainage, agricultural land, and settlements, and infrastructure were merged using a weighted multi-criteria GIS method to develop an environmental flood impact index. The results suggest that the event's largest environmental impacts were recorded along the Bhotekoshi/Lhende Khola and Trishuli river corridors as the flood inundation, vegetation disturbance, channel modification, erosion, sedimentation, steep terrains, and human exposure overlapped. Overall, the study demonstrates the importance of remote sensing and terrain information in combination with hydrometeorological records to evaluate flood and cascading mountain hazards in the Himalayas.

Keywords: Remote Sensing, GIS, Hydrometeorology, August 2026 Flood, Rasuwa, Nepal Himalaya.

الملخص

أحدثت الفيضانات المدمرة التي وقعت في شمال نيبال خلال شهر أغسطس 2026 تغييرات جوهرية في مسارات الأنهار، وقيعان الوديان، والغطاء النباتي، والرواسب في ممرات نهري بوتيكوشي/ليندي خولا وتريشولي. وتجمع هذه الدراسة بين تقنيات الاستشعار عن بعد، ونظم المعلومات الجغرافية، وتحليل التضاريس والبيانات الهيدرومناخية لفهم طبيعة هذه الظاهرة في منطقة راسووا الواقعة في جبال الهيمالايا بوسط نيبال. وقد استُخدمت تقنيات الاستشعار عن بعد عبر الأقمار الصناعية لتقييم التأثيرات على مساحة المياه السطحية والمناطق المتضررة من الفيضانات على التوالي. وعلاوة على ذلك، وظفت الدراسة الصور متعددة الأطياف الملتقطة بواسطة القمر الصناعي سنتينل-2 لرصد الاضطرابات البيئية وحالة الغطاء النباتي والرواسب المكشوفة والحطام والتغيرات في مسارات الأنهار. كما طُبِّقت مؤشرات الفرق النباتي المعياري والفرق المائي المعياري ونسخته المعدلة لتقييم التأثيرات على الغطاء النباتي وحالة المياه السطحية. وجرى تحليل نموذج الارتفاع الرقمي لتحديد مدى تأثير الارتفاع، والانحدار وشبكة التصريف والخصائص المورفولوجية للوديان على مسارات الفيضانات وتدفقات الحطام. وبالإضافة إلى ذلك، أُجريت مقارنات بين الصور الملتقطة قبل الحدث وبعده لتحديد حالات تآكل ضفاف الأنهار واتساع مجاري الأنهار والترسيب وتراكم الحطام. واستُخدمت السجلات الهيدرومناخية الصادرة عن إدارة الهيدرولوجيا والأرصاد الجوية لتقييم العلاقات الزمنية لهطول الأمطار ومستويات الأنهار ومطابقتها مع بيانات نطاق الفيضان المستمدة من الأقمار الصناعية. وأخيراً، دُمجت بيانات نطاق الفيضان وفقدان الغطاء النباتي والتعرية والترسيب والتضاريس وشبكات التصريف والأراضي الزراعية والتجمعات السكانية والبنية التحتية باستخدام طريقة نظم المعلومات الجغرافية متعددة المعايير الموزونة لتطوير مؤشر بيئي لتأثير الفيضانات. وتشير النتائج إلى أن أشد التأثيرات البيئية للحدث سُجِّلت على طول ممرات نهري بوتيكوشي/ليندي خولا وتريشولي حيث تزامنت وتداخلت ظواهر غمر الفيضان واضطراب الغطاء النباتي وتغير مسارات الأنهار والتعرية والترسيب مع طبيعة التضاريس شديدة الانحدار والمناطق المأهولة بالسكان. وبشكل عام، تبرز الدراسة أهمية الاستشعار عن بعد وبيانات التضاريس، مقترنةً بالسجلات الهيدرومناخية في تقييم مخاطر الفيضانات والمخاطر الجبلية المتتابعة في منطقة الهيمالايا.

الكلمات المفتاحية: الاستشعار عن بُعد، نظم المعلومات الجغرافية، الهيدروميتيورولوجيا، فيضان أغسطس 2026، راسوا، جبال الهيمالايا، نيبال.

1. Introduction

Floods are naturally hazardous phenomena occurring in a number of mountainous and lowlands areas. In particular, they are disastrous in mountainous and foothill zones, where steep slopes, continental climatic conditions, monsoon-type rainfall, glaciers, and dense river networks co-exist. Nepal is highly vulnerable to various flood events that complexly interact with each other as the country is characterized by a wide range of elevations from the lowlands of Terai to the high Himalayas. The river systems of Koshi, Gandaki, and Karnali basins in Nepal are highly susceptible to flooding due to monsoon precipitation, snow and ice melt, steep slopes, and mass movements. Consequently, such flood events affect regional settlements, agriculture, hydropower plants, transport infrastructure, and ecosystems as a whole. However, previous studies (Sharma et al., 2019; Shrestha et al., 2020) highlight that the topography, geology, and high monsoon rainfall in Nepal increase the vulnerability of the country to flood disasters. Moreover, research on flood events in Nepal is mainly focused on the flat topography of the southern part of the country. Yet there is a need for a deeper comprehension of flood processes occurring in the central and western parts of the country — characterized by a complex mountainous relief. Thus, the current study is dedicated to an assessment of flood risk in mountainous and foothill areas of Nepal.

The use of satellite remote sensing for flood monitoring has become more critical than ever due to the spatial discontinuity of conventional ground observations and their limited availability during extreme events (Teng et al., 2017; Schumann et al., 2022; Shaltami et al., 2026). While optical satellite sensors can provide valuable information on inundation, vegetation damage, exposed sediments, and land-surface changes, they are often hindered by clouds in the case of monsoon related flooding. Synthetic Aperture Radar (SAR), on the other hand, can penetrate through clouds and observe flood areas during both day and night, and hence Sentinel-1 is particularly appropriate for flood detection and rapid mapping of floods (Shen et al., 2019). Recent studies in Nepal have demonstrated the value in using multi-temporal Sentinel-1 SAR change detection in order to map flood extent and flood dynamics. Regional analysis of Nepal's Terai for 2019-2024 revealed large temporal variability in flood occurrence, and a very strong positive relationship was found between three-day cumulative rainfall and satellite-derived flooded area (Khatiwada et al., 2026).

The effects of flooding on the environment can be more than just days of water coverage. Extremely high-energy floods can erode riverbanks, change river channel shape, mobilize significant amounts of sediment, damage crops and forests, and deposit debris throughout valley floors (Lamichhane et al., 2025). These processes can occur at the same time as other phenomena in mountainous areas like landslides, rockslides, glacier-related mass movements and debris flows, which compound or add on to the effects of just rainfall and runoff from normal flood events. This is especially pertinent for the Himalayan region, due to the potential impact of retreating glaciers, fluctuating snow and ice conditions, permafrost degradation and unstable mountain slopes in contributing to such extreme events (Nie et al., 2021; Li et al., 2024).

The catastrophic event that occurred in northern Nepal on 26 August 2026 serves as an excellent case study to illustrate this complexity. Initial satellite and field reconnaissance suggest that the disaster to the Nepal-China border was triggered by a glacier and rockslide avalanche that led to a debris flow entering the Lhende Khola/Bhote Koshi river and downstream to the Trishuli River. Indeed, the event caused extensive damage to populated places along the route of the 100 km long path and significant amounts of debris and sediments in the river system (USGS, 2026; CLaSH, 2026). Moreover, the satellite imagery confirmed that the disaster has caused significant changes to the river system downstream and the formation of new lakes and water bodies upstream the region (CLaSH, 2026; Stimson Center, 2026). However, when it comes to such a complicated phenomenon as mountain flood episodes, hydrometeorological information should be combined with space measurements. Indeed, rainfall records alone may not be sufficient in the case of flood events triggered by a combination of factors, such as glacier slides, landslides, and river blockage by debris and subsequent water releases of the dammed river. On the other hand, while satellite imagery can document changes to the river channels, the distribution of the debris, and the areal extent of flooding, it says little about the weather conditions that may have triggered the event. As such, the combination of both methods can provide more accurate information about the potential link between changes in the water bodies and meteorological conditions than either method alone (Rounce et al., 2016; Khadka et al., 2026). The Department of Hydrology and Meteorology (DHM) of the Government of Nepal can provide a wealth of meteorological data that may be helpful for examining the 2026 flood event. In particular, the daily weather reports from DHM contain valuable information about the state of the weather and hydrological conditions in the area. As such, they can complement the satellite imagery

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described above by providing additional insight into the trends in the weather and flood patterns. Indeed, the analysis of the reports in combination with the satellite imagery can be used to assess whether the observed changes in the river system had been triggered by a period of anomalous rainfall or a sudden geomorphological event such as a landslide or a rockslide avalanche. Furthermore, combined analysis may reveal if the 2026 event was a part of a larger pattern or rather an isolated incident.

The August 2026 disaster is also pertinent in the context of the growing concern about glacier-related hazards in the Himalaya. Nepal is home to a significant number of growing glacial lakes and potentially dangerous glacier-related systems, according to remote-sensing studies. An assessment of the Nepal Himalaya revealed the presence of 131 glacial lakes exceeding 0.1 km^2 in size in 2015, out of which 11 were classified as very-high-risk and 31 as high-risk based on the criteria of hazard characteristics and downstream impacts (Rounce et al., 2017). More recent research has extended this view to the China–Nepal transboundary region, illustrating that potentially dangerous glacial lakes can threaten highways, bridges, settlements, buildings and other infrastructure along key transportation corridors (Khadka et al., 2024).

Against this background, the present study attempts to use an integrated remote-sensing and hydrometeorological approach to study the August 2026 flood disaster. The research utilized Sentinel-1 SAR backscatter observations to delineate flood-affected areal extent and identify changes in radar backscatter signatures, while Sentinel-2 used to characterize surface-water advances, vegetation damage, and exposed sediment and debris-related transformation processes. Using the processed information, a digital elevation model (DEM) employed to understand the interrelation between topography and flood disaster. The study used remote-sensing data alongside hydrometeorological data from the Department of Hydrology and Meteorology to understand the processes that led to the change in the hazard over time and its relationship with the hydrological response. The processed information utilized to establish an integrated environmental flood impact index that considers flood-affected areal extent, vegetative damage, channel adjustments, and erosion and deposition processes related to the morphological characteristics of the study area. Overall, the information contributes to a better understanding of the August 2026 disaster while advancing the scientific insights into the application of satellite remote sensing in studying flood events in topographically complex and hydrologically diverse areas such as the Nepalese Himalayas. Specifically, the study highlights the differences in the spatiotemporal characteristics of rainfall-induced inundation processes from glacial, landslide, and debris flow-related hazards that complicate the post-disaster assessment and management in the study area. The results contributed to post-flood environmental assessment, monitoring, and flood-hazard risk management and mitigation in Nepal.

Research on floods in Nepal so far has been focused on studying the patterns, causes and socioeconomic effects of monsoon floods, especially in the Terai region and the large river basins. The review of flood disaster research in Nepal highlighted that most of the previous studies used to rely on field and empirical based data while the application of recent satellite remote sensing techniques was found to be limited (Sharma et al., 2019). Furthermore, the review suggested that multispectral optical imagery is not suitable for flood detecting purposes due to frequent cloud cover during the monsoon season while SAR has a great potential for flood monitoring (Sharma et al., 2019). Recent studies have shown the potential of using multi temporal sentinel 1 SAR change detection method for regional flood mapping and flood dynamics analysis in Nepal (Khatiwada et al., 2026). The advances in the development and wider availability of Sentinel-1 SAR have enhanced the capacity to map floodwater in Nepal. The recent multi-temporal research investigated flood dynamics in the Terai between 2019 and 2024 using Sentinel-1 imagery and change-detection methods. The study showed that SAR-derived flood maps enable understanding of substantial temporal and spatial variations in inundation and identified recurrent flood exposure in parts of Parsa, Bara and Rautahat. Moreover, the researchers found a strong positive relationship between three-day cumulative rainfall and flooded area, cumulative rainfall above approximately 130 mm identified as a preliminary threshold for major flood events in the study area. The findings highlighted the importance of using satellite-based inundation information combined with rain measurement for the quantitative understanding of flood events (Khatiwada et al., 2026). The earlier Nepalese studies investigated individual flood events and river basins using remote sensing and GIS, showed the usefulness of the satellite-derived land-cover information, terrain parameters, hydrological variables, and spatial multi-criteria approaches for identifying flood-prone areas (Duwadi et al., 2025; Subedi et al., 2025). Nevertheless, the Nepalese flood literature has mostly focused on conventional monsoon flooding, mainly in the southern flood plains, whereas comparatively fewer studies have examined sudden high-altitude cascading events incorporating interactions among glacier-related processes, landslides, debris flows, and river flooding (Sharma et al., 2019; Mondal et al., 2026). This difference highlighted the important research gap regarding integrated assessment of complex flood and cryospheric hazards in northern Nepal and the wider transboundary Himalayan region. A second major line of research focuses on glacial lakes and glacial lake outburst floods. Rounce et al. (2016) developed a remote hazard and risk assessment framework for glacial lakes in the Nepal Himalaya, using remotely sensed information. They considered the scenarios of outburst of glacier lakes triggered by mass movements in adjoining glaciers, moraine stability, expansion of the lake and downstream impact. Their study showed that remote sensing could provide a systematic and repeatable basis for screening potential glacier-related hazards and prioritizing lakes for subsequent detailed study and risk reduction activities. Rounce et al. (2017) performed a satellite-based assessment of glacial lakes within the Nepal Himalaya and identified 131 lakes greater than 0.1 km 2 in 2015. In order to evaluate the risks and hazards associated with glaciers, they examined lake characteristics, potential triggers, moraine stability, lake expansion, and downstream exposure. They classified 11 lakes as very high risk and 31 as high risk, indicating that potentially hazardous glacial lakes and associated outburst-flood risk are widespread throughout Nepal. Long-term remote-sensing studies have shown that Himalayan glacial lakes are highly dynamic objects. Satellite-based inventories spanning several decades have captured changes in both the number and the surface area of glacial lakes throughout the Nepal Himalaya, which reflect the combined effects of glacier retreat and changes in cryospheric conditions (Nie et al., 2017; Khadka et al., 2018). Landsat time-series research has furthermore shown that abrupt reductions in lake area, in conjunction with either sediments or sediment tails downstream, can be used to identify and date past GLOFs, and their spatio-temporal distribution (Veh et al., 2018). These studies highlight the value of using multi-temporal satellite data to understand the context of glacier related flood events, particularly in remote Himalayan setting where such events may not be easy to access for ground based investigations. More recent research has turned from assessments of individual glacial lakes towards transboundary hazard assessment. Khadka et al. (2024) combined remote sensing, GIS and hydrodynamic modelling to explore glacial-lake hazards and their downstream consequences in four strategically important China–Nepal transportation corridors. Their inventory found 2,688 glacial lakes in 2022 while the Keyrung–Kathmandu corridor was assessed as having high GLOF susceptibility. Hydrodynamic simulations showed that potential GLOFs could affect about 103 km of China–Nepal highways, 103 bridges, two major dry ports and 3,301 buildings in both countries. The study stressed the importance of joint monitoring, early-warning systems, information exchange and coordinated disaster-management strategies between China and Nepal (Khadka et al., 2024). This research direction is particularly relevant to the Rasuwa and Bhote Koshi–Trishuli region which is part of a transboundary Himalayan river system where high-altitude cryospheric processes can have rapid downstream effects. Gouli et al. (2025) assessed GLOF risk in the Poiqu–Bhote Koshi and Gyirong–Trishuli transboundary basins using an integrated framework that combined remote sensing, machine learning and hydrodynamic modelling. Their analysis identified highly susceptible glacial lakes and assessed the downstream inundation and exposure of buildings, bridges, hydropower facilities and roads, showing the importance of combining complementary techniques to assess complex glacier-related hazards in the China–Nepal border region. Recent research on the 2024 cascading GLOF in the Thame Valley has demonstrated the value of using multiple-optical satellite data to reconstruct changes in glaciers and glacial lakes and to investigate the cascading mountain hazards. Khadka et al. (2026) have used multi-source satellite imagery to track glacier and lake evolution from 1976 to 2024 and have combined these observations with field measurements, climatic data and numerical modelling to reconstruct the cascading GLOF process and its downstream effects. These developments show a broader progression in glacier-related hazard research from simply identifying and inventorying glacial lakes towards integrated assessments of lake evolution, triggering mechanisms, cascading processes, downstream exposure and hydrodynamic consequences (Khadka et al., 2026). Despite this, an important research gap remains. Nepalese flood-mapping studies have focused substantially on rain-driven flooding, particularly in the Terai and southern flood plains, while glacier-related research has more commonly focused on glacial-lake inventories, GLOF susceptibility and pre-event hazard assessment (Sharma et al., 2019; Rounce et al., 2017; Khadka et al., 2024). Fewer studies have integrated post-event Sentinel-1 SAR flood mapping, Sentinel-2 environmental-change detection, DEM-based geomorphic analysis and official hydrometeorological observations to reconstruct an actual catastrophic cascading event across a high-mountain river corridor. Recent work on the 2024 Thame cascading GLOF demonstrates the value of combining multi-source satellite observations, climatic data, field information and numerical modelling but the combined use of SAR-based flood mapping, optical environmental-change analysis and DHM observations is an important opportunity for research in northern Nepal (Khadka et al., 2026). The August 2026 disaster therefore provides an important opportunity to bridge conventional flood mapping and cryospheric-hazard research.

The present study bridges this gap by taking advantage of satellite-based flood detection, combined with hydrometeorological and geomorphic analysis. Instead of viewing the August 2026 event solely as a typical monsoon flood, we have looked at the interplay between rainfall, river conditions, glacier/ice-rock collapse, debris transport, channel modification and downstream inundation. This multi-faceted approach builds on previous flood-mapping and GLOF studies while extending their scope to the rapid assessment of a newly occurring catastrophic event in the Nepal Himalaya. The location and physiographic map (Fig. 1) depict the area of study located in northern Nepal. The figure shows that Rasuwa is a mountainous region with very high relief. The valleys are deep, as they are cut by a number of rivers. The Bhotekoshi/Lhende Khola and Trishuli river corridors can be seen as the routes connecting mountainous and foothill areas. The image also indicates that settlements, roads, and bridges are located within small valleys and are therefore exposed to debris flows and floods.

1.1. Geological Setting of the Study Area

The Rasuwa–Upper Bhotekoshi/Lhende Khola study area is located in the Central Nepal Himalaya near the Nepal–China (Tibet) boundary. This area is characterized by a tectonically complex geological setting within the Himalayan orogenic belt, where the Lesser Himalayan Sequence, Main Central Thrust (MCT) zone, and Higher Himalayan Sequence are distributed from south to north. Detailed geological studies along the Bhotekoshi River between Syabru Besi and Rasuwa Gadhi identify these three major tectonic units (Rai et al., 2017). Low- to medium-grade metamorphic rocks such phyllite, schist, quartzite, limestone, and dolomite make up the majority of the Lesser Himalayan Sequence. In the Rasuwa–Bhotekoshi sector, rocks of the Kuncha Formation and associated metasedimentary units are exposed. Northward, these rocks are structurally related to the Main Central Thrust zone, which contains strongly sheared schist, gneiss, and other metamorphic rocks (Upreti, 1999). The Higher Himalayan Sequence forms the higher-elevation part of the study region to the north and consists mainly of high-grade metamorphic rocks such as gneiss, schist, quartzite, migmatitic, and locally granitic/orthogneissic bodies. The Higher Himalaya is separated from the Lesser Himalayan rocks by the MCT system (Le Fort, 1975; Rai et al., 2017). The area is characterized by significant deformation, folding, faulting, and thrusting, reflecting ongoing convergence between the Indian and Eurasian plates (Upreti, 1999). The MCT is particularly important because it separates the weaker lower-grade Lesser Himalayan rocks from the high-grade crystalline rocks of the Higher Himalaya. This geological architecture contributes to steep valley geomorphology, fractured and sheared bedrock, and locally unstable slopes, which are crucial factors in understanding erosion, debris movement, and flood impacts on the Bhotekoshi/Lhende Khola valley (Dhital, 2015).

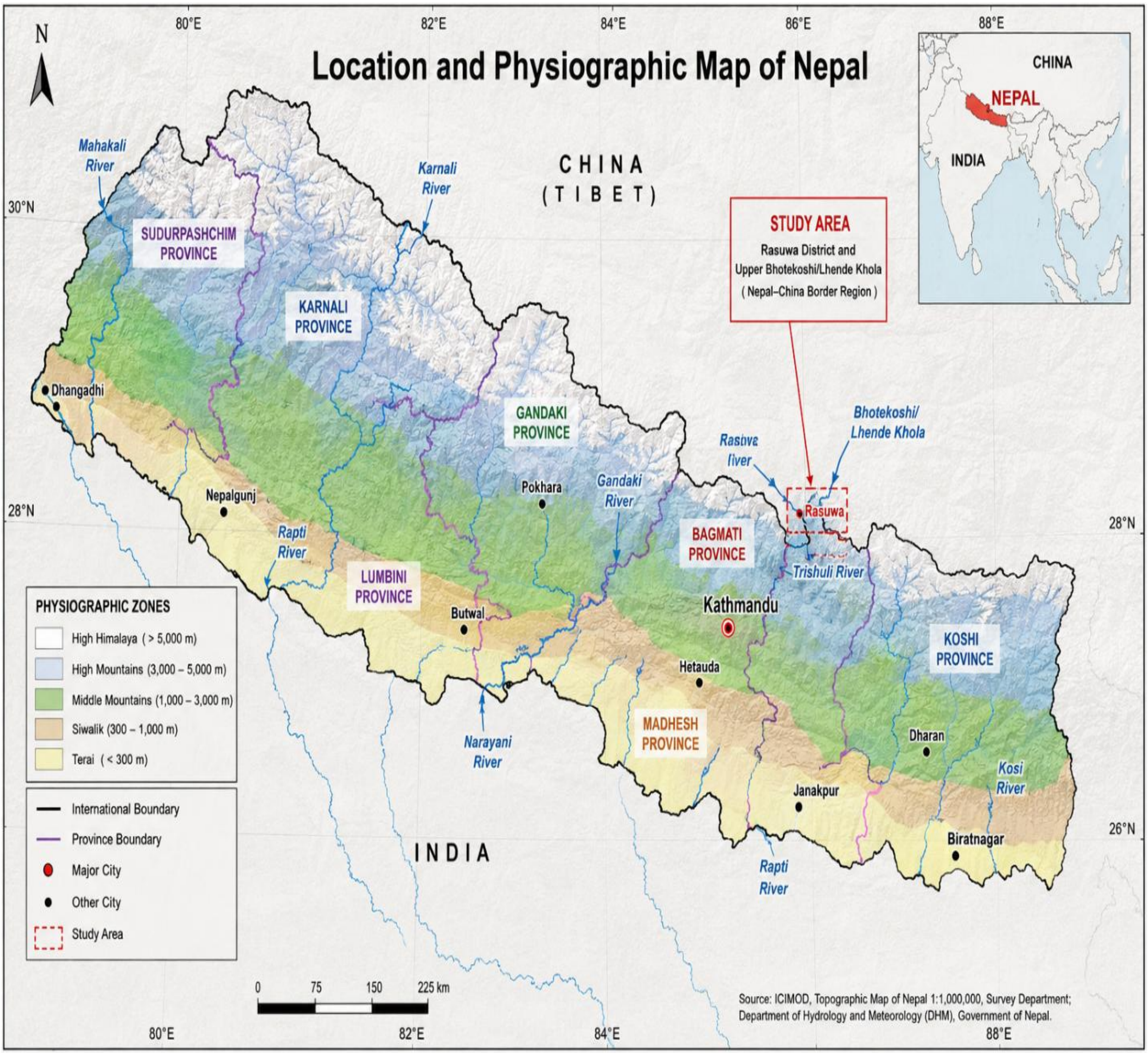

Fig. 1: Location and physiographic map of Nepal.

2. Objective

The primary goal of this study is to evaluate the spatial and environmental effects of the August 2026 flood disaster in Rasuwa, central Nepal Himalaya using an integrated remote sensing, GIS, terrain and hydrometeorological approach.

The following objectives are proposed:

(1) Delineate the flood-affected area using pre- and post-event sentinel-1 SAR image and identify changes in surface-water conditions

(2) Determine pre- and post-flood landscape condition using sentinel-2 multispectral image

(3) Assess vegetation damage associated with flooding, sediment burial, debris movement and surface disturbance using NDVI and NDVI-change analysis

(4) Map flood-water expansion and surface-water changes using NDWI/MNDWI and compare it with SAR derived extent of flood area

(5) Analyze terrain controls on flooding and debris movement using DEM derived elevation, slope, drainage and valley characteristics

(6) Identify riverbank erosion and channel modifications such as channel expansion, scouring, abandoned channels and other landform changes

(7) Map sediment and debris redistribution along Bhotekoshi/Lhende Khola and Trishuli river corridor

(8) Examine the relationship between rainfall, river-water level and flood extent using hydrometeorological observation data from Department of Hydrology and Meteorology

(9) Develop an integrated environmental flood impact index comprising flood extent, vegetation loss, erosion and sedimentation, terrain, drainage, land use, agricultural areas, settlements and infrastructure

(10) Identify areas for prioritized post-disaster assessment, rehabilitation, environmental monitoring and future flood risk reduction.

3. Methodology

A combination of remote sensing, GIS, terrain and hydrometeorological methods was employed to investigate the August 2026 flood disaster in Rasuwa, Nepal. The data on administrative, physiographic, rivers, settlements, roads, and other features were combined to understand the study area's physiography. The pre-flood and post-flood Sentinel-2 satellite imagery was initially processed using the B4–B3–B2 true color combination to determine the landscape's condition and produce the flood extent map, respectively. Similarly, the pre-event and post-event Sentinel-1 Ground Range Doppler (GRD) synthetic aperture radar (SAR) data were processed using calibration, speckle filter, terrain correction, and backscatter coefficient procedures to determine the flood-affected regions. The pre-event and post-event SAR images were compared, and the flooded area was identified using permanent water, new water bodies, and non-flooded pixels. Additionally, the post-flood Sentinel-2 was processed using B12–B8–B4 True Color Space to detect the exposed sediments, deformed surfaces, vegetation condition, and river channels. The vegetation condition was assessed based on normalized difference vegetation index (NDVI) which consists of a pixel's red and near-infrared (NIR) values. Specifically, the pre-event and post-event Sentinel-2 flood extent was overlaid on the normalized difference water index (NDWI)/modified normalized difference water index (MNDWI) to identify the burned vegetation and surface water features. Similarly, the flood extent was compared with the SAR flood mask derived from the pre-event and post-event SAR scenes. A digital elevation model (DEM) was processed and used to generate elevation, slope, drainage, and valley features to evaluate the terrain's influence on the flood concentration, deposition, and debris flows. The pre-event and post-event imagery were evaluated using multispectral information and image interpretation to identify the deformed river channels, river overflows, channel widths, stable channels, deposited sediments, abandoned channels, and debris accumulation. Furthermore, the multispectral data's combinations were used to identify the exposed sediments, debris flow deposits, alluvial fans, channel deposits, and other deformed surfaces. The hydrometeorological data from the Department of Hydrology and Meteorology (DHM), Government of Nepal, were combined with the above-described flood extent to evaluate the cumulative rainfall, daily rainfall, and river-water level to understand the disaster's temporal behavior. Additionally, the relationship between rainfall and flood and rainfall and water level were analyzed statistically. However, if the disaster was not triggered by heavy rains, as anticipated, the remote sensing-based flood extent would have no significant relationship with rainfall. The standardized flood extent, vegetation loss, river bank erosion, sediment deposit, slope, elevation, drainage density, land use, agricultural land, human exposure, and infrastructure were combined using a weighted multi-criteria GIS approach to generate an integrated environmental flood impact index. The flood impact score was categorized into very low, low, moderate, high, and very high categories. As a result, the flood impact assessment was conducted using the weighted multi-criteria approach.

4. Results and Discussion

The pre-flood Sentinel-2 B4-B3-B2 image (Fig. 2) shows the landscape before the August 2026 disaster. Vegetated slopes, river channels, settlements, roads, and valley floors are clearly visible in the image. The narrow river corridors and developed valley floors are crucial as they indicate the possible places of flood and piling of debris, affecting the settlements and structures.

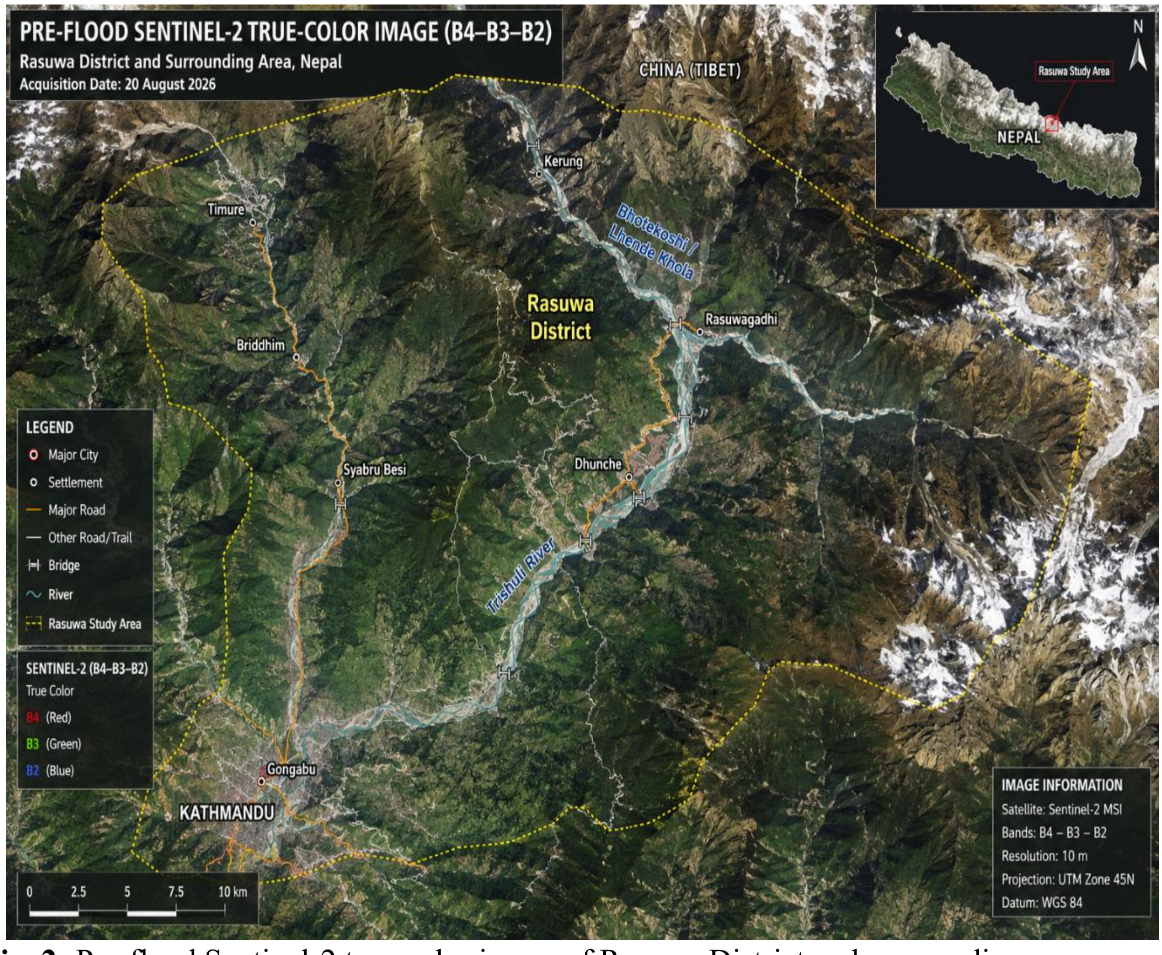

Fig. 2: Pre-flood Sentinel-2 true-color image of Rasuwa District and surrounding area.

The pre-event Sentinel-1 image (Fig. 3) offers a radar baseline less affected by the persistent cloud cover of the Nepalese monsoon. Differences in the VV and VH backscatter are attributed to variations in water bodies, vegetation, exposed rock, built-up surfaces and mountainous terrain. The river channels generally show relatively low radar backscatter compared to rougher land surfaces, while settlements and steep rocky areas show stronger and more heterogeneous responses. This baseline is important in order to distinguish actual changes in the reflectivity after the event from the normal spatial variations of the radar response.

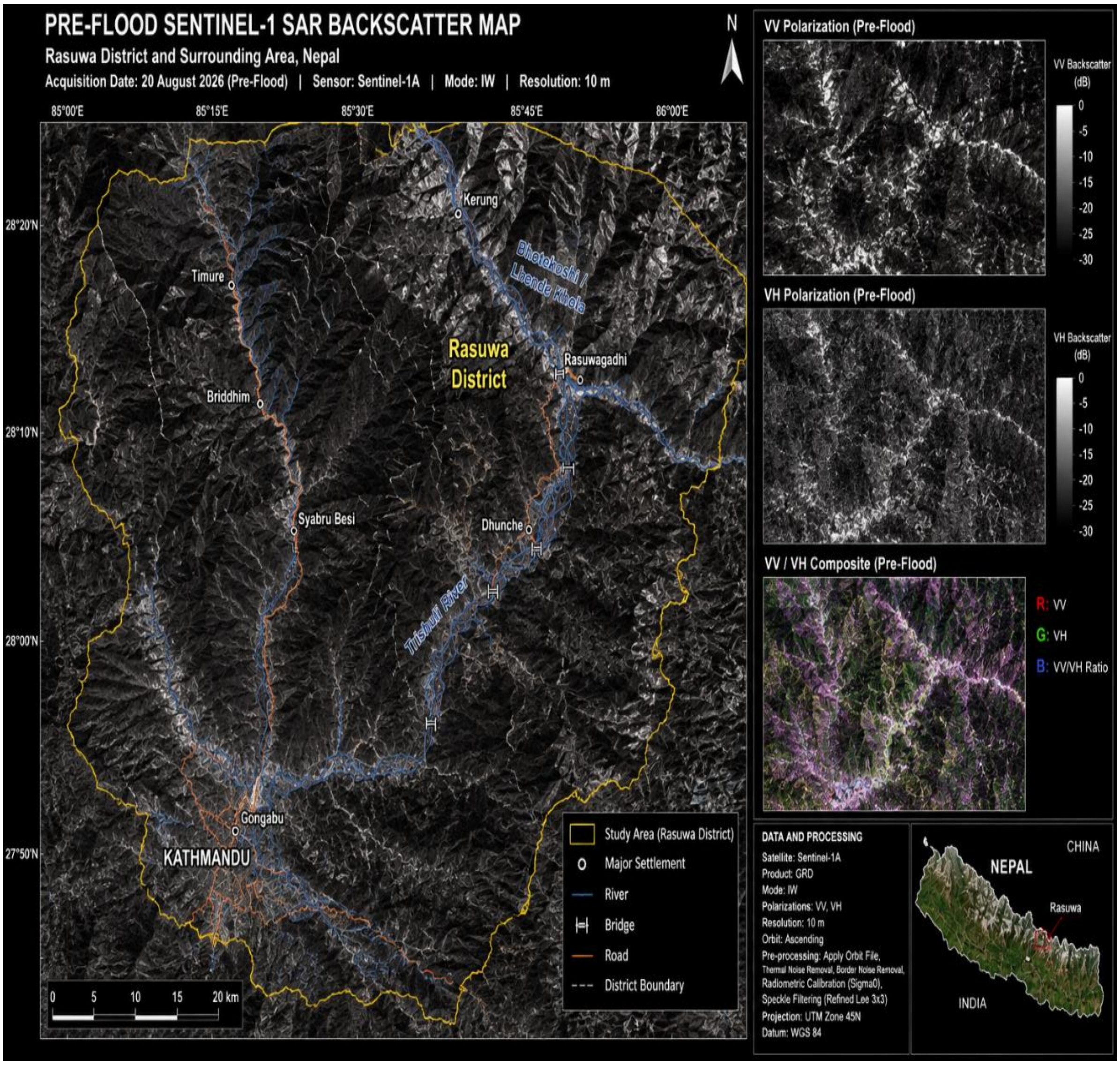

Fig. 3: Pre-flood Sentinel-1 SAR backscatter map of Rasuwa District and surrounding area.

The post-event Sentinel-1 image (Fig. 4) shows significant changes to the Bhotekoshi/Lhende Khola and Trishuli river corridors. Newly flooded surfaces and altered channel sections are highlighted by areas of changed backscatter while valley floors disturbed by the event and surfaces of debris are also evident. The clustering of change found on a confined valley implies that floodwater and debris was funneled preferentially into an existing drainage channel. The value of a SAR observation is also noted given potential restrictions on optical observations due to cloud cover during the monsoon period.

The flood-inundation map (Fig. 5) is the main piece of spatial evidence for the disaster because it differentiates between the areas of permanent water, new water, and non-flooded land. The majority of the new water areas were found along river channels, the bottom of the valley, and low areas that were connected to the drainage system. It can be noticed that the pattern of flooded regions is not random but is confined by the river's geometry and the valley's shape. The comparison with the water areas before the event showed the disaster-related increase of water and differentiated it from permanent water sources.

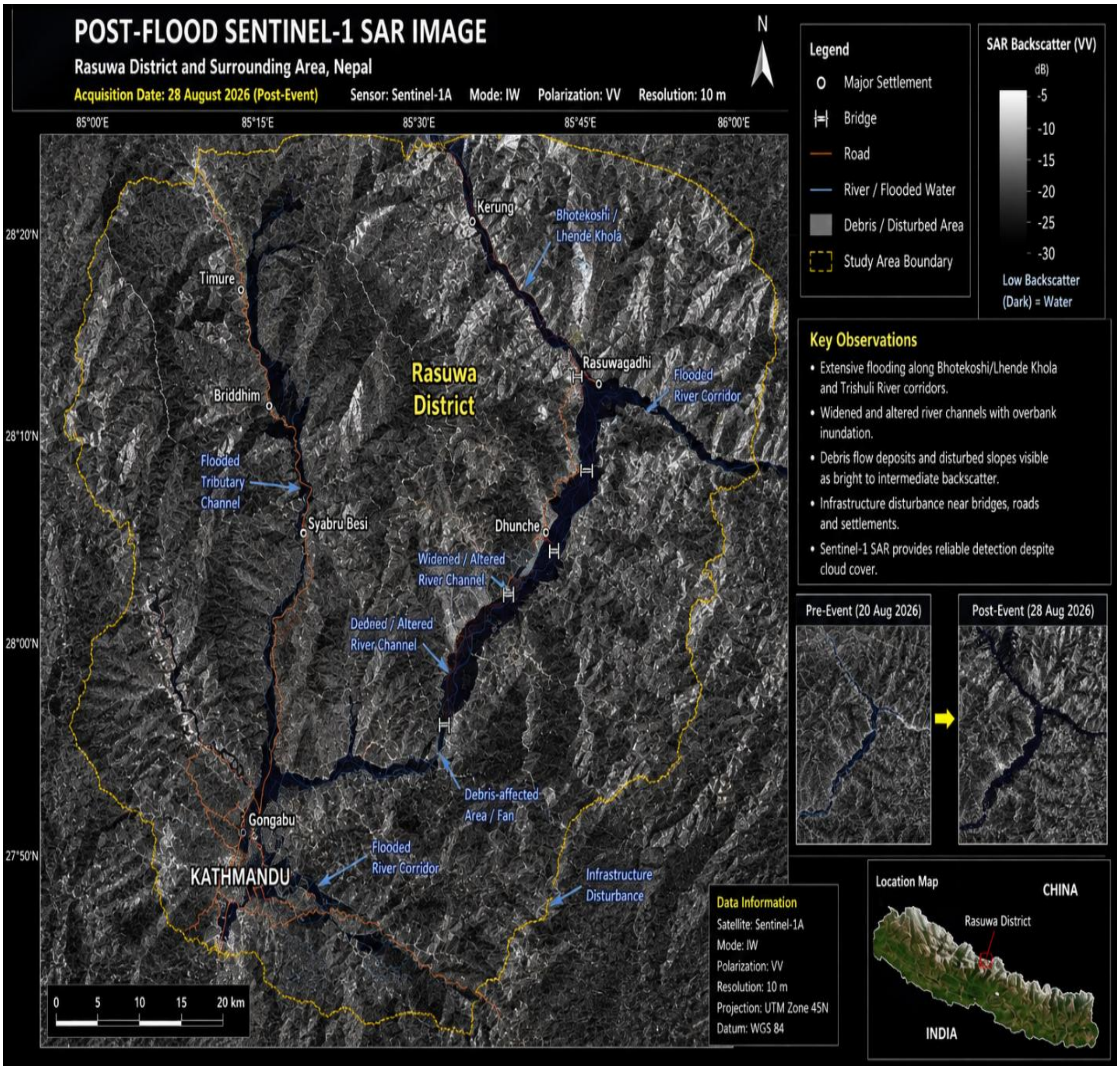

Fig. 4: Post-flood Sentinel-1 SAR image of Rasuwa District and surrounding area.

The post-flood Sentinel-2 false-color image (Fig. 6) highlights the environmental disturbance that is not easily discernible in the true-color image. Exposed sediments and debris appear as distinct spectral features against the vegetation, whereas the disturbed valley floor and modified river channels delineate areas of particularly intense surface disturbance. Vegetated slopes are generally continuous, except at the main river corridors, implying that the flood and debris flow paths encompassed the largest extent of environmental disturbance.

The comparison of the NDVI (Fig. 7) illustrates the reduction of the vegetation condition in the affected zones of the inundation, a deposit of sediments and a displacement of debris. The relatively high values of the index indicate good vegetation condition before the disaster. After the event, the low values were observed in the zones affected by flood where vegetation was submerged, buried, removed or disrupted. On the contrary, the areas not affected by the flood (the main flood path) have significantly fewer changes. This allows concluding that the changes in vegetation were not random and are related to the flood.

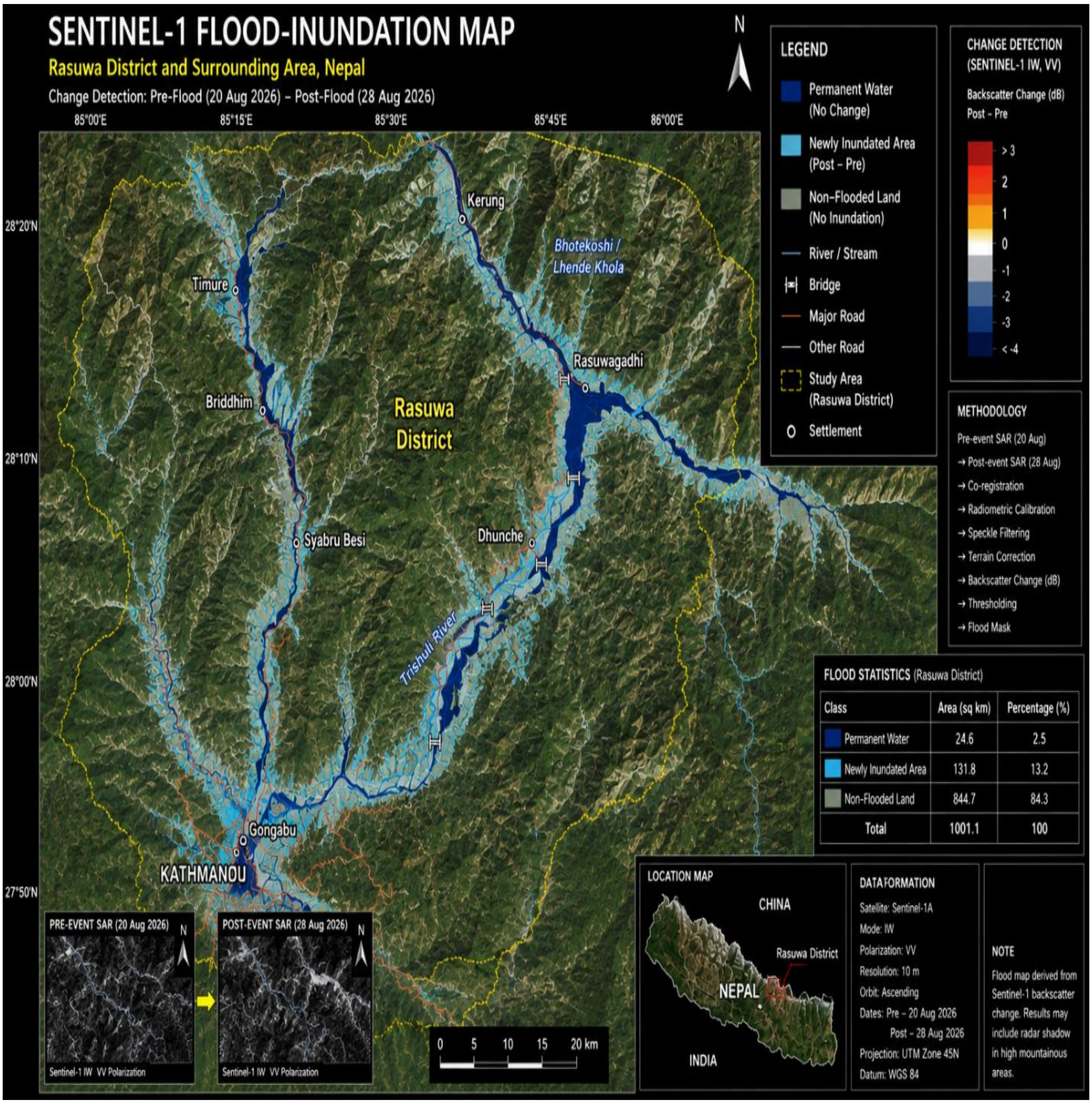

Fig. 5: Sentinel-1 flood-inundation map of Rasuwa District and surrounding area.

The change in the NDVI was classified into classes (Fig. 8), revealing the pattern of vegetation response that can be interpreted as an indicator of the flood's environmental impact. Thus, the areas of severe and moderate losses are mainly associated with flood channels, valley floors and debris-affected surfaces, where the vegetation was most exposed to the flow of water, burial by sediments, and mechanical damage. The class of stable vegetation is distributed mainly in the slopes and areas not affected by the flood, while the local areas of recovery could have been previously inhabited by vegetation. Therefore, the map of Fig. 8 illustrates the key ecological aspects of the flood impact.

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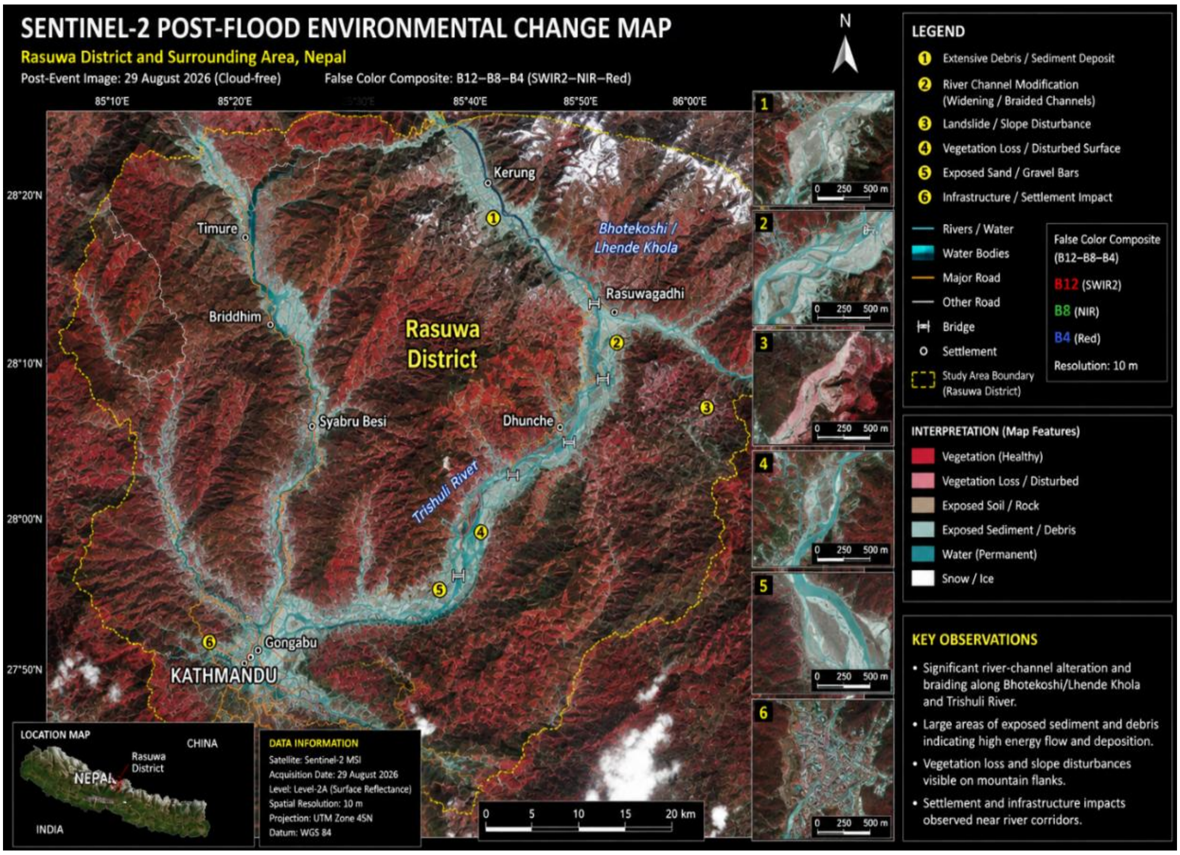

Fig. 6: Post-flood Sentinel-2 environmental change map of Rasuwa District and surrounding area.

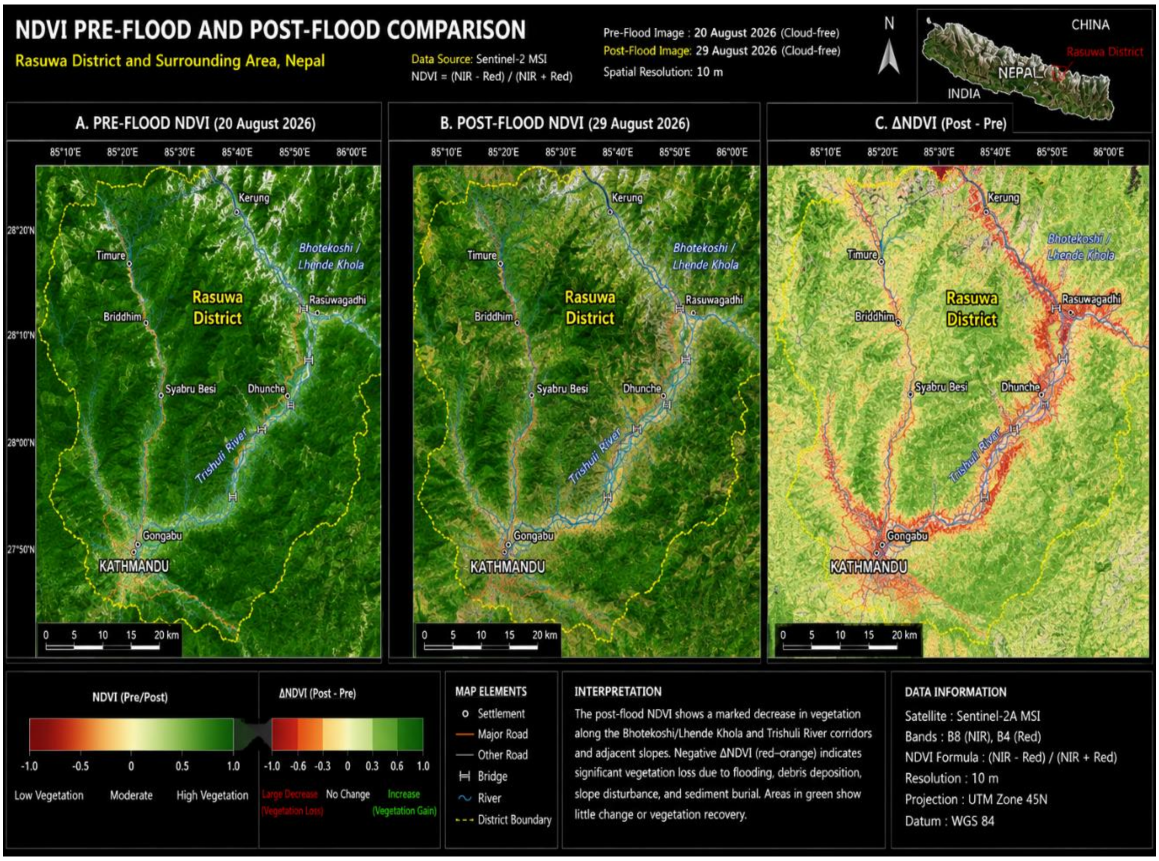

Fig. 7: Pre- and post-flood NDVI comparison of Rasuwa District and surrounding area.

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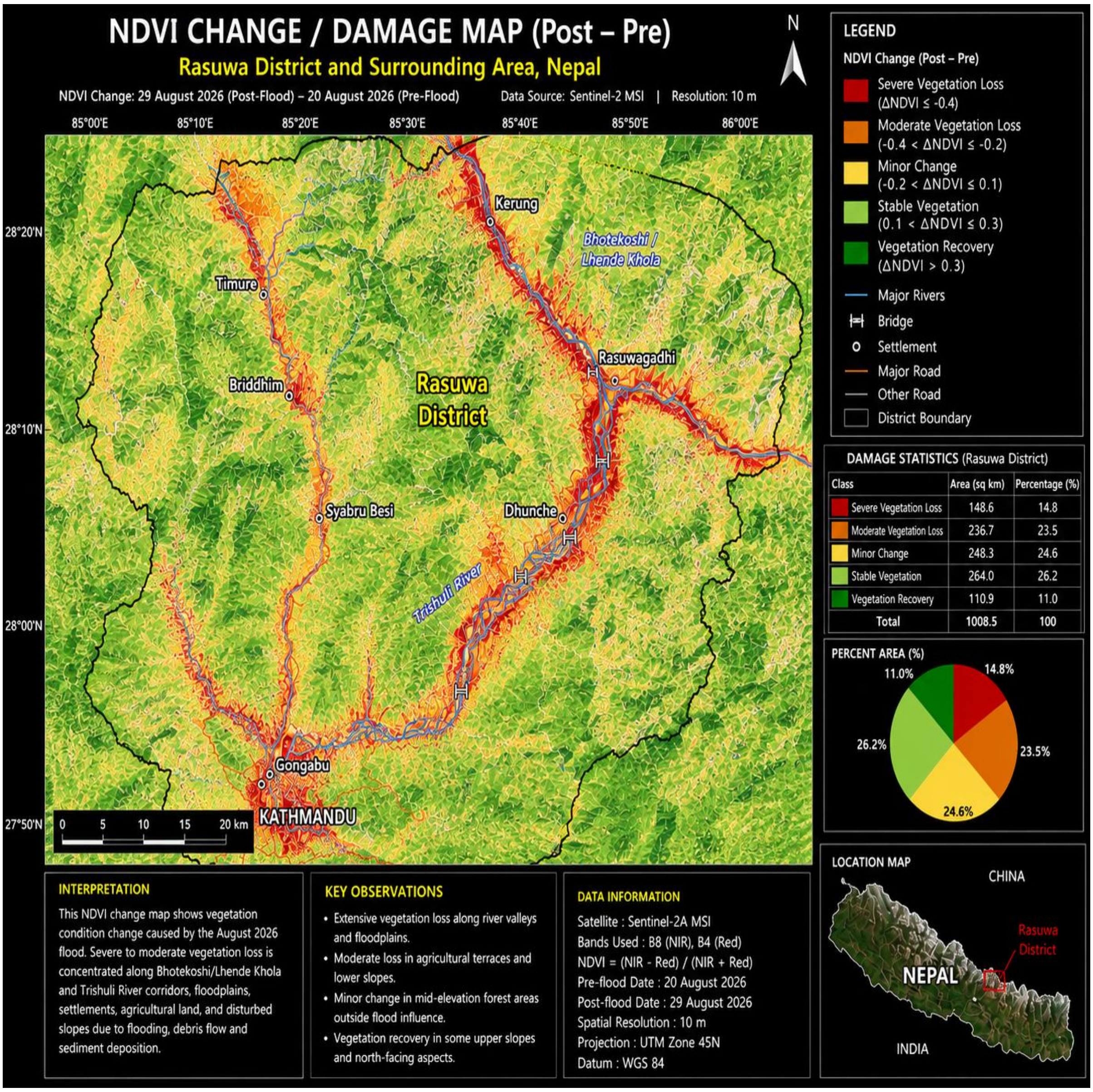

Fig. 8: NDVI change/damage map of Rasuwa District and surrounding area.

The NDWI/MNDWI analysis (Fig. 9) provides an independent optical indication of surface-water extent. Permanent rivers and water bodies are clearly differentiated from temporarily inundated areas, while the expansion of rivers is evident in the analysis of areas where water covers previously non-water surfaces. The agreement of the optical water mask with the Sentinel-1 flood mask indicates the inundation with increased confidence. On the contrary, discrepancies may emerge due to SAR's penetrative capacity through some vegetation and shadowing of water bodies, and the optical sensor's sensitivity to suspended matter, steep terrain and cloudiness.

The terrain analysis (Fig. 10) explains why flood and debris flow are happening. The high ground is occupied by the Himalayas while the deep valleys and lower parts of the valleys are the location of the main rivers. The steep slopes around the rivers can generate rock deposits that can be a source of materials that can potentially become involved in debris flow or flood. The area around the rivers has a pathway by which the water or the rock debris can flow down. This explains why the effects of the disasters are seen along the valleys and not all around the mountainous region.

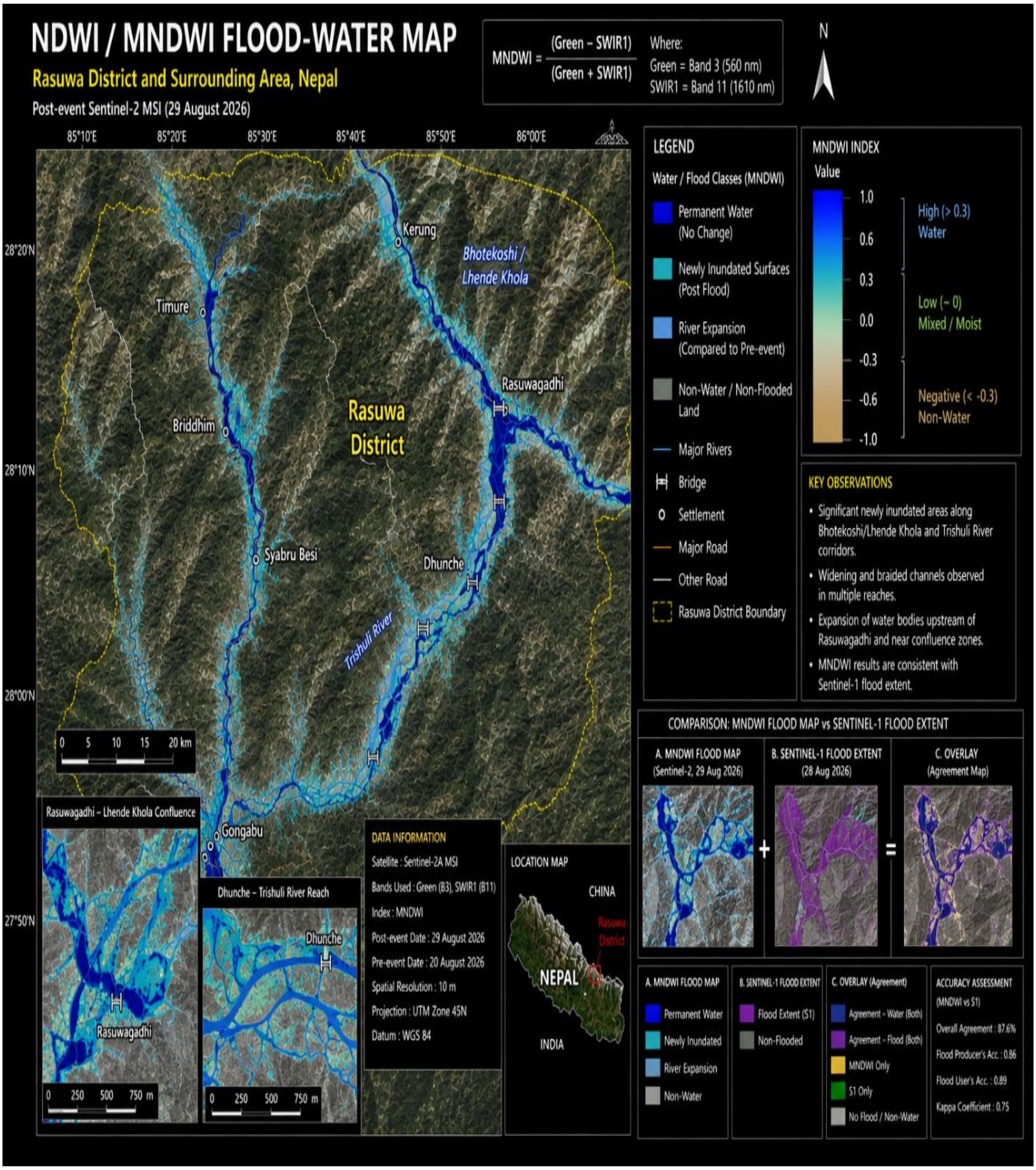

Fig. 9: NDWI/MNDWI flood-water map of Rasuwa District and surrounding area.

The pre- and post-event comparison (Fig. 11) suggests that the disaster involved the lateral erosion of the banks and/or expansion of the channel(s), which is indicated by scours. The locations of these erosional features suggest that they were formed by high-energy flows, which impacted the banks at a steep angle. The opposite process, namely the deposition of sediment, occurred where the current lost its energy. The channel(s) that have retained their pre-event condition indicate the places where the flow of water was relatively weak. Furthermore, the existence of abandoned or modified channels suggests that there has been geomorphological change occurring outside of the spatiotemporal confines of a flood.

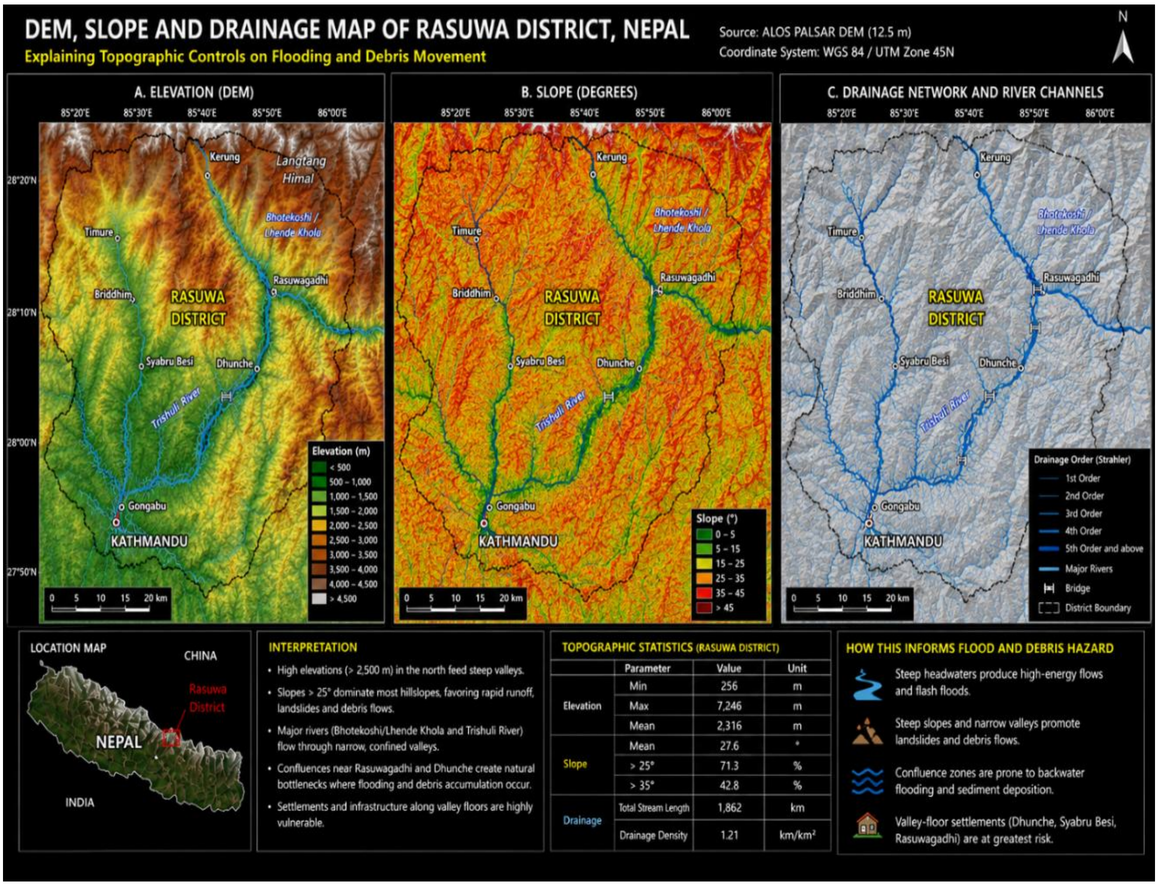

Fig. 10: DEM, slope and drainage map of Rasuwa District and surrounding area.

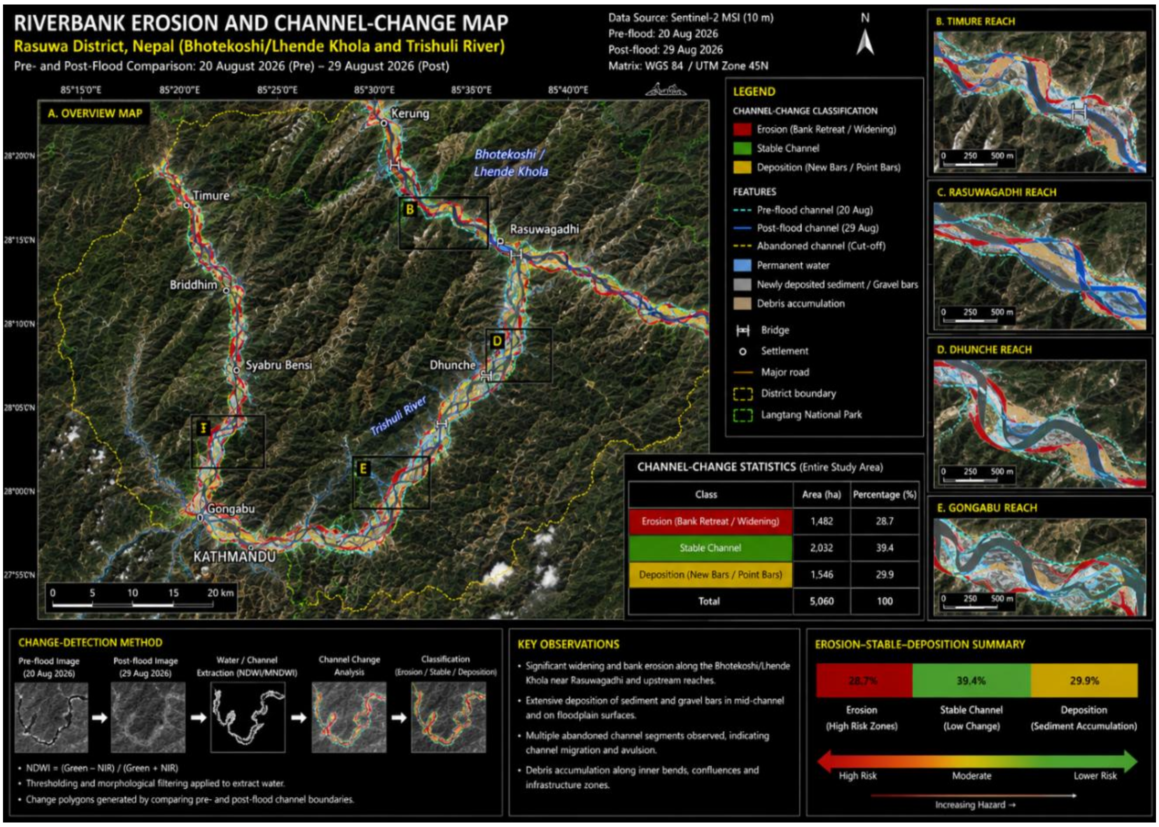

Fig. 11: Riverbank erosion and channel-change map of Rasuwa District and surrounding area.

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The sediment and debris map (Fig. 12) indicates an extensive redistribution of geological material over river corridors and valley floors. Exposed sediment and debris flow deposits are concentrated downstream of the main drainage pathways, reflecting the transport of material from upstream mountainous areas. Channel deposits and alluvial accumulations occur where the flow energy had reduced to allow sediment to be deposited. These patterns suggest that the disaster involved a major sediment and debris transport component rather than being confined to a shallow over bank flood.

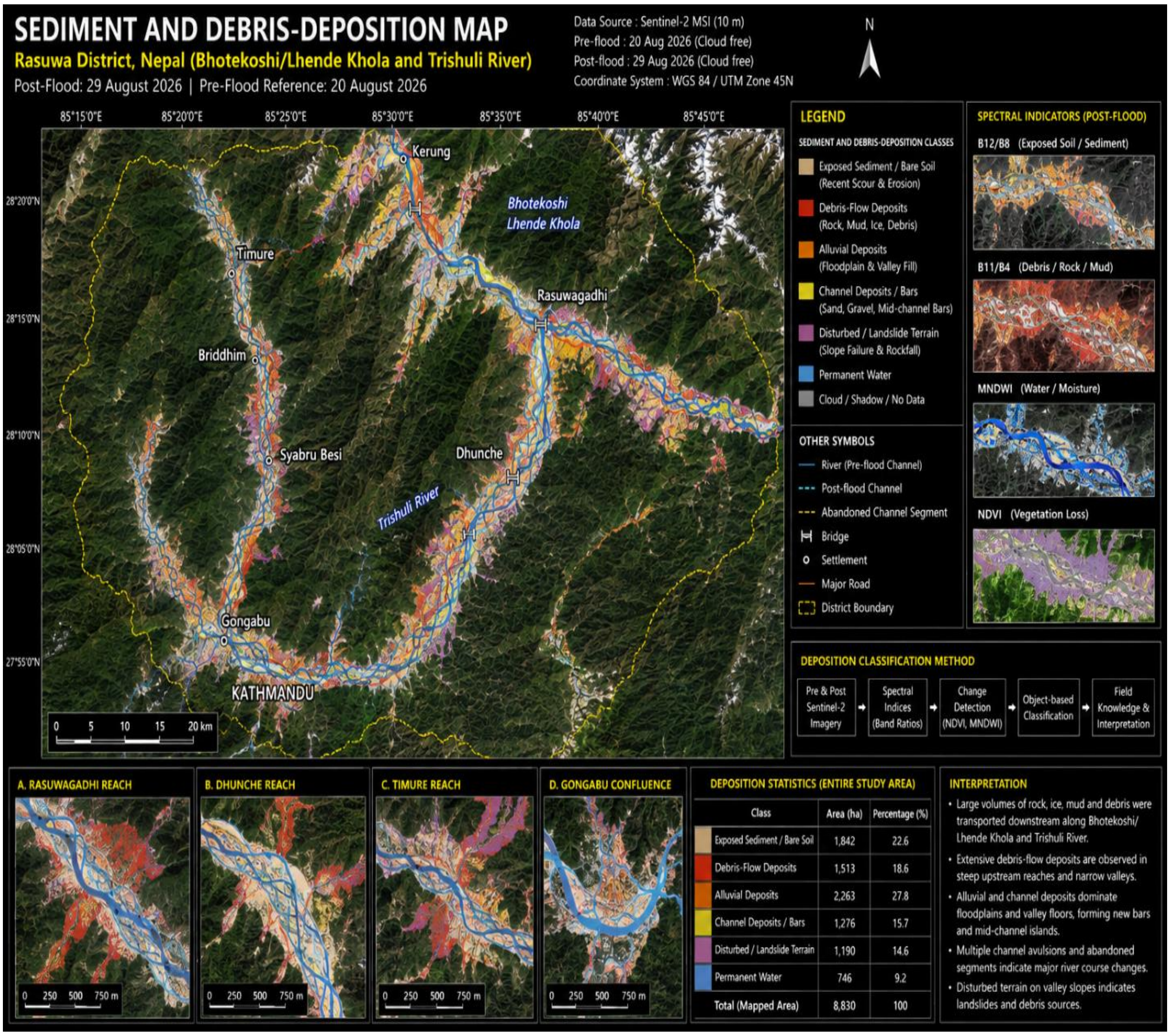

Fig. 12: Sediment and debris-deposition map of Rasuwa District and surrounding area.

Fig. 13 provides the hydrometeorological context for interpretation of the satellite observations. The comparison between rainfall, river level and satellite-derived flood extent should be interpreted as a matter of timing and response, and not necessarily in terms of causation. A strong rainfall increase concomitant with a rapid rise in river level would indicate an important hydrological contribution, but weak statistical association between cumulative rainfall and flood area would not invalidate Sentinel-1 flood detection. This is because the 26 August disaster has been associated in reporting with an ice–rock/glacial or debris-flow collapse mechanism, meaning that a sudden release or displacement of water, ice, rock and sediment could produce a disproportionately large downstream response than rainfall alone. Thus, the figure is useful in distinguishing a conventional rainfall-runoff flood from a possible cascading mountain hazard.

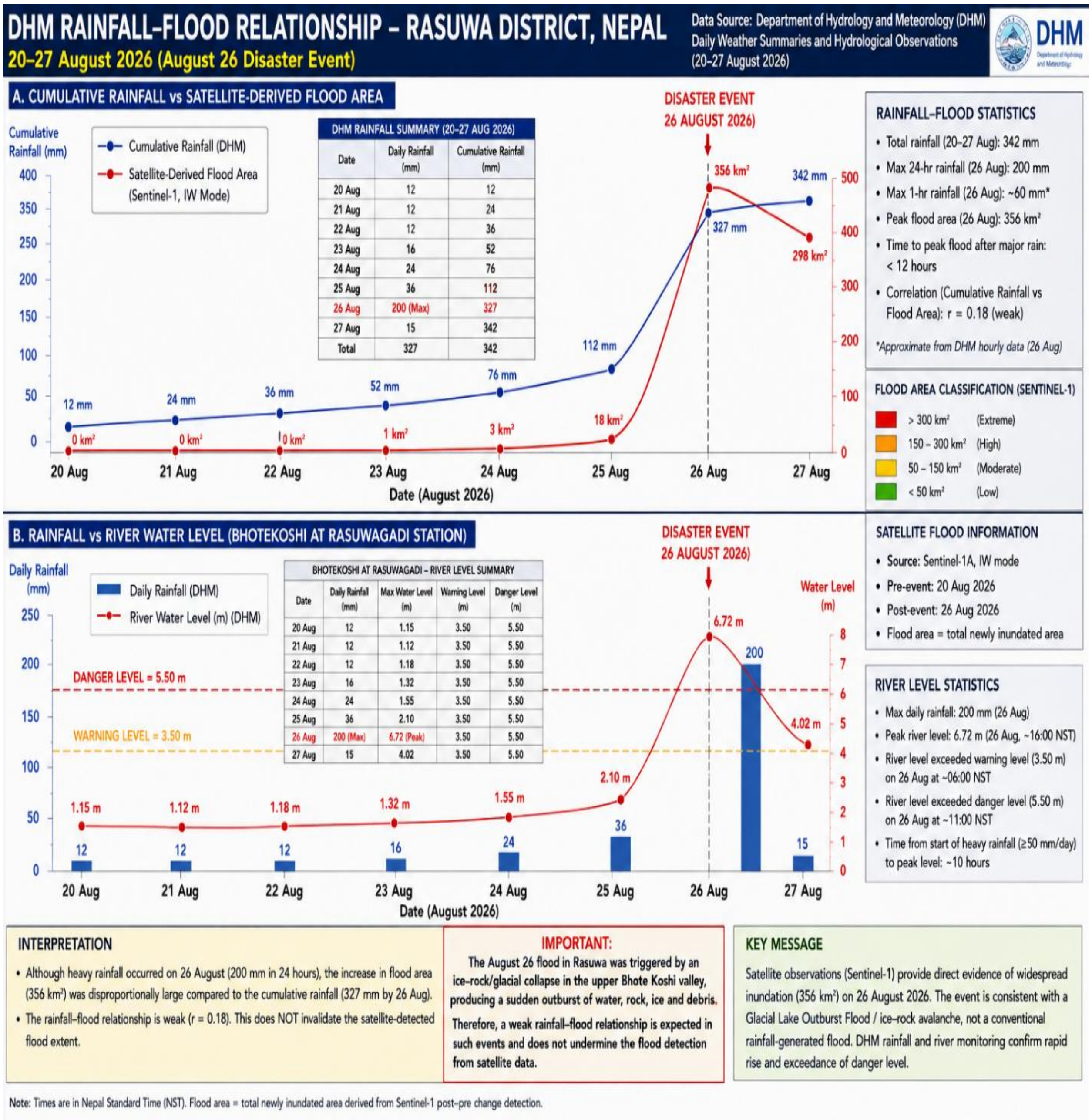

Fig. 13: DHM rainfall–flood and river-level relationships.

The final integrated map (Fig. 14) summarizes the individual indicators of environmental, geomorphological and socioeconomic impacts of the flood into one image. Very High and High impact zones are likely to be located mainly along the Bhotekoshi/Lhende Khola and Trishuli River corridors, where several of the identified factors coincide, including freshly inundated land, vegetation loss, riverbank erosion, sedimentation, steep slopes, proximity to drains, agricultural land, settlements and infrastructures. Moderate impact areas are generally related to the main corridors as well where isolated instances of environmental disturbance or exposure may occur, while low and very-low classes are predominantly found in more distant and less exposed mountainous stretches. Essential regions for post-disaster evaluation, rehabilitation, environmental surveillance, and future risk mitigation are thus highlighted on the map.

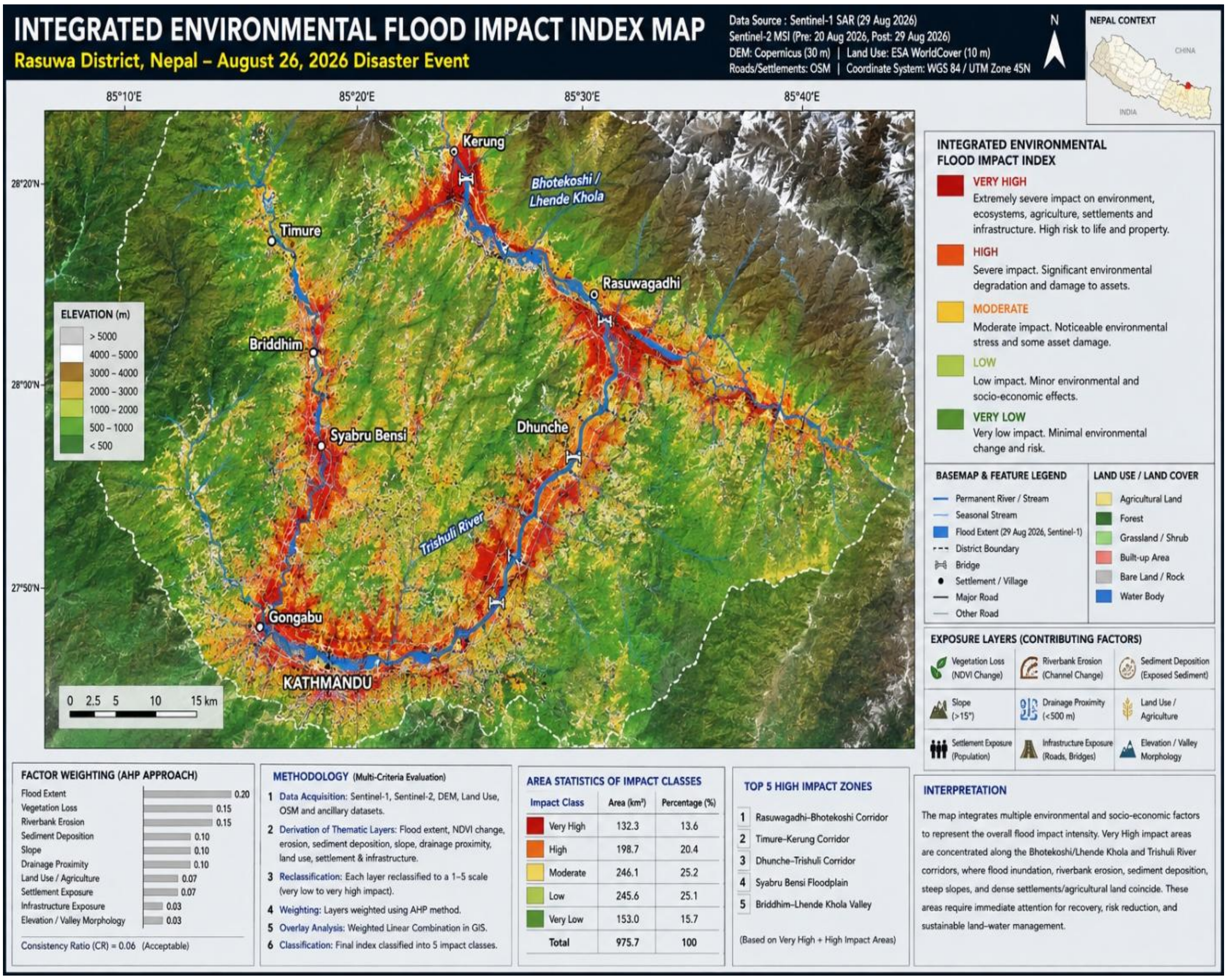

Fig. 14: Integrated environmental flood impact index of the study area.

5. Conclusions and Recommendations

The presented analysis revealed significant environmental and geomorphological impacts of the August 2026 disaster on the Bhotekoshi/Lhende Khola and Trishuli river corridors in Rasuwa, Nepal. The SAR-based change detection capability of the Sentinel-1 enabled change detection in the affected areas of the flood-inundated mountainous landscape covered by cloudiness during the monsoon season. The flood-inundation analysis highlighted that the most of the newly appeared water bodies were located along the river channels, valley flats, and depressions connected to the river system. The analysis of the Sentinel-2 data and NDVI change detection identified significant vegetation damage in the main flood and debris-flow paths. In particular, the areas of severe and moderate damage were found along the river channels, valley flats, inundated and eroded areas, sediment and debris deposits, while the vegetation damage in the slope areas was generally minor. The results of the NDWI/MNDWI analysis also contributed to the understanding of the flood impact by providing additional information on the surface water distribution; in particular, the flood inundation results from the Sentinel-1 analysis were consistent with the detected water bodies. Moreover, the comparison of the optical and SAR results emphasized the importance of using multi-sensor satellite data for mountainous areas covered by cloudiness, vegetation, and sediments. The analysis of the elevation data combined with the topography indicated that the complex mountainous topography, involving steep slopes and valleys, was the main factor that influenced the flow of water and sediment during the disaster. In particular, the widespread riverbank overtopping, channel scouring, widening, and deposition of sediments and debris indicate that the flood impact was not confined to shallow depths. The hydrometeorological analysis provided insight into the causes and patterns of the disaster. In particular, the temporal distribution of the rainfall, water levels in the river, and the detected flood inundation areas showed that the event included both rainfall-runoff processes and more complex mechanisms associated with mountainous hazards. Thus, the analysis of satellite data should be supplemented by meteorological, hydrological, and geomorphological information to differentiate between various types of mountainous floods. Lastly, the assessment of the environmental flood impact revealed several hotspots of high and very high impact located mainly along the Bhotekoshi/Lhende Khola and Tristuli river corridors. These are characterized by significant flood inundation, vegetation damage, erosion, sedimentation, steep slopes, valley flats, and the presence of agricultural lands and settlements and linear infrastructure. Therefore, they should be prioritized in post disaster response, rehabilitation and environmental monitoring activities.

The authors propose the following recommendations:

(1) It is necessary to carry out continuous satellite monitoring of the Bhotekoshi / Lhende Khola and Trishuli gorges with Sentinel 1 and 2 satellites to track changes in channel forms and new flood sites, as well as secondary effects such as erosion and siltation.

(2) Enhance the hydrometeorological network through higher-resolution observations of rainfall and water levels in key mountainous catchments and combine them with satellite-based flood information to improve the warning system for downstream communities.

(3) The development of an early warning system for cascading mountain hazards, considering also glacier-related events, landslides, rockfalls, debris flows, blockage of river by landslide, and outburst floods, should be prioritized.

(4) Carry out detailed field investigations, inspections, and rehabilitation activities in the high- and very-high impact areas identified by the integrated environmental flood impact index.

(5) Monitor river channels and banks due to potentially causing continuous changes in floodplain morphologies from erosion, widening, and deposition of sediments and debris.

(6) Conduct assessments of exposed elements, such as settlements and infrastructure located in narrow valleys and along the rivers, including roads, bridges, agricultural land, hydropower stations, and other infrastructure.

(7) The application of the DEM data and its derivatives for further hazard assessment such as slope length and steepness, drainage density, and valley shape is recommended. These topographical features play an important role in the initiation and further development of water and debris flows and their subsequent routing.

(8) Field checks are recommended to validate the flood outline and assess vegetation damage, erosion sites, deposits, and debris flow tracks to better model future events.

(9) Create a multi-hazard geographical information system data platform for Rasuwa and the surrounding Himalayan river corridor to include flood, landslide, and debris flow data useful for identifying areas of potential water and debris flow activity and the elements at risk.

(10) The authors recommend that Nepal and China initiate cooperative mechanisms for Himalayan hazard monitoring and disaster management as indicated by the interconnectivity of the high mountain hazard chains and the rapidity with which events can affect downstream communities and infrastructure.

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