Journal Pre-proof

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PII: S2666-5921(25)00043-5

DOI: https://doi.org/10.1016/j.nhres.2025.04.001

Reference: NHRES 259

To appear in: *Natural Hazard Research*

Received Date: 16 January 2025

Revised Date: 9 March 2025

Accepted Date: 3 April 2025

Please cite this article as: Lamichhane, K., Karki, S., Sharma, K., Khadka, B., Acharya, B., Biswakarma, K., Adhikari, S., KC, R., Danegulu, A., Bhattarai, S., Regmi, A., Subedi, M., Bhattarai, P.K., Unraveling the Causes and Impacts of Increasing Flood Disasters in the Kathmandu Valley: Lessons from the Unprecedented September 2024 Floods, *Natural Hazard Research*, https://doi.org/10.1016/j.nhres.2025.04.001.

Unraveling the Causes and Impacts of Increasing Flood Disasters in the Kathmandu Valley: Lessons from the Unprecedented September 2024 Floods

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Abstract

Understanding the underlying causes of flood disasters is essential not only for developing effective flood management strategies but also for evaluating past policies and mitigation efforts. This study investigates the multi-dimensional causes and impacts of the increasing flood disasters in the Kathmandu Valley and the surrounding Roshi catchment, with a specific focus on the unprecedented September 2024 floods. Using a diverse range of data sources-including field observations, open-ended interviews, published studies and reports, remote sensing, socio-economic and hydro-meteorological data, as well as institutional, legal, and policy frameworks-we identify key factors contributing to the rising flood risk in and around the valley. The causes of flooding were broadly categorized into four main areas: catchment characteristics, anthropogenic activities, hydro-meteorological factors, and policy and institutional frameworks. The extreme rainfall events of September 2024 and the resulting floods further exposed the Kathmandu Valley's vulnerability, causing over three dozen fatalities and millions in economic losses. Unlike previous years, the flood impacts were exacerbated by debris flows and landslides from surrounding hillslopes, along with sediment contributions from mining sites and encroached riverbanks, intensifying the severity of inundation. Despite early warnings of heavy rainfall from concerned agencies, inadequate preparedness and response significantly amplified the disaster's impact, revealing critical gaps in Nepal's disaster management framework. Instead of a one-size-fits-all approach, effective flood management in the Kathmandu Valley requires a collaborative, multi-dimensional strategy tailored to its unique challenges. The September 2024 floods underscore the urgent need for systemic reforms in urban planning, policy reforms and enforcement, inter-agency collaboration, strengthened local government, and disaster risk management. Our analysis provide critical insights for enhancing flood resilience and improving future flood risk management strategies in a holistic manner.

Keywords: Urban flood management, Extreme precipitation, Unregulated mining, Anthropogenic factors, Disaster preparedness

1. Introduction

Floods rank among the most frequent natural disasters globally, with a tremendous capacity to cause widespread devastation, including significant loss of life, extensive economic damage, and severe environmental threats (Kundzewicz et al., 2014; Arnell & Gosling, 2016; Sajjad et al., 2023; Chaudhary et al., 2024). Natural and human-induced factors contribute to these events. The natural causes include heavy rainfall, riverine floods, and high tides. Moreover, human activities such as obstructed or poorly maintained drainage channels, river encroachment, improper land use, unmanaged sand mining, and deforestation in upstream regions exacerbate the impacts (Tingsanchali, 2012). Additionally, climate change has exacerbated the frequency and intensity of rainstorm flood disasters, making them among the most pressing threats to human survival and social development (Daksiya et al., 2021; Li & Sivapalan, 2020; Aerts et al., 2014). Given these factors, urban areas, particularly those situated in flood-prone regions, are increasingly susceptible to the devastating impacts of flooding, a concern that is especially relevant for rapidly urbanizing areas such as the Kathmandu Valley Watershed (KVW). Different studies at KVW have revealed that rapid urbanization has altered the water balance, leading to increased runoff, increased susceptibility to flood inundation and reduced groundwater recharge (Acharya et al., 2023, Danegulu et al. 2024).

Urban settlements and cities often develop in floodplains due to their flat topography, improved accessibility and fertile soil, which support both agricultural activities and infrastructure growth (Tingsanchali, 2012). In the case of the KVW, this pattern is particularly evident, as valley development has increasingly encroached upon floodplains, resulting in significant challenges in managing surface runoff and exacerbating flood risks. Similarly, KV is characterized by a substantial proportion of impermeable surfaces, which hinder the absorption of rainfall into the ground. As a result, excessive surface runoff is generated, contributing to elevated flood levels and widespread inundation (Morris et al., 2004). The city's rapid urbanization and inadequate flood management systems exacerbate its susceptibility to such events (Pauleit & Duhme, 2000).

KVW has experienced several significant flooding events over the years. The 1954 flood was among the earliest recorded floods, causing extensive damage to agricultural lands and infrastructure (Sharma et al., 1996). The 1981 flood, triggered by intense monsoon rains, affected parts of Kathmandu, highlighting the vulnerability of the valley's unplanned urban expansion (ICIMOD, 2009). The 1993 flood, one of the most devastating floods, was caused by heavy monsoon rainfall and resulted in over 130 fatalities and widespread destruction (Shrestha, 2000). Similarly, the 2002 flood caused inundation in low-lying areas due to excessive rainfall combined with inadequate drainage systems (MoHA, 2004). The 2008 flood, though smaller in scale, further underscored the need for resilient infrastructure, as it disrupted local communities and economic activities (ICIMOD, 2010).

The unprecedented rainfall that struck central Nepal from September 26–28, 2024, set record-high 24-hour rainfall totals at 25 weather stations nationwide (DHM, 2024). Over 60 hours of continuous rain triggered landslides and debris flows, severely affecting the Kathmandu Valley and nearby areas. The unprecedented rainfall event in central Nepal was triggered by a large-scale low-pressure system located over northern India, combined with a secondary cyclonic disturbance over western India. This interaction resulted in deep cyclonic flow and moisture convergence. The systems facilitated the movement of powerful southwesterly winds, which carried moisture from both the Arabian Sea and the Bay of Bengal toward the Himalayan region (DHM, 2024). This disaster impacted 2.59 million people across 518,403 households, resulting in 250 fatalities, 18 missing persons, and significant injuries. Economic losses exceeded 1% of Nepal's GDP, amounting to USD 340.74 million with extensive damage to infrastructure, including water and sanitation systems, bridges, highways, and hydropower plants (NDDRMA, 2024). Agriculture also suffers greatly, with damage to thousands of hectares of crops and livestock, alongside disruptions to health and education facilities. Although assessments are still ongoing, the scale of destruction has been immense.

Flood events and their associated damage are widely reported across various government reports and media platforms, including social media, but the focus typically diminishes once the flood season ends. In Nepal, while the immediate impacts are acknowledged, the root causes of these floods are rarely analyzed in depth. This lack of comprehensive analysis not only limits the understanding of the specific factors contributing to flood events but also impedes the formulation of targeted, evidence-based policy decisions. Past studies on flood inundation issues either focus only on the modeling aspect or mapping aspect neglecting socio-economic and policy aspects. Taking a more holistic approach to analyzing flood events by considering environmental, infrastructural, and socioeconomic factors would offer valuable insights and support more effective disaster risk reduction and long-term flood management strategies which is the foundation of this study. KVW has already experienced several devastating floods, yet their detailed studies are not widely available. Even when available, they are mostly descriptive of the events. The combination of quantitative, semi-quantitative, and subjective discussions is lacking, making it difficult to fully realize the severity of flood hazards. Moreover, feasible policy recommendations are often missing.

This paper aims to bridge the existing gap in flood-related research by identifying the probable causes of flooding in the KVW. On the basis of these findings, potential measures are recommended with the objective of informing relevant authorities, policymakers, and the government to take both immediate and long-term actions to address flood risks in the valley and other urban areas of Nepal. On the basis of this comprehensive analysis, this paper proposes both short-term and long-term mitigation strategies aimed at improving flood resilience in the region.

2. Study Area

The Kathmandu Valley, located in Bagmati Province in central Nepal, spans latitudes 27°32'00" N to 27°49'16" N and longitudes 85°13'28" E to 85°31'53" E, covering the districts of Kathmandu, Lalitpur, and Bhaktapur, as depicted in **Figure 1(a)**. The valley, with a catchment area of approximately 625 km^2, is an intermountain basin with elevations ranging from 1200 to 2700 m above mean sea level (**Figure 1(b)**). The valley experiences an average annual rainfall of 1621 mm, surpassing the standard average annual rainfall of 1570.4 mm (DHM, 2023). The valley's rivers flow toward the center, converging into the Bagmati River, whose main tributaries include the Bishnumati, Hanumante, Manohara, Dhobi Khola, Balkhu, Kodku, Manamati, and Nakhkhu River, which drain through the Chobhar gorge. Among the nine rivers in the region, six flow through Kathmandu District, two through Lalitpur District, and one through Bhaktapur District, as shown in **Figure 1(b)**. In this study, we demarcated the KVW using catchment area at the downstream most hydrological station i.e. Khokana in Lalitpur district. Accordingly, KVW doesn't cover whole area of the three valley districts. Additionally, we have included Roshi River watershed that lies adjacent to Nakhkhu river sub-watershed of the KVW as it was severely impacted by the floods.

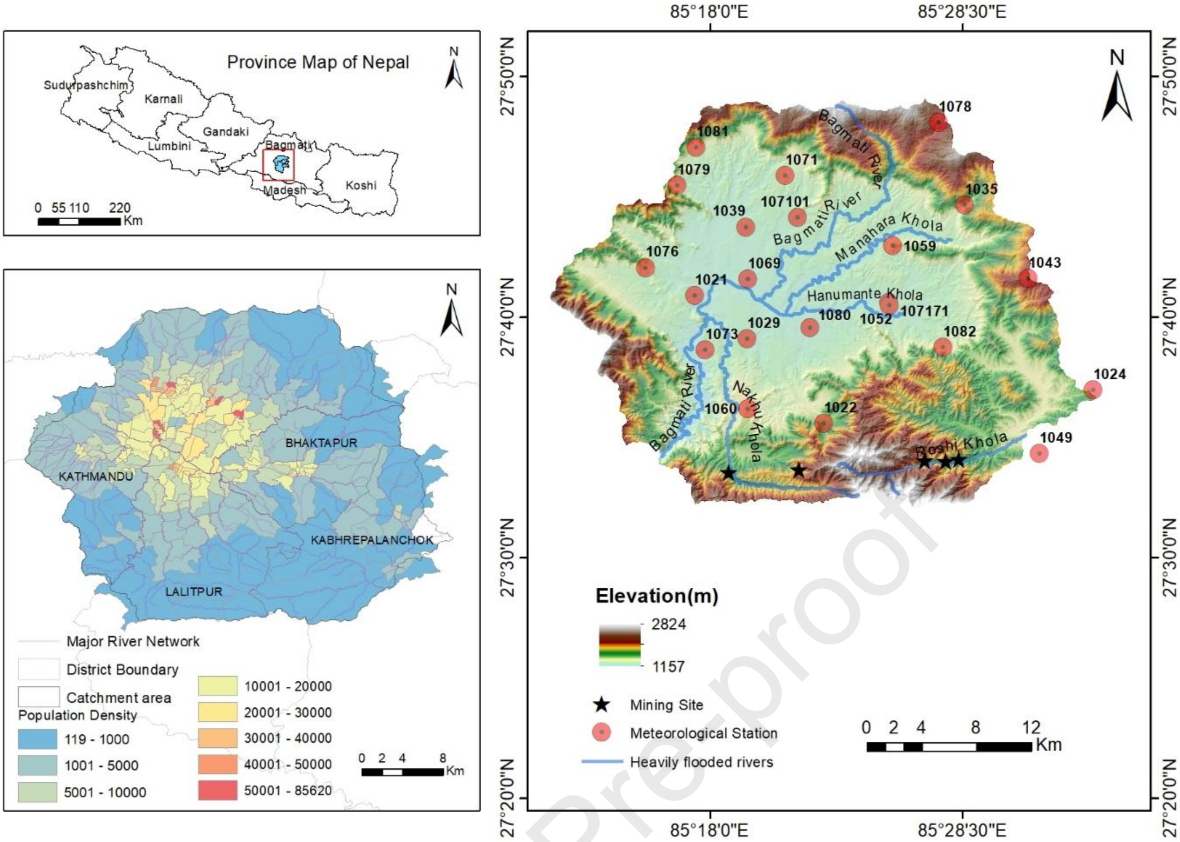


***Figure 1**: (a) Map of federal Nepal highlighting the Kathmandu Valley and the surrounding areas; (b) Elevation map of the study area, river networks, and meteorological stations; and (c) Ward-level population density within the study catchments.*

The Kathmandu Valley comprises various local government divisions, including three key urban centers—Kathmandu Metropolitan City, Lalitpur Metropolitan City, and Bhaktapur Municipality—along with sixteen additional local administrative units (municipalities and rural municipalities). According to the 2021 census, the valley is home to approximately 2.94 million residents and serves as a key hub for the country's major commercial activities, educational and health facilities and agricultural production (CBS, 2021). The population density is also greater in areas close to rivers, as illustrated in **Figure 1(c)**. The combination of geological, topographical and meteorological factors, along with socioeconomic conditions, makes the KVW one of the region most susceptible to flooding in Nepal, particularly settlements close to river floodplains in the Bagmati Corridor (Mesta, 2022). This problem is further exacerbated by a changing climate, urbanization, and river encroachment, as reported by Danegulu et al. (2024) and Pradhan & Pokharel (2017).

3. Methodology

This research employs a comprehensive, multidisciplinary methodology to identify and analyze the causes and impacts of floods in September 2024, linking these factors to broader flood issues in and around the KVW. It further aims to propose both short- and long-term solution measures for KVW flooding problems and, consequently, for other urban areas of Nepal. Data collection involved field visits for onsite observations, drone surveys to capture detailed aerial imagery, public consultations to gather insights from local communities and stakeholders, hydrometeorological data, Sentinel-2 images before and after flooding for satellite imagery analysis, and a review of published literature and news reports to provide context and historical references. These diverse data sources were synthesized to perform preliminary damage assessments in most impacted areas, evaluating the physical, economic, and environmental impacts of floods. Field surveys and drone imagery have been increasingly used in disaster assessments to provide accurate spatial data for affected areas (Giordan et al., 2018). Public consultations enhance community engagement, which is critical for understanding localized vulnerabilities and perceptions (UNDRR, 2019). The detailed flowchart of this study is depicted in **Figure 2**. **Table 1** presents multiple data that are applied in this study to understand the flood disasters of KVW.

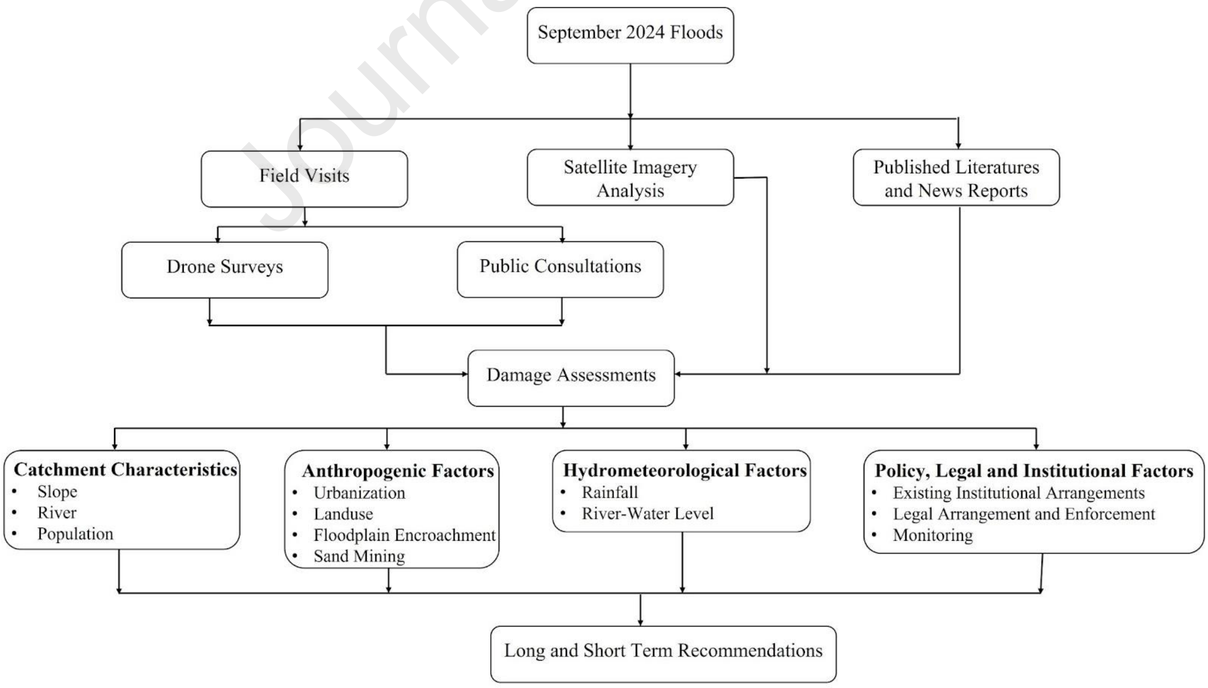


Figure 2*: (a) Illustration of the methodological framework followed in this study.*

***Table 1**: Data used in this study with their sources*

SN	*Data*	*Source*
1	*Rainfall, Discharge and river water-level data*	*Department of Hydrology and Meteorology (DHM), Nepal*
2	*Satellite imagery*	*Copernicus Sentinel data, European Space Agency (ESA)*
3	*Population data*	*Central Bureau of Statistics (CBS), Nepal*
4	*Digital Elevation Model (DEM)*	*FAB DEM, https://data.bris.ac.uk/data*
5	*Land use Land Cover data*	*ICIMOD's Regional Data Center (RDS)*
6	*Mining site related data*	*Google Earth and field visits*
7	*Other secondary data*	*Literatures, news articles, field visits, reports*

The assessment considered key contributing factors, including catchment characteristics (such as slope, river systems, and population distribution), anthropogenic influences (such as urbanization, land-use changes, floodplain encroachment, and sand mining), hydrometeorological factors (including rainfall patterns and river-water levels), and policy, legal, and institutional frameworks (such as governance structures, law enforcement, and monitoring systems). Studies have shown that catchment and hydrological parameters are pivotal in shaping flood behavior and impacts (Smith et al., 2020), whereas anthropogenic activities such as unplanned urbanization often exacerbate flood risks (IPCC, 2022). Reviewing institutional frameworks and policies is vital for identifying gaps in flood management and proposing actionable solutions (World Bank, 2018). This comprehensive analysis culminated in the development of long- and short-term recommendations, addressing the need for improved flood management strategies, infrastructure resilience, policy reforms, and community-based disaster preparedness to mitigate future flood risks effectively.

Additionally, satellite imagery analysis was performed to compare the catchments before and after flooding. The methodology employed for this analysis follows the approach outlined in Scheip and Wegmann (2021). Sentinel-2 data were used because of their high spatial resolution and multispectral capabilities, allowing accurate detection of vegetation changes. Normalized difference vegetation index (NDVI) values were calculated for both the pre- and post-flooding periods to assess vegetation health. The relative difference in the NDVI (rdNDVI) was then computed to highlight areas that experienced significant changes. Thresholds were applied to categorize the severity of impact, creating a comprehensive map of flood effects. Spatial analysis was conducted by overlaying river networks and flood-prone areas to correlate the observed changes with proximity to watercourses.

4. Preliminary Damage Assessment

4.1. Field Observations

A preliminary damage assessment was carried out through field reconnaissance in some of the most severely affected areas in central Nepal, including Tikabhairab and Nallu in Lalitpur, Roshi in Kavrepalanchowk, and various locations within KV. Walkthroughs along rivers, public consultations, and drone mapping were utilized to identify the nature and extent of damage, providing insights into the flood dynamics triggered by extreme rainfall events. Data on additional infrastructure, assets, and human losses were gathered from officially published reports. The floods impacted houses, roads, agricultural land, hydropower headworks, irrigation canals, bridges, and other critical infrastructure.

The Nakhkhu River catchment in the Lalitpur district flows through steep slopes in the upper reach. It has two mining (sand, aggregate and boulder) sites: one in the Lele River subcatchment and the other in the Nakhkhu main catchment approximately 2 km upstream of Tikabhairab. The flood resulted in widening and deepening of river channels in the upper reaches of Nakhkhu (also called Nallu). This reach lies upstream of the mining site. On the other hand, aggradation of the riverbed along with widening of the river width was observed in the lower reach, which is approximately 2 km downstream of the mining site. Mined materials stacked close to the riverbank were transported by floods, which further increased the sediment load in the river, which can be attributed to the aggradation of the riverbed between the mining site and Tikabhairab. River bed materials became coarser after the flood events, indicating the transport of materials from debris flows, landslides and upstream mining sites. Bank cutting and scouring near banks have caused several houses to overturn and be uprooted. One of the main features of this extreme rainfall event was the massive amount of sediment brought by the tributaries to the main river channel. This sediment mobilization has intensified flood dynamics and hence damage characteristics. While much of the debris flow and sedimentation along the tributaries can be attributed to land plotting on steep hillslopes and the unregulated excavation of hillslopes for road construction, the extreme rainfall has exceeded the threshold, triggering landslides and debris flows even on well-vegetated hillslopes.

Figure 3 depicts the widespread damage caused by flooding along the Nakhkhu River, with significant impacts observed on settlements and a nearby mining site. **Figure 3a** highlights the extent of damage near the mining site, illustrating severe sediment deposition and scouring that affected the surrounding area. The aftermath of a flood includes the destruction of infrastructure, which is visible in sediment-laden riverbanks and nearby structures. **Figure 3b** shows a damaged building located close to the river that was scoured and subsequently collapsed due to intense hydraulic forces during the flood. Similarly, **Figure 3c** shows the houses that collapsed into the river downstream of the mining site, likely due to weakened foundations and bank erosion during the event. **Figure 3d** shows heavy sediment accumulation at the confluence of tributary streams and the main Nakhkhu River, which caused significant damage to nearby buildings and approached a pedestrian suspension bridge. These images collectively highlight the role of sediment transport and deposition, scouring, and mining activities in exacerbating flood-induced destruction in the region.

***Figure 3**: (a) Nakhkhu River, settlements, and mining site post-flood showing damage due to sediment deposition and scouring; (b) damaged building near the river, scoured and collapsed upright during the flood; (c) houses collapsed upright into the river downstream of the mining site; and (d) heavy*

sediment accumulation at the confluence of tributary streams and the main Nakhkhu River, with damage to buildings and the pedestrian suspension bridge approach.

The Roshi River catchment in the Kavrepalanchowk district lies adjacent to the Nakhkhu catchment. The characteristics of the catchment and damage resemble each other. There are several mining sites operated by dozens of crusher industries upstream of the Roshi River. The Roshi River also flooded in 1981, but the scale of damage was minimal, and the river did not change its course (Darji and Ahmad, 2024). Field observations revealed that the river was narrowed to a minimal width for settlements, road construction, crusher industries, etc. Consequently, the Roshi River changed its course during the flood event and deposited more than 3 m of sediment in several reaches close to the riverbank burying houses and agricultural fields. Sediments from hillslopes as well as mined materials led to the aggradation of the riverbed from upstream to downstream near the Panauti hydropower project dam site. Approximately 5 m of deposition was measured upstream of the dam site. Several landslides, including debris and woody debris flows, have occurred along hillslopes, even those with high vegetation cover. Local level officials linked these factors to the fragility of the hillslopes caused by the 2015 Nepal Gorkha earthquake.

Figure 4a presents a wide aerial view captured by a drone, showing the flood-affected areas with a visibly widespread floodplain on the Roshi River bank, Kavrepalanchwok. Debris is spread across multiple buildings and agricultural lands, emphasizing the scale of devastation. **Figure 4b** depicts the mining activity upstream of **Figure 4a**, where an entire mountain is literally being cut down. **Figure 4c** is a collapsed house situated within the floodplain approximately 400 m downstream of **Figure 4a**, likely toppled due to scouring that undermined its foundation parallel to the river's path. **Figure 4d** further 200 m downstream highlights another building inundated by floodwaters, with sediment and debris deposited throughout its ground floor.

***Figure 4**: (a) Aerial view of flood-affected areas downstream of the mining sites along the Roshi River, showing widespread floodplain and debris deposition over buildings and agricultural land; (b) mining site with sediment deposition resulting from hillslope excavation, showing the accumulation of loose material near the riverbank; (c) a collapsed house likely caused by scouring of the foundation parallel to the river path; and (d) a building inundated by floodwaters with extensive sediment and debris deposition on the ground floor.*

Figure 5 illustrates the severe and overlapping impacts of two distinct disasters—flooding and landslide/debris flows—on buildings and infrastructure. **Figure 5a** depicts the compound geohazards observed around Tikabhairab Bazar, Lalitpur, where extensive roadside landslides and flooding are both visible in a single frame. Similarly, **Figure 5b** presents a wider perspective of the area, showing some buildings, a road, and large areas of agricultural land subjected especially to debris flows. **Figure 5c** depicts landslides on both the left and right sides of the powerhouse (Panauti hydropower). These landslides on both banks of the Roshi Khola caused approximately 1.5 m of thick debris deposition, leading to the shutdown of the powerhouse. **Figure 5d** depicts the damage from scouring due to floodwaters, as well as the destruction caused by a landslide originating from the mountain side, emphasizing the dual threats faced by the building. The images collectively demonstrate the devastating consequences of being located in such a vulnerable area, where both river and mountain hazards contribute to destruction, leaving little to no opportunity for buildings to escape these impacts.

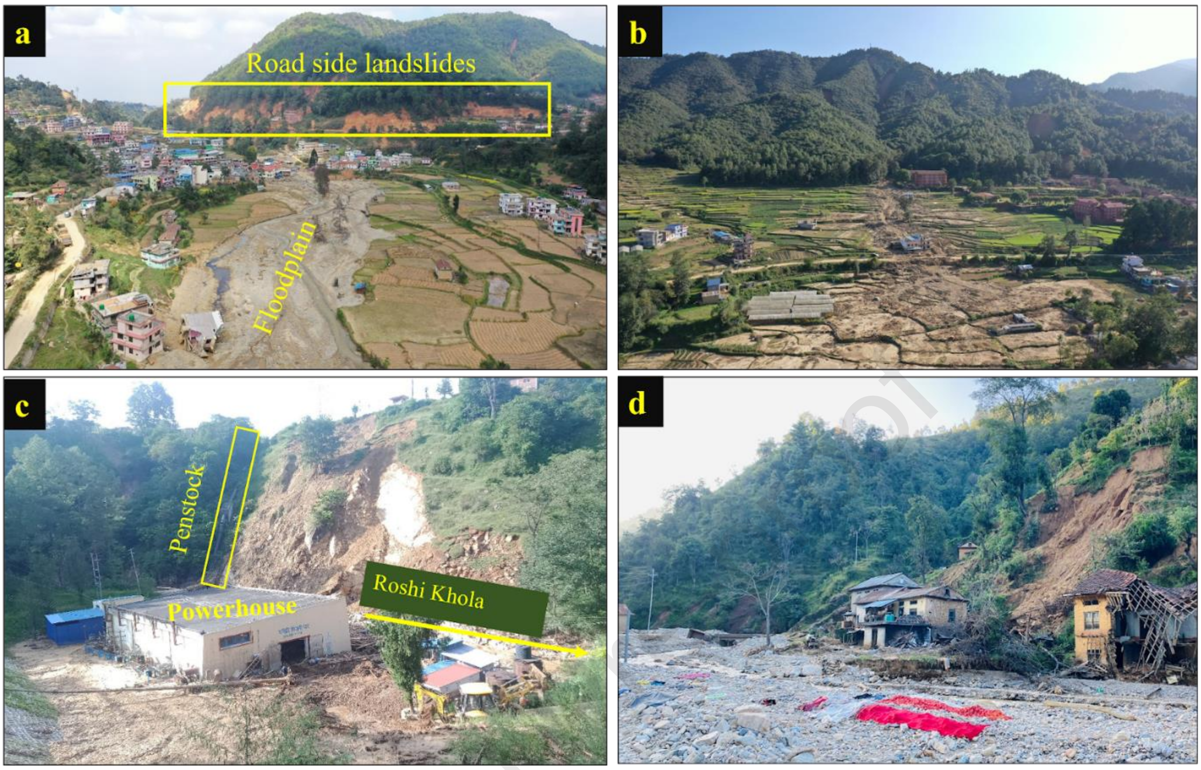


Figure 5: (a) Compound geohazards at Tikabhairab Bazar, Lalitpur, showing roadside landslides and flooding, (b) debris flow impacts on buildings, roads, and agricultural land, (c) landslides causing debris deposition and shutdown of Panauti hydropower, (d) flood scouring and a mountainside landslide threatening a building.

Figure 6 illustrates the extensive damage caused by the September 2024 floods in the Kathmandu Valley, particularly in Lalitpur and the regions surrounding the Manohara, Hanumante, Bagmati, and Nakhkhu rivers. The observed damage includes structural failure, sediment deposition, and disruption of essential infrastructure. Specifically, **Figure 6a** depicts severe erosion and collapse of the bridge abutment and road along the Manohara River, approximately 300 m upstream of its confluence with the Hanumante River. This type of structural failure is common in flood events where high flow velocities erode embankments and undermine foundations (Fischenich, 2001). **Figure 6b** highlights extensive silt deposition in a park near the confluence of the Manohara and Hanumante Rivers, resulting from the reduced flow velocity at these locations. **Figure 6c** shows tilted electric poles caused by base subsidence due to prolonged waterlogging, leading to power disruptions. **Figure 6d** presents the submerged Sankhamul Park downstream of the Manohara and Bagmati confluence, where floodplain expansion to 150–200 m was observed, a phenomenon linked to inadequate natural floodplain management (Smith et al., 2020). Further downstream, **Figure 6e** shows damage at UN Park along the Bagmati River, where the flood's intensity swept away a truss bridge, indicative of insufficient structural resilience against high-discharge events (Shrestha et al., 2021). Finally, **Figure 6f** shows an unusually high flood level at Chobhar Gorge, the primary outlet of the Bagmati River from the Kathmandu Valley, exacerbated by restricted channel capacity and sediment deposition at this critical drainage point.

Figure 6: *(a) Damage to bridge abutment and road along the Manohara River, (b) silt deposition in a park submerged by floodwaters near the confluence of the Manohara and Hanumante Rivers, (c) tilted electric poles caused by base subsidence after flood submergence, (d) submerged Sankhamul Park 100 m downstream of the confluence of the Manohara and Bagmati Rivers, (e) flood damage at UN Park along the Bagmati River, where a truss bridge was swept away (yellow line in figure indicates alignment of bridge, and (f) the Chobhar Gorge, the outlet of the Bagmati River from Kathmandu Valley, showing unusually high flood levels.*

Additionally, the area surrounding the Nakhkhu River, particularly from its confluence with the Bagmati River to approximately 500 m upstream, has been identified as a flood hotspot (**Figure 7**). Significant alterations to the Nakhkhu River occurred between 2007 (**Figure 7a**) and 2024 (**Figure 7b**), including the construction of concrete embankments that shifted the river's original path from 2007. Settlements have been established on the old river path, which experienced flooding during the three-day extreme rainfall event of 2024 (**Figure 7c**). Overall, in the Kathmandu Valley, extensive inundation was observed, resulting in the sweeping away of adobe houses in slum areas built along the Bagmati River, as well as damage to reinforced concrete fences, brick fences, and the accumulation of debris piles in parks. These events emphasize the need for robust flood management practices, including infrastructure resilience and sediment management strategies, as supported by findings from recent flood impact studies (Giordan et al., 2018; Smith et al., 2020). The observed impacts align with the global trends of urban flooding exacerbated by unplanned development.

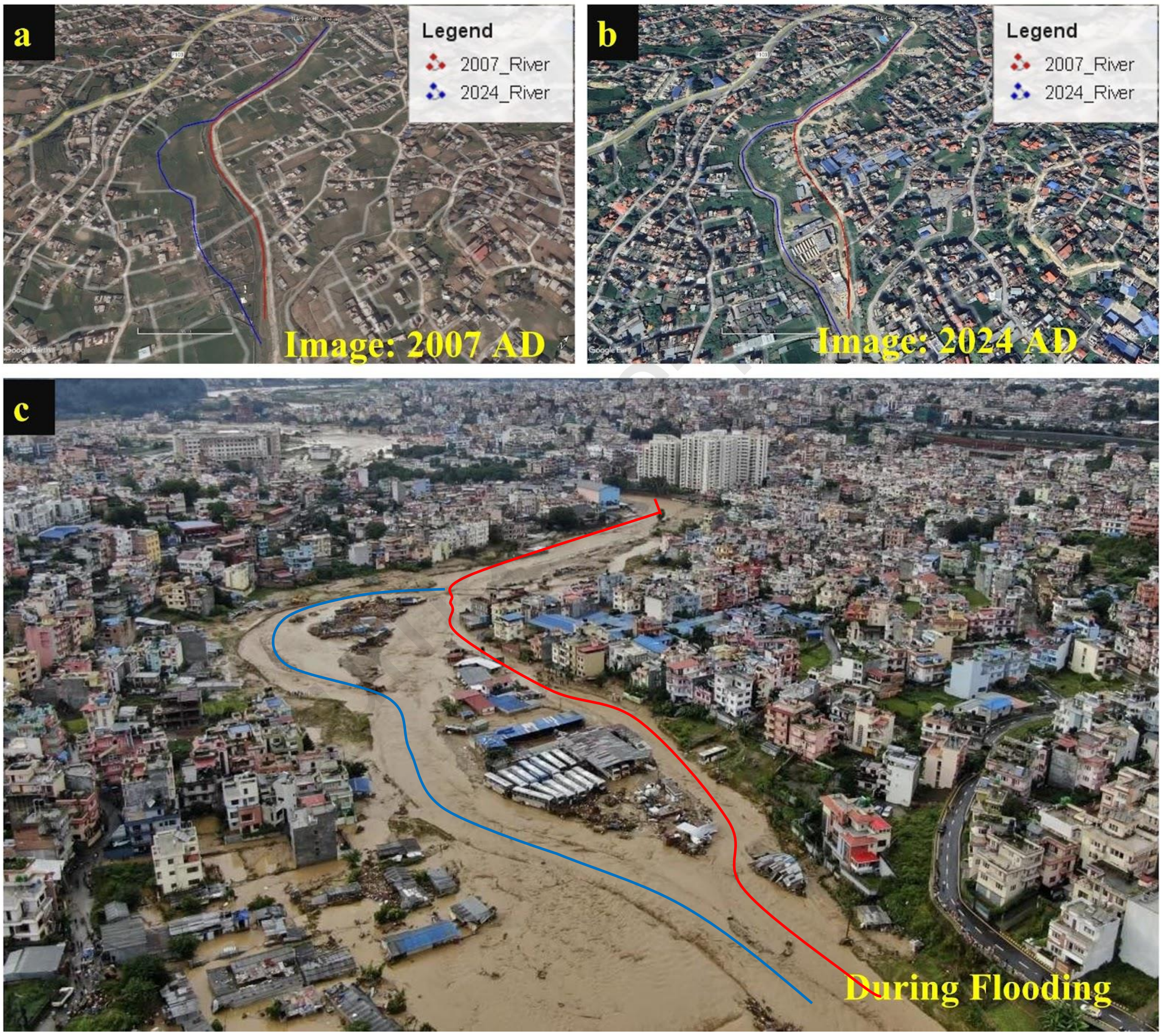


Figure 7: *(a) Google Earth image of the Nakhkhu River area, approximately 500 m upstream of its confluence with the Bagmati River, from 2007 AD; (b) the same location as that observed in 2024 AD; and (c) photographs of the same location during the flood event on September 28, 2024 (Photo: Gopen Rai). The flow direction is from the bottom to the top.*

4.2. Satellite Imagery Analysis

Satellite imagery analysis was performed to obtain an overview of the extent and location of flood inundation. Sentinel-2 imagery composites were analyzed for pre- and post-disaster scenarios. The relative difference normalized difference vegetation index (rdNDVI) map, which is a measure of changes in vegetation health and land cover caused by a flood event, was determined on the basis of the pre- and post-flood NDVI maps, as shown in **Figure 8**. This map is color-coded to categorize the severity of impact: areas in dark blue indicate severe damage with significant vegetation loss, those in light blue denote moderate impact, and those in yellow represent minor changes. Light red shading, on the other hand, represents areas that experienced no significant changes or even vegetation recovery and growth (dark red). Rivers, such as Bagmati, Manahara, Hanumante, Nakhkhu, and Roshi Khola, are marked for reference, as they play a critical role in shaping flood impacts across the valley. The rdNDVI map highlights that flood-affected areas are predominantly concentrated along these riverbanks, emphasizing their susceptibility to flood-induced changes. **Figure 9** represents the relative difference in the normalized difference vegetation index (rdNDVI) before and after flooding for selected river networks where significant flood impacts were observed. All these rdNDVI results are consistent with the visual inspections observed during post-flood reconnaissance. The visual contrasts of the 3rd NDVI help in understanding the spatial extent of flood impacts. This analysis demonstrates the effectiveness of remote sensing techniques in monitoring natural disasters such as flooding. This study provides valuable insights into the spatial distribution of flood-induced damage, emphasizing the vulnerability of areas along riverbanks and identifying regions where vegetation recovery is underway. Such studies are critical for disaster management, guiding mitigation efforts and resilience planning in flood-prone regions such as the Kathmandu Valley.

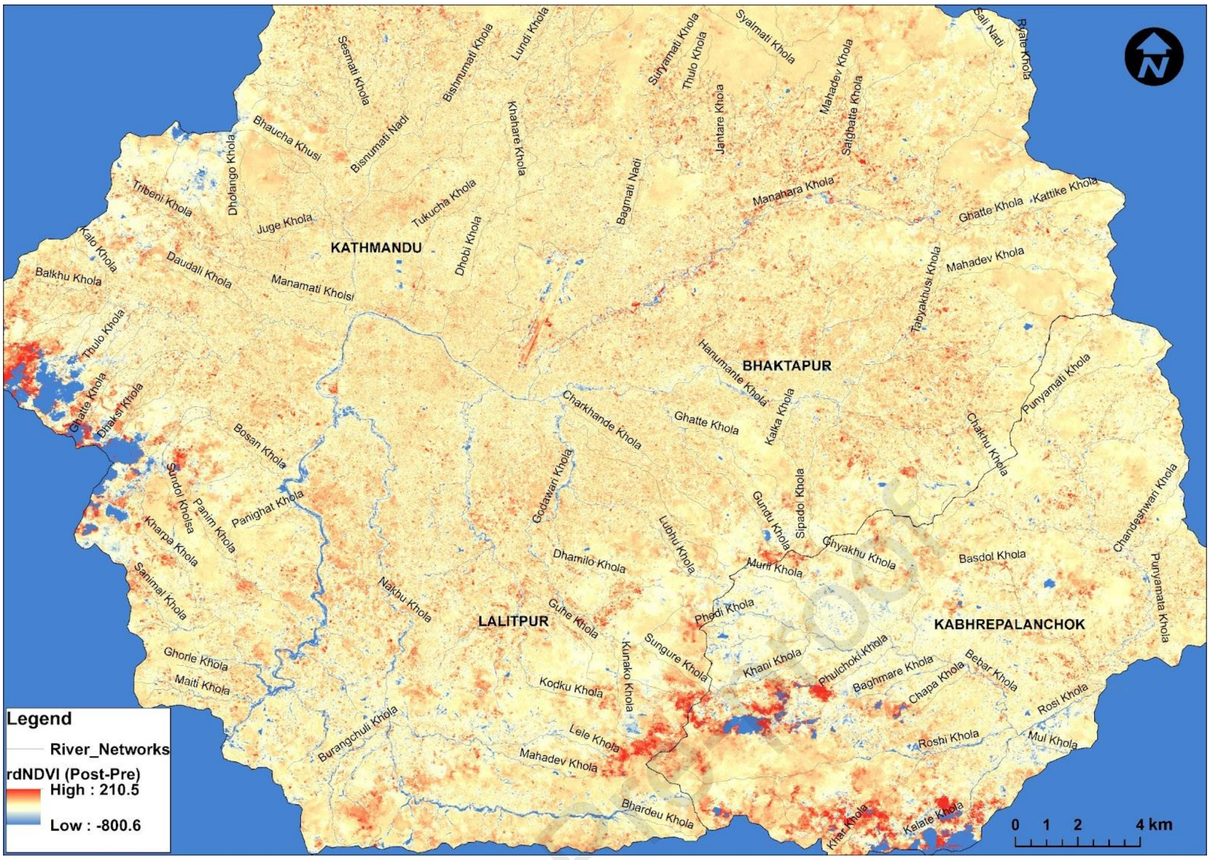


Figure 8: *The relative difference in the normalized difference vegetation index (rdNDVI) of the study area before and after flooding.*

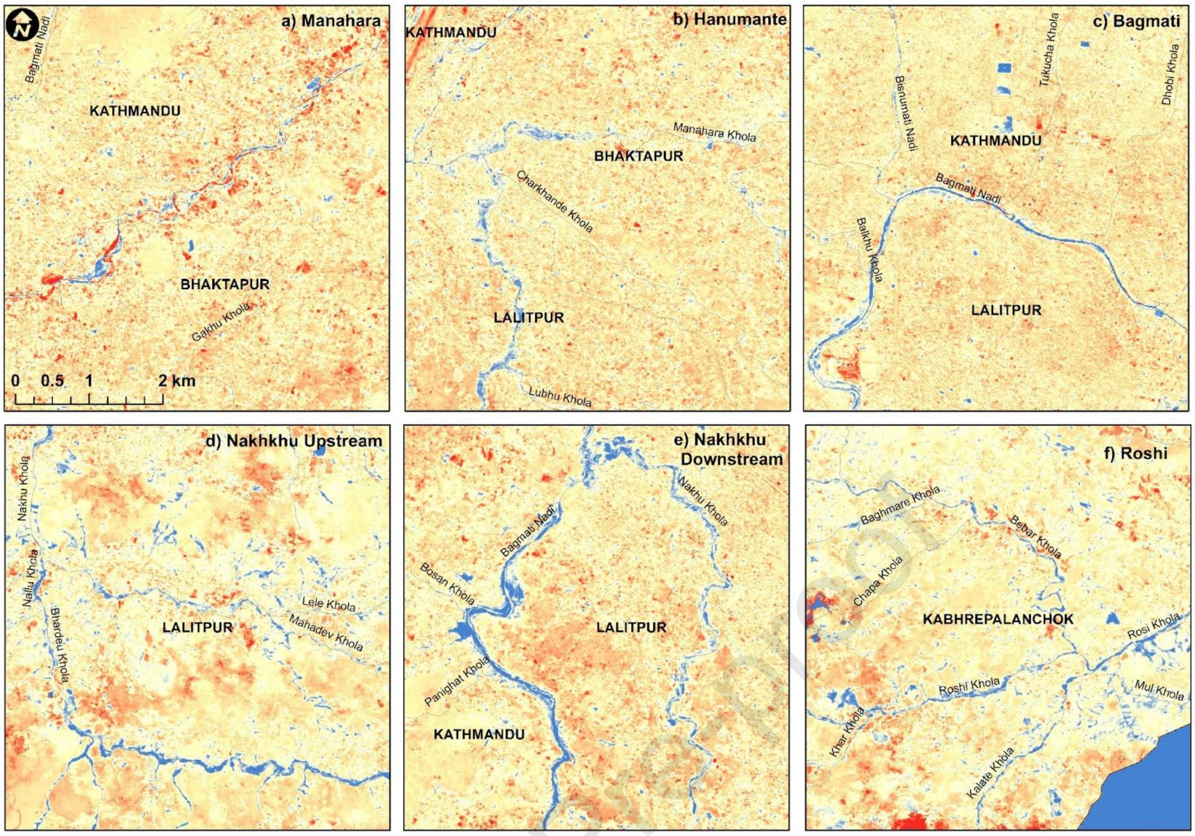


Figure 9: *Relative difference in the normalized difference vegetation index (rdNDVI) before and after flooding for selected river networks where significant flood impacts were observed: (a) Manahara River, (b) Hanumante River, (c) Bagmati River, (d) Nakhkhu River upstream, (e) Nakhkhu River downstream, and (f) Roshi River.*

5. Potential Factors Contributing to the September 2024 Flood

The interplay of various natural and anthropogenic factors significantly influences the severity of floods, which is also true for the September 2024 flood. This section identifies and presents the critical contributors to the worsening flood scenarios of KVW, broadly classified into two types: first, natural factors (including catchment characteristics such as area, slope, vegetation, river width, and hydro-meteorological conditions like rainfall and river level), and second, anthropogenic factors such as unplanned urbanization, poorly engineered river management works, river encroachment, and unregulated mining activities. Those factors which humans don’t have control over like catchment area, slope, rainfall, etc. are grouped into natural factors while those which occurred as a direct result of human interventions like urbanization, river management structures and hence encroachment, and mining related activities are categorized as human induced or anthropogenic factors which is further explored, highlighting their roles in exacerbating flood risks. The following subsections aim to provide a comprehensive analysis of these factors, laying the groundwork for understanding their individual and combined impacts on KVW flood disasters.

5.1. Catchment Characteristics

One of the inherent natural factors contributing to flooding in the rivers of KVW is the catchment's characteristics, including its shape, topography, and river profile. As illustrated in **Figure 1(b)**, the bowl-shaped catchment surrounded by steep hillslopes facilitates rapid drainage of flow toward the flat central part of the valley. Longitudinal profile of major rivers was extracted from the DEM as presented in **Figure 10** which provides an idea of the flood characteristics of KVW (Karki et. al, 2023). Longitudinal profile reveals that as tributaries such as Nakhkhu, Manahara, and others converge with the Bagmati River, the river's slope significantly decreases upon entering the valley bottom. These tributaries exhibit steeper slopes in their upstream regions, resulting in a higher flow discharge for a given cross-section, thereby increasing the likelihood of flooding. The analysis reveals that over 43% of the slope of the KVW ranges between 0° and 15°.

In contrast, the Roshi River has a steep-to-mild profile (**Figure 10)** and does not experience notable long-term inundation. Instead, this river was marked by the transport of massive amounts of sediment from upstream catchments, material debris flows from tributaries and landslides from hillslopes, which caused excessive sedimentation and scouring during extreme rainfall events. Notably, both the Nakhkhu River and the Roshi River typically have low flow volumes during the dry season. **Figure 11** shows the river width at selected points along the upstream and midsections within the study area and downstream sections of the Bagmati, Manohara, Hanumante, Nakhkhu, and Roshi Rivers. Within the KVW, the rivers exhibit a gradual increase in width as they flow downstream, which also corresponds to a decrease in flow velocity and a greater likelihood of inundation. In contrast, the Roshi River, which traverses mild to steep topography, shows no significant variation in width along its course.

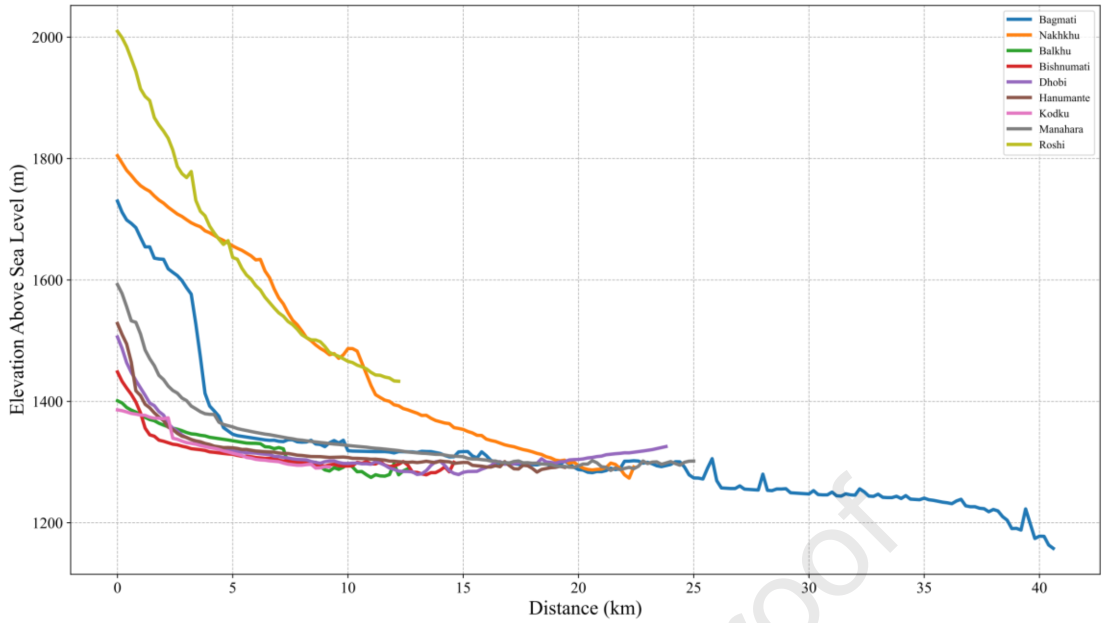


Figure 10*: Longitudinal profile of major river tributaries of KVW derived from 30 m resolution FAB DEM riverbeds showing horizontal distance vs elevation changes (the starting point in each of the rivers is considered at a point where the upstream catchment area is 5 sq. km).*

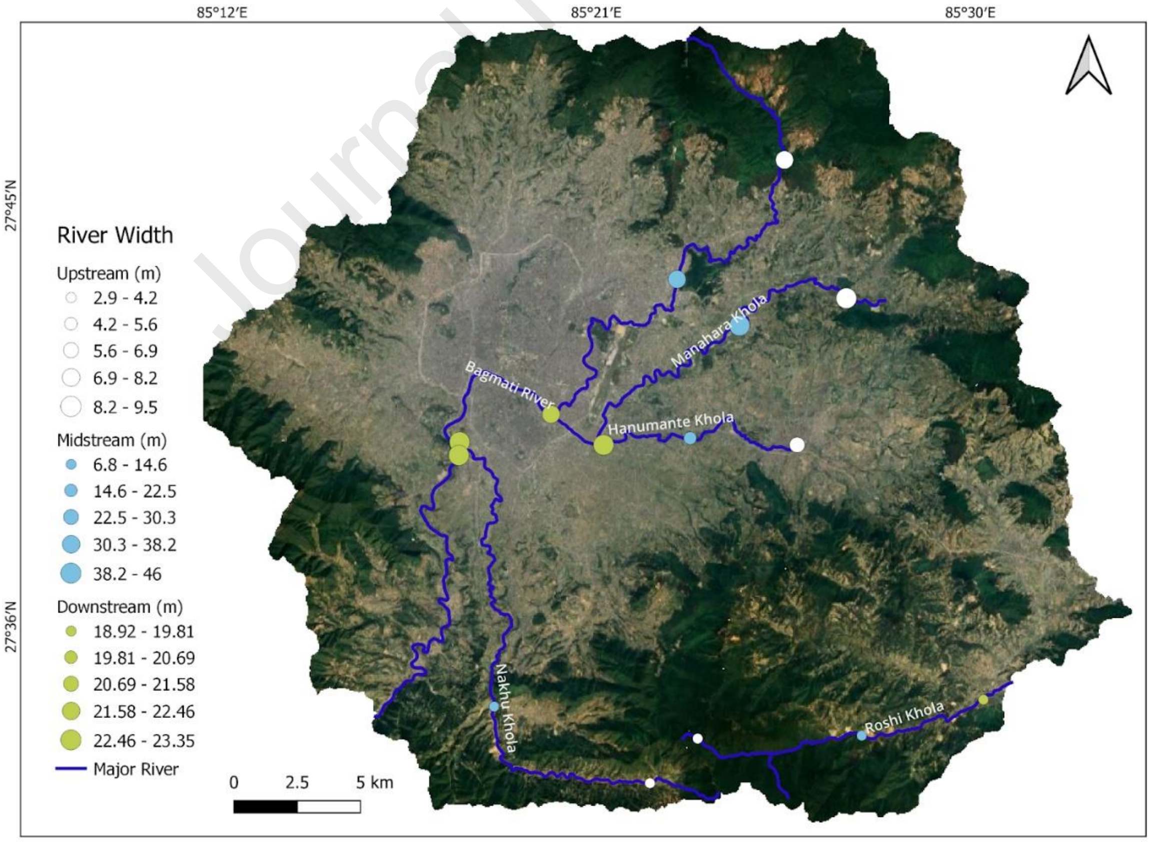


Figure 11*: River width analysis of several major rivers at tentative upstream, midstream, and downstream locations within the study area.*

5.2. Anthropogenic Factors

Flood disasters result from a combination of natural factors and human-induced activities, amplifying their severity and impact (Karki & Acharya, 2020). Based on the past literatures & analysis, field observations and reports, we identified unplanned urbanization, river encroachment, rapid population growth, and unregulated mining as the major human factors contributing to the increasing flood risk in the KVW (Danegulu et. al 2024). Here we analyzed the built-up area expansion close to the river bodies that illustrates both the increased risk and exposure to flooding. Urban areas within catchments, such as KVW, have experienced rapid and unplanned development, significantly altering the hydrological response of the region (Acharya et al., 2023). **Figure 12** shows the land use land cover (LULC) changes from 2000-2010 and 2010-2019 within the overall study area. Between 2000 and 2010, LULC changes were minimal, with slight increases in both forest and built-up areas, as shown in **Figures 12a** and **12b** and quantified in **Table 2**. In contrast, the period from 2010-2019 experienced more rapid changes, with agricultural land decreasing significantly from 44.06% to 35.94%. The built-up areas, in particular, experienced a sharp increase, increasing from 12.37% to 19.68%, as depicted in **Figure 12c**. **Figure 12d** illustrates the transitions between land types and is quantified through the transition matrix in **Figure 13**. Notably, 69.88 sq. km of land has been converted into built-up areas between 2000 and 2019. For a more detailed analysis of land use changes close to the river network and flood plains, a 200-meter buffer zone (100 meters on either side of the river's central line) was created, and land use changes were examined within that buffer (**Table 3**). Interestingly, 10.41% of the buffer zone was built-up area in 2000, which increased to 12.31% by the end of 2010 and then rapidly increased to 20.15% by 2019. These findings are critical in shaping the exposure to flood damage and strictly enforcing landuse policies. Rapid and haphazard changes in land use and land cover (LULC) in urban areas such as the KVW have directly contributed to increase in urban flooding (Danegulu et al., 2024).

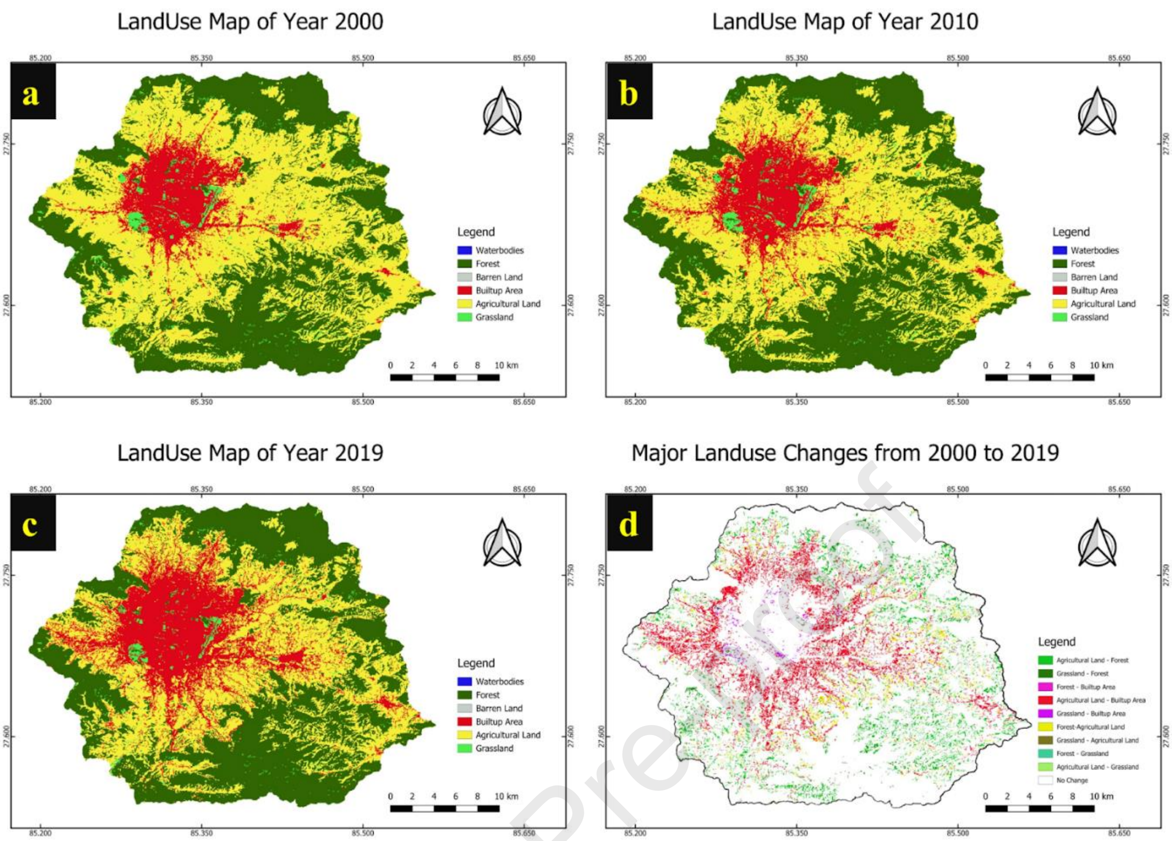


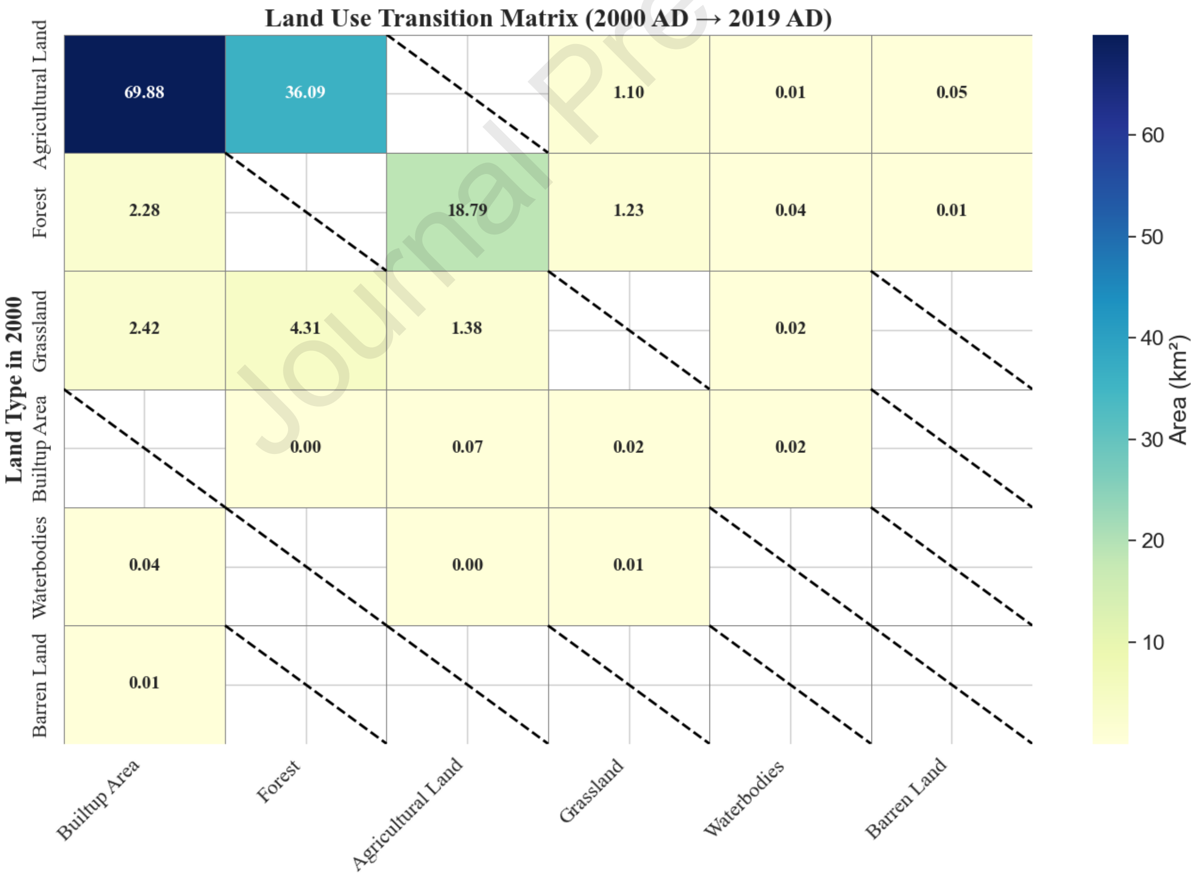
Figure 12: *Land use map of the study area: (a) in 2000, (b) in 2010, (c) in 2019, and (d) changes in land use type from 2000-2019: a transition analysis of land cover shifts (modified from the ICIMOD web portal).*

Table 2*: Area and percentage distributions of land use types in the overall study area in 2000, 2010, and 2019.*

Land Type	**2000 AD**		**2010 AD**		**2019 AD**	
	Overall Study Area		**Overall Study Area**		**Overall Study Area**	
	Area (km^2)	**Percentage (%)**	**Area (km^2)**	**Percentage (%)**	**Area (km^2)**	**Percentage (%)**
Agricultural	378.65	46.64	357.74	44.06	291.75	35.94
Forest	330.90	40.76	339.09	41.77	348.97	42.98
Built up Area	85.26	10.50	100.44	12.37	159.76	19.68
Grassland	16.93	2.08	14.49	1.78	11.15	1.37
Water bodies	0.10	0.01	0.07	0.01	0.15	0.02
Barren Land	0.04	0.00	0.04	0.01	0.09	0.01

444 ***Table 3***: *Area and percentage distributions of land use types in the 200 m buffer zone along major river*
445 *systems in the Kathmandu Valley (100 m on each side) in 2000, 2010, and 2019.*

Land Type	**2000 AD** 200m Buffered Zone Along Major Rivers		**2010 AD** 200m Buffered Zone Along Major Rivers		**2019 AD** 200m Buffered Zone Along Major Rivers	
	Area (km^2)	**Percentage (%)**	**Area (km^2)**	**Percentage (%)**	**Area (km^2)**	**Percentage (%)**
Agricultural	87.95	53.93	80.52	49.37	73.38	44.99
Forest	55.34	33.93	59.91	36.74	54.71	33.55
Built up Area	16.98	10.41	20.07	12.31	32.85	20.15
Grassland	2.77	1.70	2.53	1.55	1.98	1.21
Water bodies	0.05	0.03	0.06	0.04	0.15	0.09
Barren Land	0.00	0.00	0.00	0.00	0.01	0.01



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447 ***Figure 13:*** *Heatmap of land use transitions from 2000-2019: visualizing changes between land use*
448 *categories.*

The absence of comprehensive urban planning in Kathmandu Valley has resulted in overcrowding, especially in core urban areas due to significant rural-to-urban migration, driven by factors such as infrastructure development, educational facilities, political unrest and expanding employment opportunities (Ranjitkar & Manandhar, 1981; Bohra-Mishra & Massey, 2011; Thapa & Murayama, 2010; Poudel et al., 2023). Human settlements have emerged along the right of way of rivers as evident from Table 2, and rapid urban expansion within the floodplains of the Bagmati, Bishnumati, Dhobi, and Balkhu Rivers and other river corridors has disrupted the natural flow of these rivers, resulting in frequent urban inundation (Katwal & Thapa, 2023).

Floodwater storage within floodplains reduces the severity of downstream flood levels (Johnson et al., 2020; Schober et al., 2020). However, encroachment upon natural waterways and floodplains for urban development has further diminished the valley's resilience to flooding. The development of river corridors as alternative road networks encroaching on floodplains has helped alleviate traffic congestion of KVW to some extent. However, these corridors, along with Dhobikhola, Bishnumati, Bagmati, Hanumante, and Nakhkhu river channelization using concrete walls, have reduced natural width of rivers, altered natural flow patterns and reduced channel capacity, leading to increased inundation even with few hours of rainfall (Danegulu et. al 2023; Thapa et al., 2024). Additionally, these structures may actually exacerbate flood risks by causing sediment accumulation in the main river channel, which can result in a perched riverbed over time, where the riverbed rises above the surrounding land (Thapa et al., 2024).

Moreover, the drainage infrastructure in the central region of the KVW was planned and constructed decades ago and is inadequate for managing water during prolonged monsoon rainfall (Shrestha & Thapa, 2021). The current drainage systems, initially designed to address the needs of past urban demands, are now inadequate to cope with the pressures of growing urbanization and the impacts of changing climate extremes (Darji & Ahmad, 2024). Consequently, areas such as Putalisadak, Teku, and Bhaktapur frequently experience inundation, as stormwater is unable to access nearby rivers (Shrestha & Thapa, 2021).

The September 2024 floods damage on the Rosi River bank and Nakhkhu River bank were largely attributed to unregulated quarrying and sand mining in its catchment area rather than just the heavy monsoon rains (Darji & Ahmad, 2024). Although the rainfall was intense, destruction was significantly exacerbated by the unchecked operations of mines and crushers along riverbanks (**Figure 14**). Even more troubling is that these stone quarries and crushers, located on the banks of the Rosi River, were found to have violated established guidelines and laws, yet the concerned authorities have consistently turned a blind eye to these infractions. Similarly, on the western side of Phulchoki, in Lele, extensive quarrying has severely degraded the mountains within Nakhkhu Khola's catchment (Darji & Ahmad, 2024).

The Rosi River had previously experienced flooding in 1981, but the damage was significantly less, and the river's course remained unchanged (Darji & Ahmad, 2024). However, dramatic changes have occurred in recent years, as both the Rosi and Nakhkhu rivers are now confined to narrow channels. The expansion of settlements, warehouses, poultry farms, and garages along riverbanks has severely restricted the natural flow of rivers. This restriction, combined with upstream quarrying, sand, and boulder mining, has increased the water velocity and introduced heavy sediment loads into floodwaters (Darji & Ahmad, 2024). As a result, the primary cause of the extensive loss of life and destruction in the Nakhkhu and Rosi valley was the confinement of the rivers to narrow channels, which led to debris-laden floodwaters overflowing into the populated floodplains, exacerbating the devastation (Darji & Ahmad, 2024).

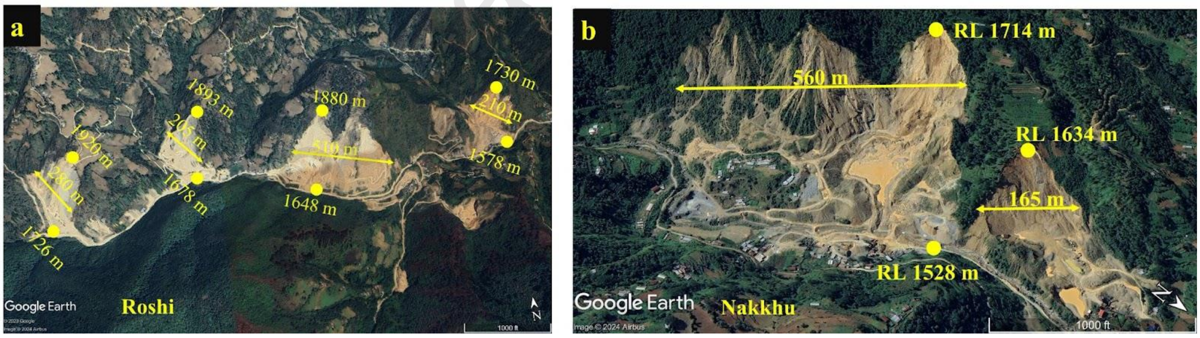


Figure 14: *Unregulated mining sites located on the banks of the (a) Roshi River and (b) Nakhkhu River.*

5.3. Hydrometeorological Factors

Central Nepal and parts of eastern Nepal experienced unprecedented rainfall from September 26-28, lasting more than 60 consecutive hours. Rainfall data across Nepal indicate that 24 stations recorded 50–100 mm, 54 stations recorded 100–200 mm, 68 stations recorded 200–300 mm, 31 stations recorded 300–400 mm, 5 stations recorded 400–500 mm, and 1 station recorded more than 500 mm of precipitation during this event (DHM, 2024). Among these stations, 25 experienced their highest-ever 24-hour rainfall since the beginning of their operation. Return periods are calculated for 23 stations where record-breaking rainfall was measured (**Table 4)**, as well as for additional stations that lie within the study area and for which data are available (**Figure 15**). Among the 23 recorded-breaking stations analyzed, 9 stations had return periods of less than 100 years, 4 stations had return periods between 100 and 500 years, 5 stations had return periods between 500 and 1000 years, and 2 stations had return periods between 1000 and 2000 years. Notably, one station recorded a return period between 5000 and 10000 years (Khopasi at 6924 years), and another exceeded 10000 years (Chapa Gaun at 13571 years). These analyses are based on hourly measured rainfall data from September 26-28 and historical daily rainfall records from 2000--2024 from the Department of Hydrology and Meteorology, Nepal.

Table 4*: Return period of 24-hr rainfall for 23 stations where record-breaking rainfall was measured.*

Station Name	**24-hr Rainfall (mm)**	**Return Period (year)**	**Station Name**	**24-hr Rainfall (mm)**	**Return Period (year)**
Sandhikharka	196.60	25.76	Khairini Tar	252.30	22.19
Godavari	290.00	521.68	Phidim (Panchther)	172.00	728.52
Tikathali	264.00	64.58	Khopasi (Panauti)	331.60	6924.32
Nangkhel	194.50	63.92	Panchkhal	232.50	1912.61
Chapa Gaun	323.50	13571.83	Dhulikhel	224.60	64.97
Jitpurphedhi	178.30	52.95	Baldyanggadi	252.00	656.75
Baunepati	190.00	148.95	Chandragadi Airport	256.00	17.04
Sakhar at Tanahun	214.00	30.21	Khumaltar	294.40	1051.24
Nagarjun	205.40	167.68	Panipokhari (Kathmandu)	206.60	786.91
Kakani	169.20	64.34	Govindabasti	264.00	46.96
Daman	410.00	645.21	Gajuri	261.20	172.62
Khokana	297.30	116.67			

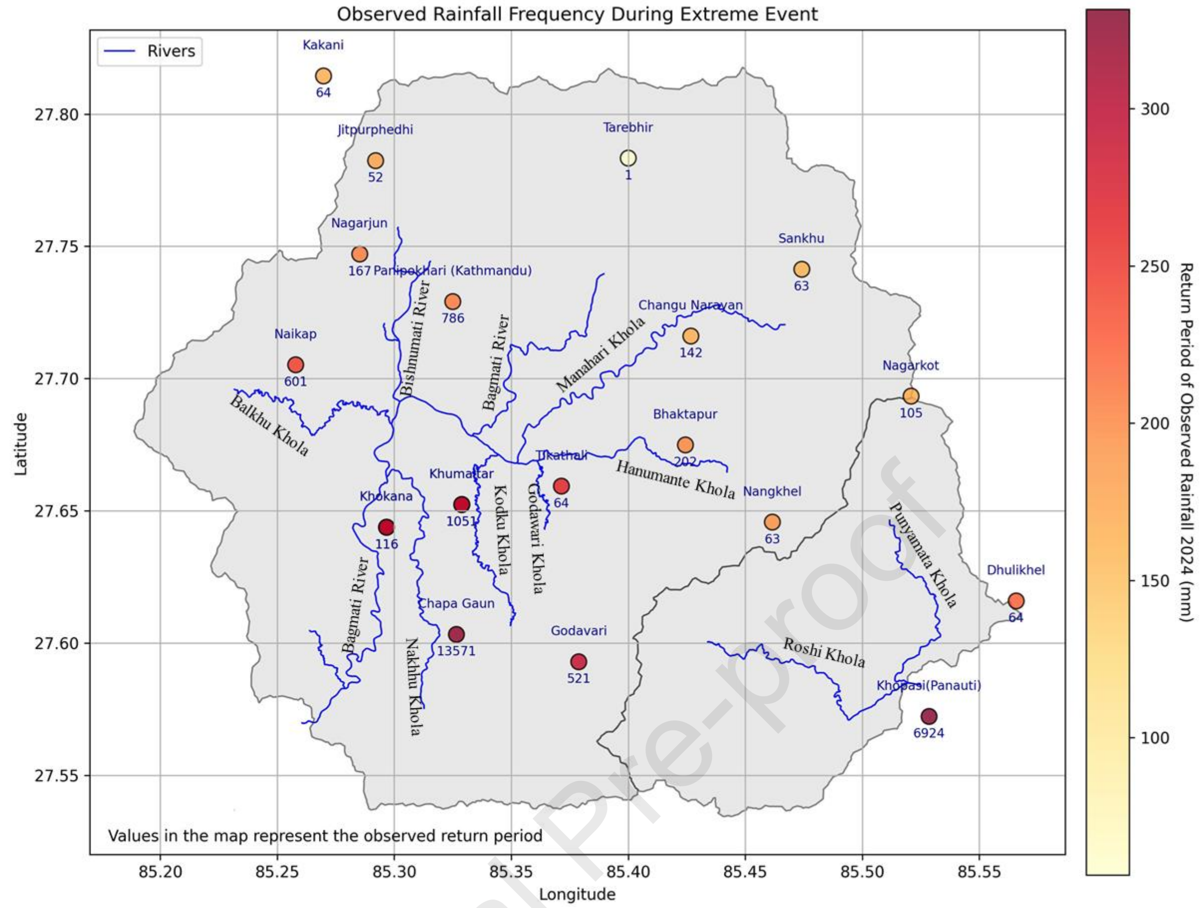


***Figure 15**: Spatial distribution of the rainfall stations within the study area and their corresponding return periods for the September 26-28, 24-hr rainfall.*

Figure 16 provides a detailed overview of the rainfall characteristics (hourly pattern) during the exceptional 3-day storm event across KV and its surroundings. The figure includes a histogram of the hourly rainfall and the cumulative rainfall observed throughout the storm event. These measurements were available from 12 meteorological stations (automatic) within the valley and surroundings, whose locations are depicted in **Figure 15**. The majority of these stations were located within or near the KV, with the Lalitpur district alone contributing five of the highest-recording stations. For example, the Godavari and Khumaltar stations in Lalitpur recorded 311.6 mm and 294.0 mm of rainfall, respectively, both significantly above 200 mm. Several other stations within KV, including Panipokhari and Budhanilkantha, also recorded significant rainfall, surpassing the 200 mm mark in their 24-hour totals.

Overall, of the 12 stations included in the hourly rainfall analysis, nine reported more than 200 mm of rainfall in 24 hours. Notably, the Nagarkot, Tathali, Sankhu, Tikathali, and Khopasi stations each set new records for 24-hour rainfall. The hourly rainfall trends mirrored the 24-hour totals, with Godavari leading the stations with the highest hourly rainfall, recording 26.8

mm between 7:00 and 8:00 on September 28. Khumaltars recorded 24.8 mm from 5 to 6 PM on the same day, whereas Tikathali measured 24.4 mm during the midnight hour on September 27. The lowest peak hourly rainfall observed was 13.6 mm at the Tathali station, which still reflects a significant intensity. In terms of cumulative rainfall over the 3 days, Godavari received the highest total rainfall of 366.0 mm, followed by Khumaltar at 340.0 mm and Tikathali at 305.8 mm.

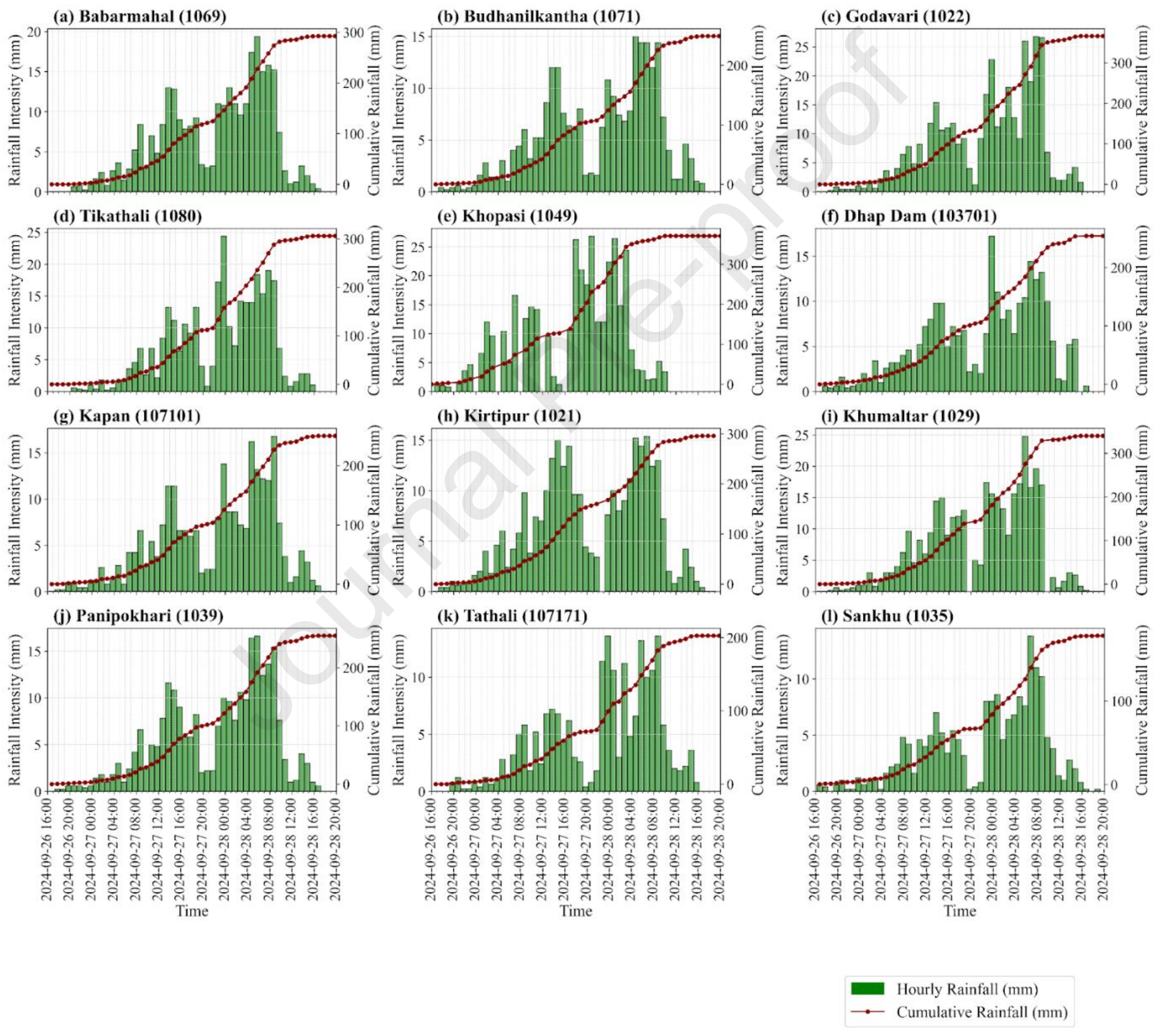


__Figure 16__: The green bars depict hourly rainfall (mm), while the red line represents the cumulative rainfall (mm) recorded over the 3-day extreme rainfall event at 12 rainfall stations located within the Kathmandu Valley and nearby severely impacted areas, including "Roshi, Kavrepalanchok".

Figure 17 depicts the river water levels measured at each gauging station during this extreme rainfall event. The timing of the maximum river levels coincides across all rivers. The first peak in river levels for all rivers occurred between noon and 6 PM on September 27, during which the Bagmati River at Khokana and Godawari Khola at Thaiba surpassed both the warning and danger levels. Following this, there was a slight decrease in river levels; however, the highest peak in all rivers occurred again at midnight on September 27, surpassing the previous day's peak and continuing to rise until approximately midday on September 28. During this period, most of the measured stations exceeded both the warning level and danger level by a significant margin (**Figure 17**). The similarity in the timing of peak river levels suggests that rainfall was evenly distributed over time. The rainfall trends show two main periods of concentration: the first from midday on September 27 to 4 PM on the same day and the second from midnight on September 27 to 8 AM on September 28. The timing of these rainfall peaks aligns with the river level peaks, indicating no significant lag between rainfall and flooding. Extreme urbanization and steep slopes in mountainous catchments have contributed to the rapid collection of runoff, intensifying flooding.

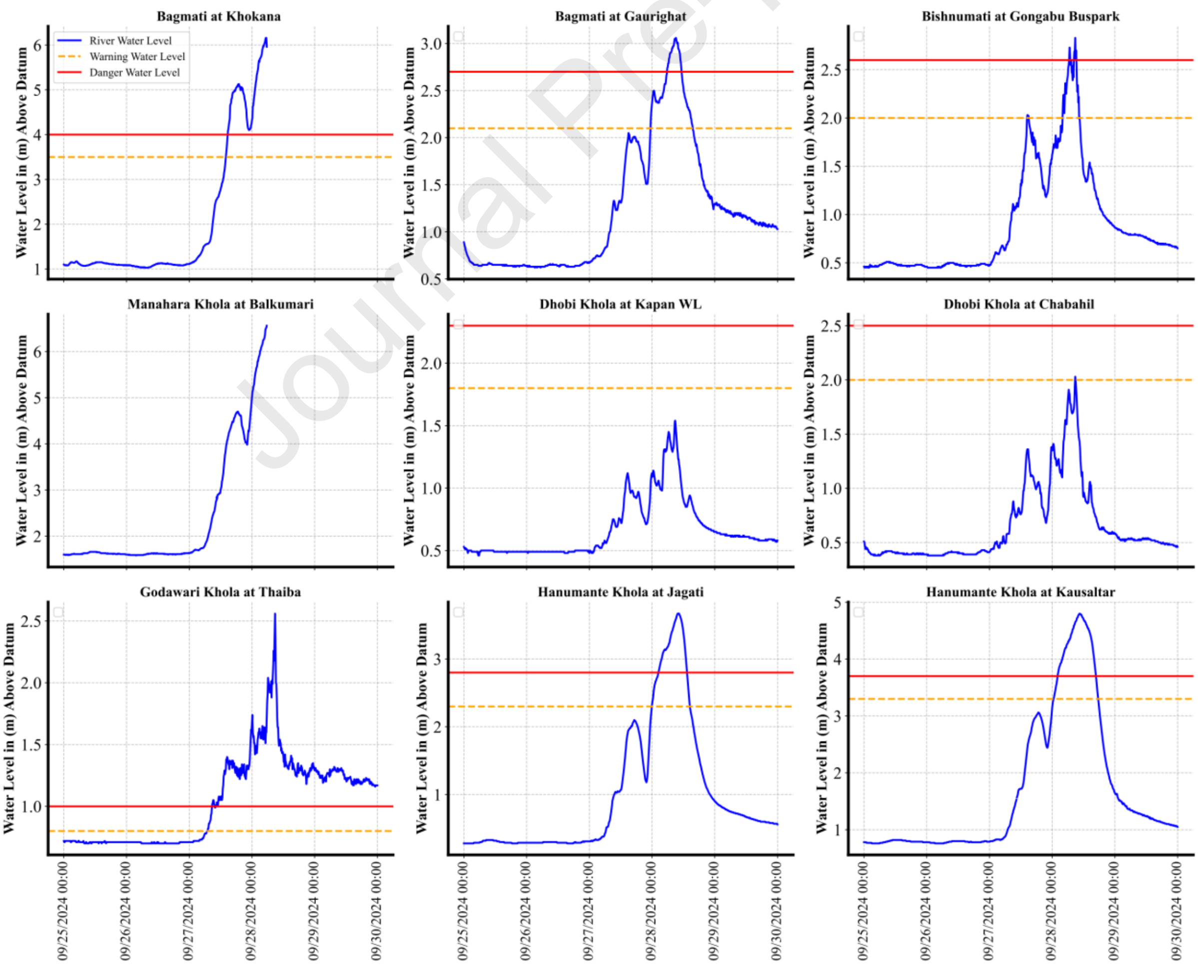


***Figure 17**: River water levels during a 3-day extreme rainfall event in the Kathmandu Valley: time series data across multiple stations with warning and danger levels indicated.*

Figure 18 shows the daily rainfall trends from the 2024 monsoon season to the extreme 3-day rainfall event recorded at 15 stations within the KV and its surroundings. The data indicate that significant rainfall (more than 1500 mm at some of the stations and more than 1000 mm in the remaining stations) had already occurred before the extreme event, likely saturating the catchments and slopes. KV also experienced heavy rainfall events in early July, late July and early August, leading to flooding on three occasions prior to the September 2024 extreme events. This pre-saturation, combined with intense rainfall from the late monsoon, triggered widespread catchment erosion, debris-laden flooding, and multiple slope failures. The cumulative impact underscores the abnormality of the rainfall received in central Nepal during September 2024.

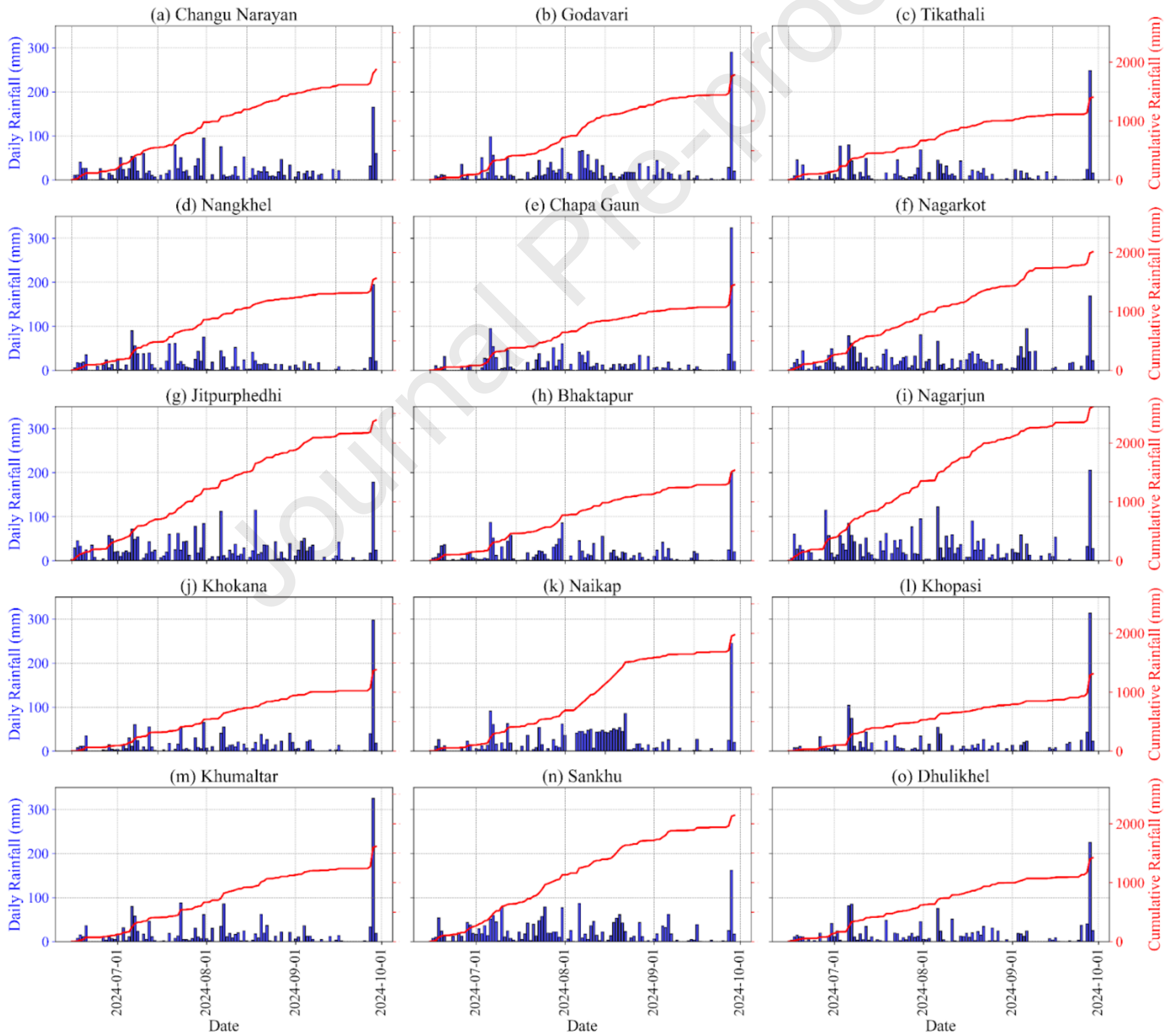


***Figure 18**: Daily rainfall (June 15–September 30, monsoon 2024) shown by dark blue bars, with cumulative rainfall trends represented by a red line, measured at meteorological stations in and around the Kathmandu Valley.*

In addition to the analysis of the 2024 monsoon and 3-day extreme rainfall, this paper analyzes the historical rainfall patterns within the study area. For this purpose, data from 15 stations with available historical rainfall records from 2000-2024 were analyzed via the Thiessen polygon method for averaging, as illustrated in **Figure 19**. **Figure 19** shows spatial distribution of maximum 24hr rainfall (mm) during 2024 September 26-28 period measured at different meteorological stations. A distinct rainfall pattern exists, with the northern part of the study area receiving relatively less rainfall intensity, whereas the southern end receives the heaviest rainfall. The catchment area is such that runoff flows from north to south. The accumulated rainfall from upstream areas, along with the intense rainfall itself, causes significant damage to the southern end.

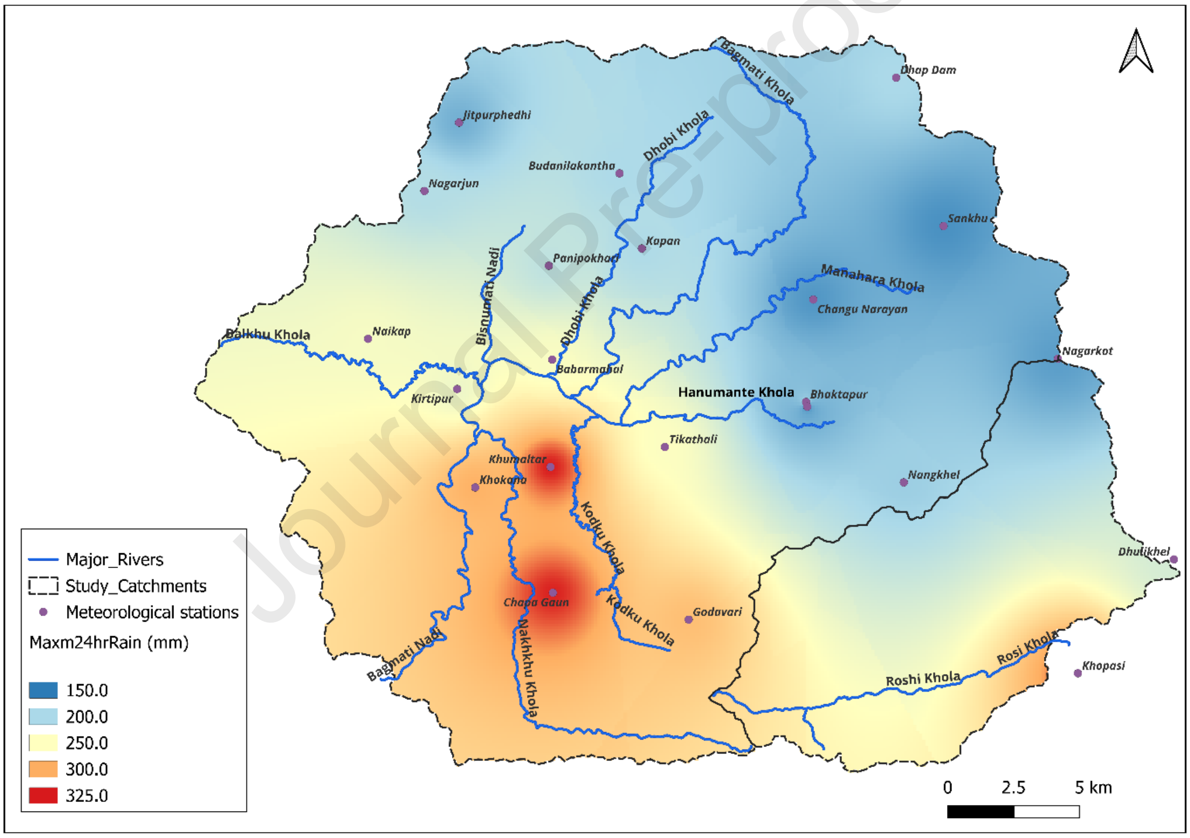


__Figure 19__: Spatial distribution of maximum 24hr rainfall (mm) during 2024 September 26-28 period measured at different meteorological stations

A graph has been presented in **Figure 20** to illustrate the annual maximum instantaneous flood peak based on the available data of the Department of Hydrology and Meteorology, Nepal (DHM) from 1993-2019 along with the maximum river water-level data of the current September 2024 flood event for comparison between this event and historical event. It can be seen that the current event exceed all the previous year's water level indicating flood discharge well above the past event.

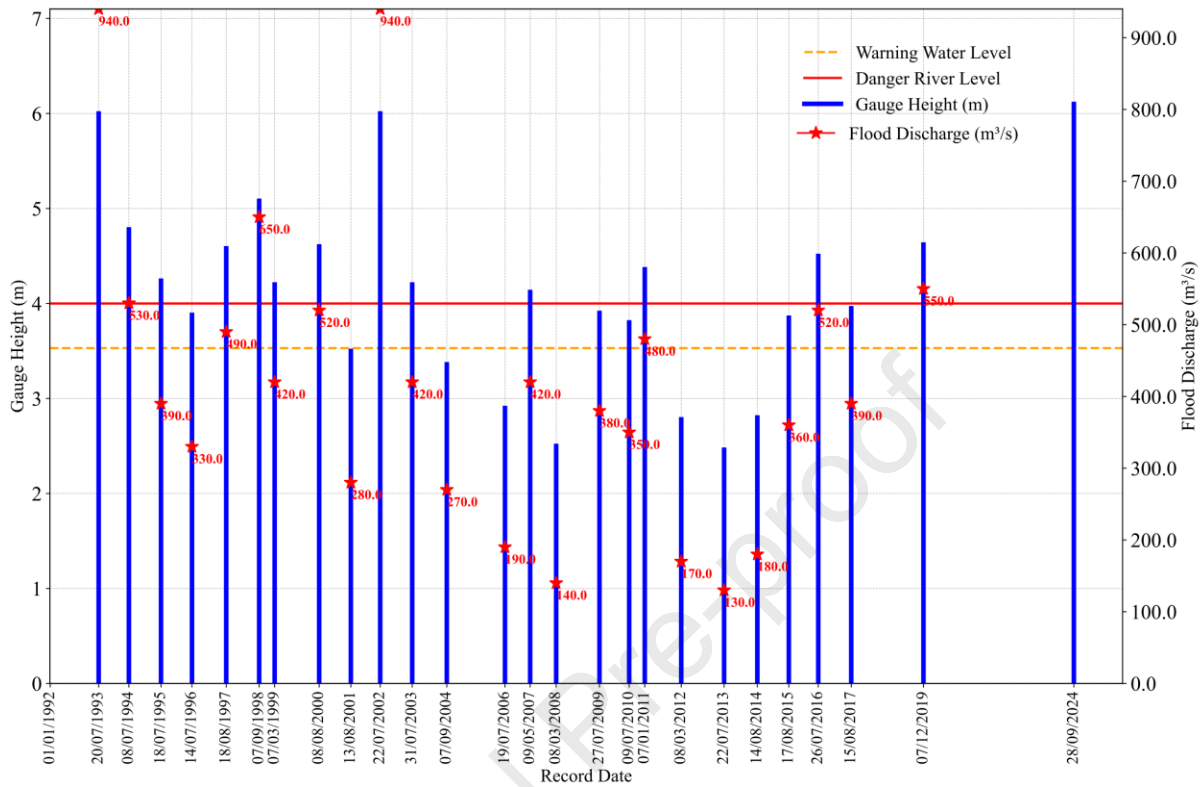
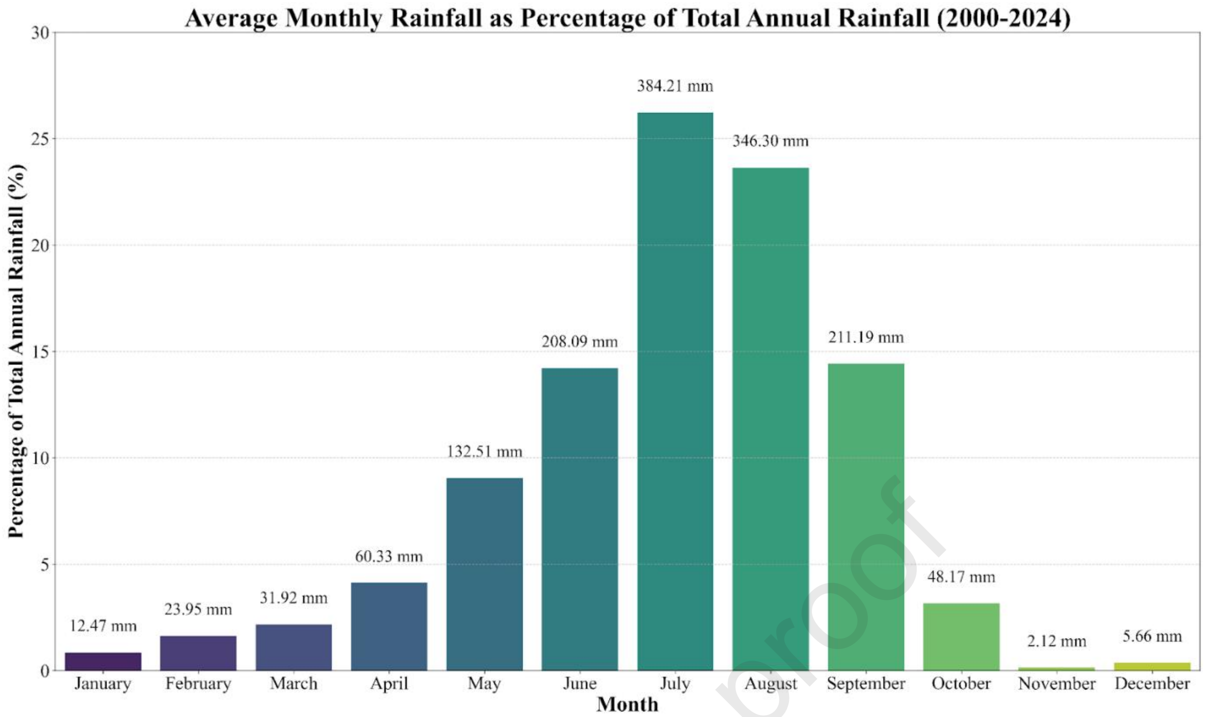


Figure 20: *Annual instantaneous peak flood along with water-level measured at Khokana Station, Lalitpur from 1993-2019 & the recent September 2024 event flood water-level.*

Figure 21 highlights that September is typically not a peak rainfall month in Nepal. The highest rainfall usually occurs in July and August, which collectively account for approximately 50% of the annual total. When June and September are included, this figure exceeds 78%. These averages, which were calculated via the Thiessen polygon method and rainfall data from the last 24 years, reveal Nepal's distinct rainfall distribution, with a significant concentration of precipitation within four months. This unique pattern amplifies the risk of flooding and landslides in areas characterized by fragile geology. **Figure 22** shows the cumulative rainfall in September of each year from 2000-2024. This reveals a noteworthy trend in the rainfall received by each station during September. Typically, rainfall during this month is quite low, but in 2024, the trend shifted, resulting in exceptionally high rainfall.



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613 ***Figure 21:*** *Average percentage rainfall and cumulative average monthly rainfall for each month of the*
614 *year, based on data from 2000–2024.*

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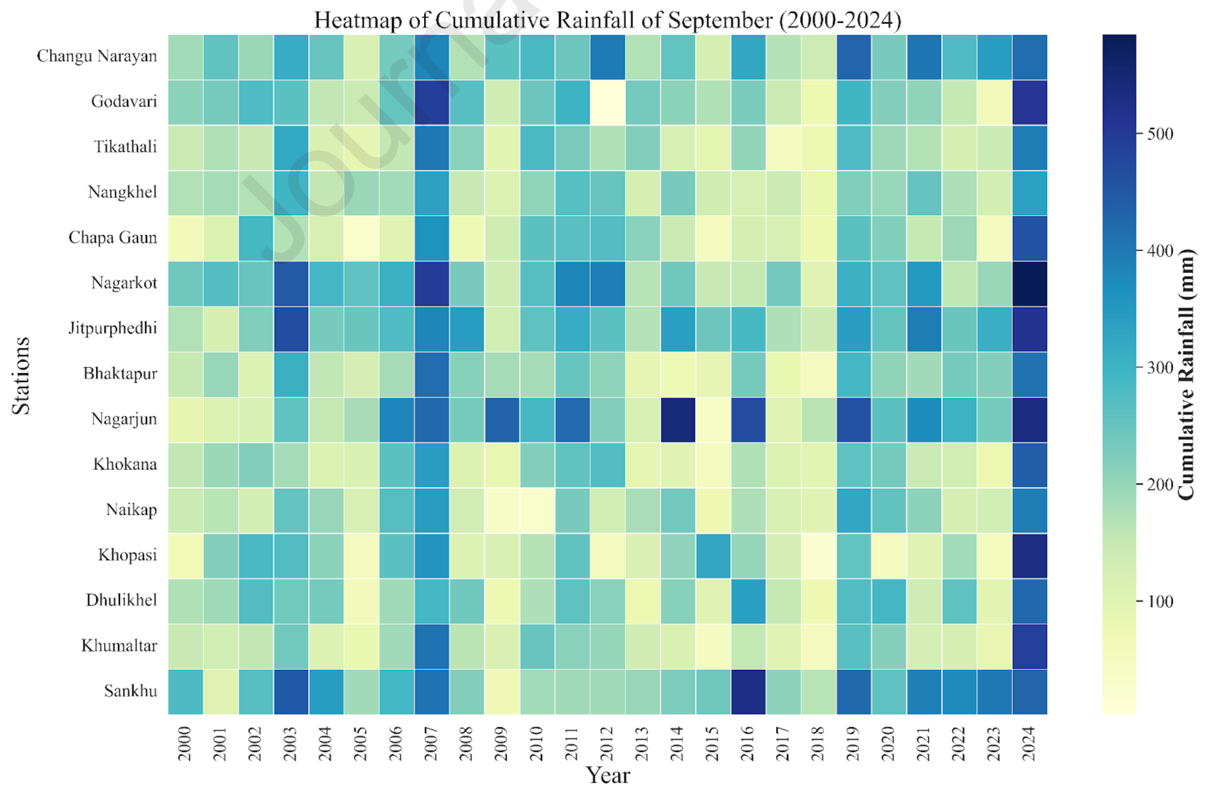

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617 ***Figure 22****: Heatmap showing cumulative rainfall in September of each year (2000–2024) across*
618 *meteorological stations within the study area where historic daily rainfall data are available.*

Figure 23 shows river level measurements across various stations within the KVW for different rivers, along with the timing of various alerts issued by the DHM. DHM issued an extreme rainfall warning on September 25, advising the public to avoid going outside unless absolutely necessary, refraining from driving at night, and remaining alert along riverbanks. If these warnings had been effectively disseminated and adhered to, the losses—particularly the loss of livelihoods within the KVW—could have been significantly reduced. However, most vulnerable communities do not receive warnings as they are issued through bulletins, which are not commonly accessed by the general public. Furthermore, even when people receive alerts, they often do not take them seriously. Although weather forecasting in Nepal has become more precise in recent years, it is still not widely integrated into the daily lives of the general population. This gap could have been mitigated through local-level interventions, especially during extreme rainfall predictions. Despite DHM issuing a series of alerts once extreme rainfall began, these measures were not utilized to their fullest potential. This highlights a broader failure at the community level to act on early predictions, despite the availability of timely warnings. Additionally, the coordination between local, provincial and federal government agencies seemed weak, which led to catastrophic damage.

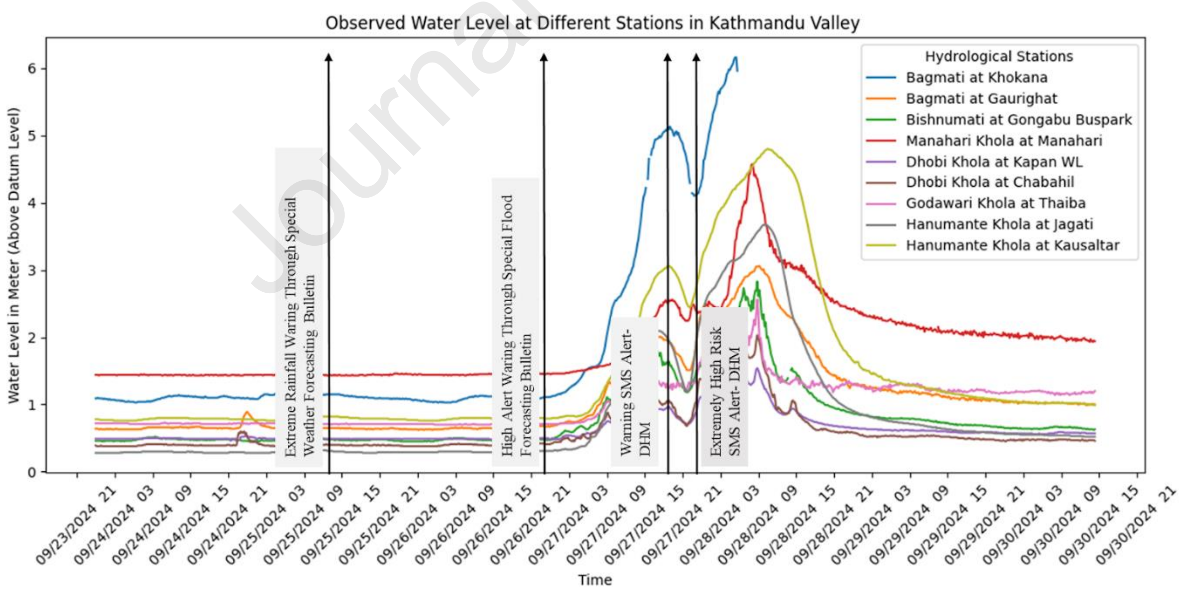

Figure 23: River level data over time for various rivers, alongside the progression of warnings issued by the Department of Hydrology and Meteorology, highlighting the timing of alerts during the event

5.4. Legal, Institutional, and Policy Factors

Flood hazards are triggered by hydrometeorological, infrastructural, and topographical factors in general. However, their transformation into disasters is linked to multiple factors beyond natural settings. The severity of the damage resulting from extreme events, pre-disaster settings, and responses during disasters and postdisaster recovery is also dictated by legal, institutional, and policy issues (Majo, 2022). Gaps in these aspects might lead to further disproportionate effects on vulnerable communities and hence exacerbate the impact (Lebel et al., 2011). In this context, the September 2024 flood disaster impact across the study area has direct linkages with legal, institutional, and policy lapses.

Various norms and guidelines define the required offset from the riverbank on the basis of the river's size when developing residential areas and infrastructure. However, the enforcement of these regulations by the government remains weak, primarily due to political and public pressure. As a result, major residential areas in Lalitpur, such as Chyasal, Imadol, Dhobighat, and Kupandole, along with hospitals in Nakhkhu, experienced severe inundation due to floodplain encroachment beyond the prescribed limits.

While the Constitution of Nepal designates disaster management as a shared responsibility among all three tiers of government, the local and provincial government levels lack adequate financial, technical, and institutional capacity to effectively manage disasters. Although disasters primarily impact local levels, resources remain concentrated at the federal level. Furthermore, coordination across the three tiers of government is weak, with the District Disaster Management Committee, chaired by the Chief District Administrator, serving as the only functional coordination mechanism. Delays in government-led evacuation efforts resulted in casualties in certain areas, which could have been avoided with effective coordination between local and federal governments. This flood event highlighted the deficiencies in Nepal's current disaster management framework. Even in the capital region, the overall response from the responsible authorities fell short of expectations.

Nepal's Standards Related to the Sale and Management of Stone, Gravel, and Sand Excavation 2020 are not adequately followed, and government monitoring remains weak (DAO Bhaktapur, 2024). Moreover, determining scientifically suitable mining locations and sustainable extraction quantities continues to be a challenge for policymakers. Significant damage in areas such as Tikabhairab, Nakhkhu, Roshi, and Panauti has been linked to crusher industries and mining activities on riverbeds and hillslopes upstream (Darji & Ahmad, 2024), which was also verified from site visits by the authors.

In summary, major gaps in the current legal frameworks are outdated provisions in existing laws (Nepal et al., 2018), limited integration of flood and sediment disaster risk reduction into land use and urban planning, legal ambiguities, overlapping mandates, weak coordination and weak enforcement of land use zoning and floodplain encroachment, among others. All these gaps led to increased vulnerability to floods in the study area, inadequate disaster preparedness and response mechanisms, and failure to address root causes such as unplanned urbanization and the regulation of mining industries.

6. Discussions

This study investigates the causes and impacts of recent flood disasters in the KVW and surrounding areas, including Nallu and Tikabhairab in Lalitpur and Roshi in Kavrepalanchowk, through rapid reconnaissance conducted immediately after flooding, GIS mapping, data analysis, and a review of secondary literature. The findings highlight the interplay of catchment characteristics as well as hydrometeorological and anthropogenic factors that contribute to the severity of these floods. This analysis aligns with trends observed in other rapidly urbanizing regions globally, such as Dhaka in Bangladesh and Jakarta in Indonesia, where a similar interplay between urban expansion, inadequate drainage, and extreme rainfall has led to catastrophic flooding (Dewan, 2013; Firman et al., 2011). These comparisons underscore the urgency of addressing urban flood vulnerabilities in KV through region-specific but globally informed approaches.

The unique topographical and hydrological characteristics of the KV and its neighboring areas, combined with the valley’s urbanized basins and disruptions in natural drainage patterns, significantly amplified flood risks, creating conditions for widespread inundation. In the surrounding regions, areas such as Nallu and Roshi experienced significant downstream sediment deposition, primarily due to unregulated mining activities in upstream locations along with haphazard road excavation and plotting on steep hillslopes. These findings also highlight the need for integrated approaches to managing compound geohazards, such as the interplay of sediment deposition, riverbank erosion, and landslides (Sidle & Ochiai, 2006). Addressing these interconnected risks requires coordinated strategies that consider both upstream and downstream impacts, leveraging lessons from other flood-prone areas with steep topography, such as the Himalayas in India or the Andes in South America.

Hydrometeorological factors account for the most significant reason behind widespread devastation. By the time extreme rainfall had occurred in late September 2024, the catchment areas had already been saturated because of heavy rainfall earlier in the monsoon season. The region has received more than 1000 mm of rainfall, significantly increasing soil moisture levels and increasing the likelihood of runoff and fragility of the hillslope. Historical data from the past 24 years show that the average total rainfall for September is 211.19 mm. However, in September 2024, the 24-hour rainfall totals at most stations within the study area surpassed this monthly average, reaching unprecedented levels. This excess rainfall, combined with the already saturated conditions, overwhelmed both the natural and artificial drainage systems, triggering flash floods and causing extensive damage across the affected regions. Climate change further exacerbates the risks posed by such extreme weather events. Rising global temperatures have been linked to intensified monsoonal patterns, with a greater likelihood of unprecedented rainfall events in the future (Hoegh-Guldberg et al., 2018). This necessitates the integration of climate-resilient infrastructure and urban planning to safeguard communities against escalating risks.

Additionally, anthropogenic factors play a critical role in increasing the impacts. The unregulated expansion of settlements along riverbanks, combined with haphazard infrastructure development, obstructed natural water flow and increased flood vulnerability. Inadequate maintenance of drainage systems and widespread dumping of solid waste into rivers further compound this issue. Furthermore, unchecked mining has destabilized slopes and increased sediment loads in rivers, heightening the risks of both flooding and sedimentation downstream. These activities generated loose sediment, which was washed away during intense rainfall. As a result, riverbeds shift, overwhelming downstream river systems and contributing to widespread flooding and sediment deposition. The unregulated nature of these anthropogenic activities also points to significant gaps in enforcement and governance. For example, weak implementation of existing mining regulations has allowed indiscriminate sediment extraction, aggravating downstream flood risks (Gautam & Andersen, 2016). Strengthening institutional capacity and ensuring accountability in policy enforcement could mitigate such avoidable impacts.

The impacts of these floods are multifaceted, causing widespread damage to infrastructure, displacement of communities, and loss of livelihoods. This study underscores the urgent need for better regulation of mining activities, improved urban planning, enhanced drainage management, and coordinated efforts across sectors to mitigate the risks of similar disasters in the future. Advances in technology, such as real-time hydrological monitoring and machine learning-based flood prediction, can offer promising solutions for reducing flood impacts (Mosavi et al., 2018). By incorporating these tools into disaster management systems, authorities can enhance early warning capabilities and make data-driven decisions for mitigation and response. Furthermore, engaging local communities through participatory planning and awareness programs can empower them to adopt adaptive practices, fostering a culture of resilience (Reed, 2008).

7. Recommendations

The September 2024 floods in the Kathmandu valley watershed revealed systemic vulnerabilities and demanded transformative actions to increase resilience. The analysis highlights that flooding in KVW is influenced by a complex interplay of factors, making a universal, one-size-fits-all solution impractical. Given the Valley's distinctive topographical, urban, hydro-climatic, socioeconomic, legal, and institutional characteristics, addressing this issue necessitates a tailored approach rather than relying on traditional, generalized flood mitigation strategies. An effective response to future challenges necessitates a coordinated and integrated framework involving all three tiers of government, relevant agencies, development partners, NGOs and INGOs, local communities, political parties, universities, and research institutions. Although achieving consensus among these diverse stakeholders may be challenging, such collaboration is essential. Disaster risk management should not be treated as an isolated activity but rather as an integral part of a comprehensive water resources and watershed management plan. This plan should encompass the sustainable management of land, water, and communities to ensure a resilient future for the KVW and its surrounding areas.

Keeping in view of multidimensional linkage of KVW flood problem such as topographical, technical, socio-economical, hydro-meteorological, community, urban characteristics, policy and legal perspective, following short-term and long-term measures are proposed. In fact, policy measures are key factors in addressing long-term solution to KVW flooding problems. without proper policy measures and their strict enforcement, other solution measures won’t prove effective. The recommended measures are based on the past lessons, current natural characteristics, socio-economic, technical, policy and financial circumstances affecting KVW flood scenario. Short-term measures are focused on controlling further deterioration of the problems while long-term plans are centered towards conserving and restoring the sustainable state of KVW and its land, water and communities from the broader water resources management perspective.

Short-term measures:

- Zoning laws should be adhered to, and settlement and infrastructure development in flood-prone areas should be avoided. Flood risk assessments should also be integrated into urban planning processes to guide sustainable growth.
- Establishing sufficient hydro-meteorological and sediment measuring stations across KVW and its vicinity to better represent and understand its characteristics.
- Collaboration with universities and research institutions on problem-based research on KVW floods to understand flood propagation mechanism, sediment movement, critical areas, etc.
- Strict enforcement of guidelines and rules on mining activities along with regular monitoring.
- Adopting citizen science approach to improve access in monitoring and measuring data and enhancing knowledge and awareness among local communities.
- Strengthening capacity of local level officials in sustainable water and watershed management.

Long-term measures:

- In the upstream reach, comprehensive watershed management plans in close coordination with community and led by local government at sub-catchment levels to increase recharge, decrease runoff and reduce sediment transport.
- In the mid-reach or semi-urban areas which are in the state of growth, identify appropriate public spaces to construct detention/retention basins to hold flood water for certain period.
- In the lower reach (urban areas), allocating sufficient path for flood passage and restricting construction within the flood plain. Also, appropriately modify the river gradient at the flat reach for quick passage of flood water.
- Revisit the legal provisions and guidelines regarding the buffer zone adjacent to river floodplains based on research and past flood events.

- Gradually transitioning of the structural flood management approach to more towards the Nature-based approach.
- Improving early warning systems to disseminate hazard information effectively allowing sufficient time for safe evacuation.
- Identification of appropriate locations, and quantification of safe and sustainable extraction quantities of mining materials.
- Improving and upgrading KVW's drainage systems to handle extreme rainfall events, and waste management practices should be improved to prevent blockages in both natural and artificial waterways.
- A centralized disaster risk database integrating local and provincial level could be developed to guide planning and resource allocation, utilizing historical flood data, hydrological models, and climate projections for better decision-making.
- Reviving indigenous knowledge in managing land, water and communities and upscaling it across the nation.

8. Conclusions

The findings from the analysis suggest that the unprecedented extreme rainfall event of September 2024 triggered floods, bank erosion, sediment deposition, debris flows and landslides. The prior events in late July and early August weakened the slopes, which could not resist the extreme rainfall in late September, leading to landslides, debris flows, etc. However, the scale of damage was the consequence of anthropogenic factors and legal and institutional factors, among other factors. The results revealed that the exposure of the communities to flooding has significantly increased since 2010, as the built-up areas within 100 m from the river banks increased markedly. The encroachment of river floodplains, narrowing river channels for river corridor development without ensuring safe flood passage, development in steep slope areas, etc., are combinations of anthropogenic factors as well as weak policies and institutional capacity. Similarly, lack of strict policy formulation, enforcement and structured coordination mechanisms among the three tiers of government constitute major gaps in the regulation of development, land and river management in the KVW. Unregulated mining of hillslopes and riverbeds by crusher industries was one of the key factors contributing to this severity of disaster triggered by this extreme event. Although DHM played a crucial role in disseminating warning information with respect to the forecast of extreme rainfall, the response from the community and, more importantly, other concerned authorities and three levels of government was below par. There is an urgent need to reformulate the coordinated mechanism for disaster management on the basis of the federal structure of Nepal, including the equitable allocation of resources. The event was characterized by landslides on upstream hillslopes, debris flows in tributaries, scouring and erosion of riverbeds and banks, coarsening of riverbeds downstream, inundation downstream, etc. With rainfall patterns becoming unpredictable due to climate change, rainfall events of similar intensity might be frequent in the future. An immediate plan for addressing similar events in urban areas across the country should be formulated on the basis of the current gaps and federal structure.

Addressing flooding in the Kathmandu Valley requires a tailored approach that considers its unique topographical, urban, hydro-climatic, socioeconomic, legal, and institutional characteristics. A coordinated and integrated framework involving all stakeholders—government, development partners, NGOs, communities, political parties, and research institutions—is essential. Disaster risk management should be integrated into a comprehensive water resources and watershed management plan, focusing on sustainable management of land, water, and communities to ensure a resilient future for the Valley and its surrounding areas.

Acknowledgment

The authors extend their sincere gratitude to the Nepal Geotechnical Society and the Department of Roads for facilitating the field visit. Special thanks are due to Er. Kalpana Adhikari and Mr. Kishor Surkheti for their invaluable support in coordinating the field activities. The contribution of Ar. Anil Bhattarai in capturing drone imagery is also greatly appreciated.

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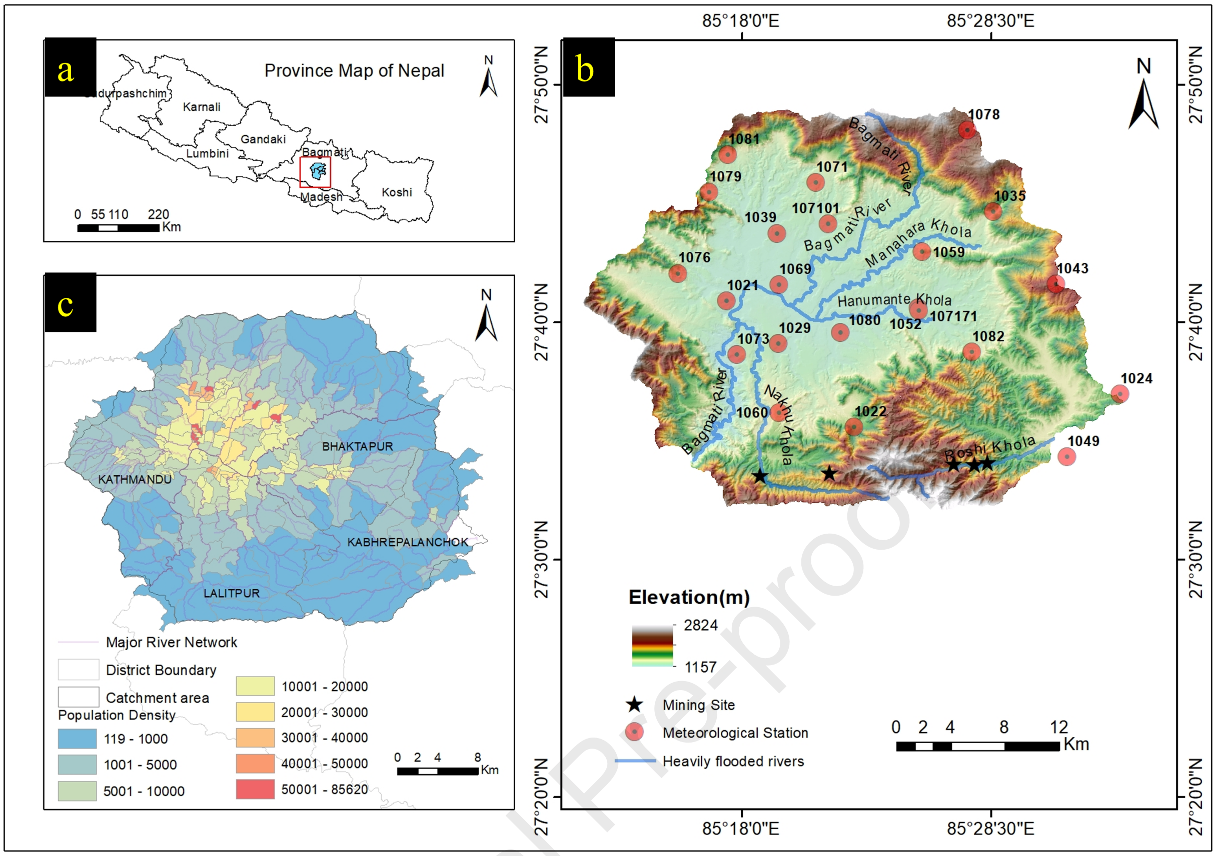
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Province Map of Nepal
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Mining Site
Meteorological Station
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Major River Network
District Boundary
Catchment area
Population Density
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5001 - 10000
10001 - 20000
20001 - 30000
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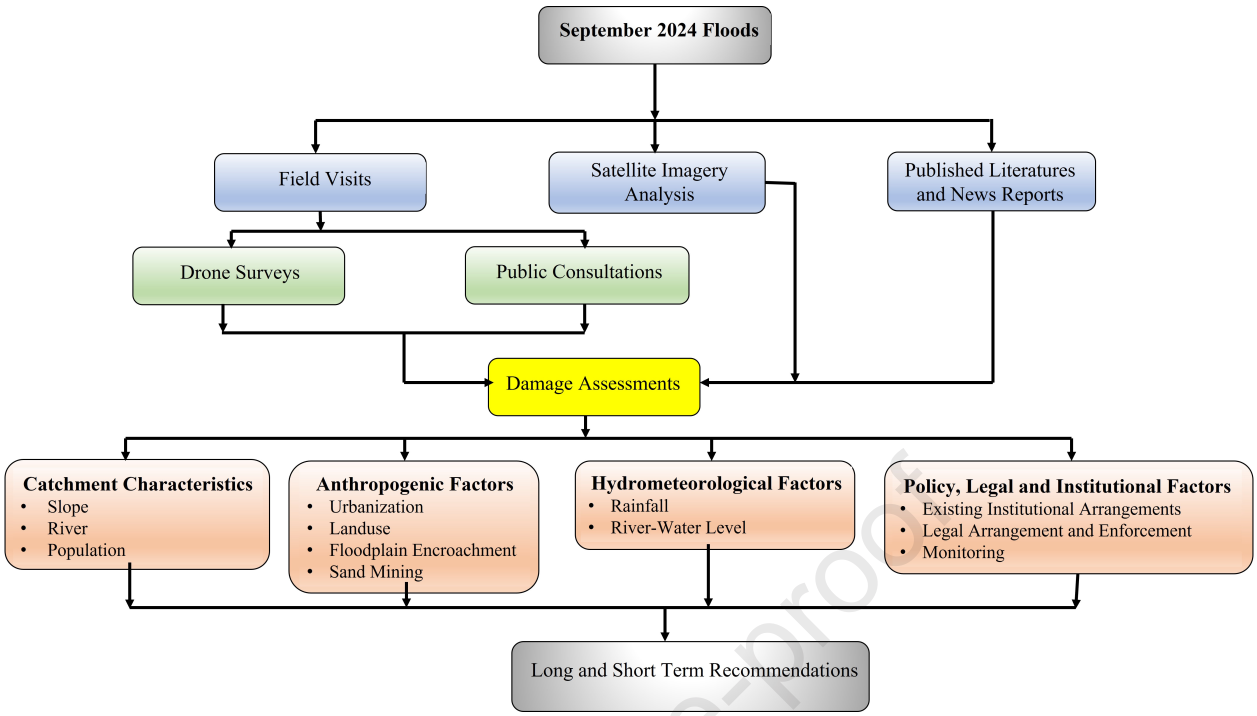
September 2024 Floods
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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: