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NATIONAL HIGHWAY DISRUPTIONS AND THEIR EFFECTS: A CASE STUDY OF THE 2024 MONSOON SEASON IN NEPAL

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ABSTRACT

Nepal's national highways, critical for connectivity and economic activities, face increasing disruptions from climate-triggered hazards such as landslides and floods. This study aims to analyze impact of 2024 monsoon on highway closures. The study integrates official closure records, GIS Map analysis, and statistical analysis to assess the impact of rainfall-induced hazards on Nepal's highways. The hazards, exacerbated by the nation's rugged terrain and intense monsoon rainfall, have shown a rising trend in recent years, causing significant and often unrecoverable losses. Major routes like the Pushpalal Highway and Kaligandaki Corridor experienced the longest closures, intensifying socio-economic impacts, including supply chain delays and hampered emergency responses. For instance, in 2024 alone, severe floods and landslides resulted in 814 highway closures across 41 national highways throughout the country. The BP Highway, a vital connection between Kathmandu and eastern Nepal, has been severely affected by flood-related hazards, leading to significant closures and extensive damage. The 2024 monsoon season starkly illustrated the growing climate vulnerability of Nepal's highway infrastructure, emphasizing the urgent need for resilient, adaptive systems. Immediate investment in climate-resilient road design, slope stabilization, and real-time monitoring is essential to safeguard mobility, emergency access, and socio-economic stability during future monsoons. An assessment for the impact of blockage due to monsoon landslide was calculated for Narayanghat – Muglin Highway (NH44), which leads to 30291 vehicle-hour or 143319 person-hour loss in 2024.

Keywords: *Highway Queu closures, Monsoon hazards, Climate resilience, landslides*

1. Introduction

Nepal's rugged topography and monsoon climate make it particularly vulnerable to rainfall-induced hazards, such as landslides and floods (Sudmeier-Rieux et al., 2012). These natural events frequently disrupt the country's transportation infrastructure, particularly the national highways, which serve as vital lifelines for the movement of goods and people (He et al., 2021). The impacts of these hazards are far-reaching, causing economic losses, delays in emergency response, and significant threats to human safety (Winter et al., 2019).

The monsoon season, which typically spans from June to September, is a critical period for Nepal, as heavy and prolonged rainfall during this time often triggers floods and landslides. Between 2000 and 2024 in Nepal, about 78% of the yearly rainfall took place during the months of June to September, with nearly half of the total, approximately, 50% falling in July and August alone (Lamichhane et al., 2025). These hazards compromise the stability of slopes and the integrity of roads and bridges, leading to frequent closures of national highways (McAdoo et al., 2018).

The increasing frequency and severity of rainfall-induced hazards in Nepal highlight the urgent need for comprehensive solutions (Kincey et al., 2024). By investing in resilient infrastructure, implementing advanced monitoring systems, and promoting sustainable land-use practices, Nepal can enhance its capacity to withstand and recover from these natural events.

In September 2024, record-breaking rainfall caused widespread destruction across Nepal, with severe floods and landslides displacing thousands of people and resulting in numerous fatalities and injuries (Disaster et al., 2024a). In addition to the loss of lives, the events inflicted heavy damage on road structures, bridges, and vehicles (Disaster et al., 2024b).

1.1 Nepal Geographical Vulnerability to Landslide

Nepal's diverse topography, characterized by the towering Himalayas, mid-hills, and the southern plains, makes it inherently susceptible to landslides. The combination of steep slopes, complex geological formations, and intense monsoon rainfall contributes significantly to this vulnerability. A national-scale assessment of rainfall-triggered landslide susceptibility in Nepal indicates that approximately 5% of the country's area exhibits a susceptibility greater than 0.5 on a normalized scale, with less than 1% exceeding a susceptibility value of 0. 75 (Kincey et al., 2024). This suggests that while certain regions are highly prone to landslides, the majority of the country has a relatively lower susceptibility. The Chure region, located in the southern foothills of the Himalayas, is particularly susceptible to landslides due to its unique geological and geomorphological characteristics (P. B. Thapa et al., 2023). The slope map of Nepal derived from STRM-based GIS data is shown in figure 1.

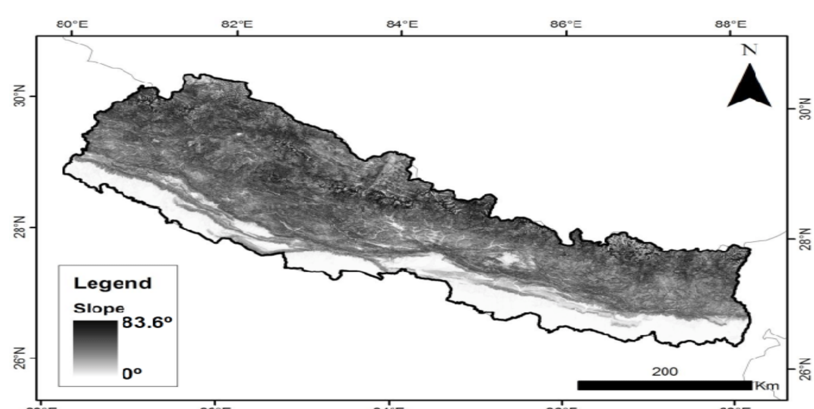

Figure 1 Slope Map of Nepal (Source: GIS enhanced data from SRTM)

The Himalayas' fragile geology, with steep slopes and complex geological structures, further exacerbates landslide susceptibility, especially during seismic events (Paudyal et al., 2021b). Research focusing on co-seismic landslide susceptibility has underscored the intricate relationship between geological features and landslide occurrences in Nepal. Recent advancements in landslide susceptibility mapping have employed various methodologies, including heuristic and bivariate techniques, to evaluate and compare the consistency of GIS-based models. Such studies aim to enhance the accuracy of landslide susceptibility maps, which are crucial for effective land-use planning and disaster risk reduction. Nepal's landslide susceptibility is influenced by a combination of geological, geomorphological, and climatic factors (A. Thapa, 2023).

Early warning systems can play a crucial role in mitigating the impact of rainfall-induced hazards (Piciullo et al., 2018). Real-time monitoring using remote sensing technologies and IoT-based sensors can provide timely alerts, enabling authorities to take preventive measures before disasters strike (Z. Q. Chen et al., 2022). Sustainable land-use planning is another essential strategy (Kato & Huang, 2021). Preventing construction in high-risk areas, enforcing regulations, and promoting reforestation can help stabilize slopes and reduce the vulnerability of infrastructure. Engaging local communities in disaster preparedness and response initiatives can further enhance resilience and ensure the effectiveness of mitigation strategies.

1.2 Road Network

Nepal's national highway network plays a crucial role in the country's infrastructure and socio-economic development. As of February 2024, the federal government had constructed a total of 34,257 kilometers of roads, comprising 18,421 kilometers of blacktopped roads, 7,697 kilometers of gravel roads, and 8,139 kilometers of earthen roads (Economic Survey, 2023-24, MOF).

1.3 Rainfall induced hazard and mitigation Measures

Several factors contribute to the increasing vulnerability of Nepal's highways to rainfall-induced hazards (Khanal et al., 2007). Climate change has exacerbated the intensity and unpredictability of rainfall events, leading to more frequent and severe floods and landslides (World Bank, 2022). The geological characteristics of Nepal, marked by fragile and young rock formations, inherently predispose the region to landslides, especially during heavy rainfall (Paudyal et al., 2021a). These vulnerabilities are compounded by inadequate planning, design, and maintenance of infrastructure, which fail to account for the challenging environmental conditions.

Addressing these challenges requires a multifaceted approach (Adhikari & Gautam, 2022). Enhancing the resilience of infrastructure is paramount (Chhetri et al., 2024). This includes designing and constructing highways with robust materials and engineering practices that account for local geological and climatic conditions (Mulmi, 2009). Advanced technologies such as geotextiles for slope stabilization and reinforced concrete linings can significantly improve the durability of road structures (Kumar et al., 2021). Furthermore, implementing efficient drainage systems to manage surface and subsurface water flow is critical to reducing the risk of erosion and slope failure (B. Chen & Fong May Chui, 2025).

In recent years, there has been a concerted effort to enhance the resilience of Nepal's road infrastructure, particularly in landslide-prone areas. This includes the implementation of slope stabilization measures, construction of retaining walls, and improvement of drainage systems to mitigate the impacts of landslides and floods on the road network. Ongoing investment in infrastructure development, coupled with the adoption of innovative technologies and sustainable practices, is essential to enhance the connectivity and resilience of Nepal's road network.

This research focuses on analyzing the trends of national highway closures caused by rainfall-induced hazards during the monsoon 2024, assessing their implications on infrastructure, vehicles, and human lives.

3. Materials and Methods

The methodology for this research integrates multiple data sources and analytical tools to examine the impact of rainfall-induced hazards on highway closures in Nepal. Official record sheets documenting highway closures during the rainy season from May 2022 to October 2024 over the past three years were utilized to plot trends and analyze patterns of disruption. Site reports from landslide-affected locations provided detailed information on the nature and extent of damage to road infrastructure.

The DoR has also developed online platforms, such as the Highway Management Information System (HMIS), to provide real-time data on road conditions, traffic, and maintenance activities. These systems aim to improve the efficiency of road network management and facilitate timely responses to infrastructure challenges

Additional data on landslides and floods were sourced from reputable online platforms and government databases. Geographic Information System (GIS) tools were employed to map closure locations enabling a spatial understanding of vulnerability hotspots. The data on closure frequency and disturbed hours, classified by highway codes, provides a deeper understanding of rainfall-induced hazards and their impact on transportation infrastructure.

To better understand the impact of highway blockages on daily life and mobility, the Narayanghat–Muglin section of National Highway (NH-44) was chosen as a case study. Due to the lack of real-time traffic data, available records from the Department of Roads (DoR) website for the year 2022/23 were used to estimate vehicle-hour and person-hour losses during the blockage.

2.1. Flood and Landslide 2024 in Nepal

In year 2024 alone, severe floods and landslides led to the closure of 43 highways, attempting 820 nos. of highway closures across the country. In July 2024, Sudurpaschim Province of Nepal, particularly Kailali and Kanchanpur districts, experienced catastrophic floods triggered by relentless rainfall starting on July 3. A record-breaking cloudburst in Dodhara Chandani deposited 624 mm of rainfall in 24 hours, the highest ever recorded in Nepal. This resulted in severe flooding, landslides, and widespread infrastructure damage, significantly disrupting daily life and causing considerable human and economic losses.

The East-West Highway, Nepal's vital transportation artery, suffered critical damage. A culvert in Suda, Bedkot Municipality, was washed away, rendering the highway impassable. Additionally, the Banbasa Bridge at Sharada Barrage was closed to four-wheelers for three consecutive days due to dangerous water levels in the Mahakali River, which surged to 255,000 cubic feet per second. These closures isolated several communities and interrupted transportation and trade routes, highlighting the vulnerability of infrastructure in flood-prone regions. The floods resulted in the deaths of five individuals in Kanchanpur. Approximately 6,322 households were directly impacted, with 1,812 households displaced.

The floods and landslides of June 2024 in Taplejung, Koshi Province, caused by continuous rainfall from June 4 to June 18, led to devastating human and infrastructural losses. Triggered by 21 distinct incidents of floods, landslides, and thunderbolts, the disaster caused widespread destruction and highlighted the vulnerability of the region to natural calamities. The disaster inflicted significant damage on local infrastructure. Four bridges, a suspension bridge, a cemented bridge, and two motorable bridges, were damaged, disrupting transportation and isolating affected areas. Additionally, a micro-hydropower plant, a crusher plant, and a museum were left at risk of landslides, underscoring the broader impact on essential services and cultural heritage (www.bipad.gov.np).

On July 12, 2024, two passenger buses traveling through Simaltal (E-W Highway) in Bharatpur Metropolitan City-29 were swept away by a landslide, carrying 65 people and plunged from the Sinduregaira culvert into the Trishuli River, approximately 100 meters below, where 62 peoples remain missing.

Figure 2 The location of the Simaltal area where two buses went missing after being swept away by the landslide into Trisuli River on Friday, 12th July (Source: https://www.thehimalayantimes.com)

The unprecedented rainfall from September 27-29, 2024, exposed the vulnerabilities of Nepal's road infrastructure to climatic extremes. With 77 stations recording over 200 mm of rain on September 28 alone, and Kathmandu experiencing its highest 24-hour rainfall in 22 years (239.7 mm), the intensity of precipitation played a critical role in triggering widespread landslides and flooding. These events disrupted major highways, including the Mechi, B.P., and Araniko highways, leaving multiple sections either completely closed or partially operational. The fragile geology of Nepal's hilly and mountainous terrain, combined with inadequate drainage systems, exacerbated the frequency and severity of these disruptions.

The consequences of these road closures were far-reaching, affecting both social and economic aspects of life. Over 30,000 security personnel were deployed to rescue more than 17,000 individuals, yet the damage to transportation networks hampered the timely delivery of relief materials and essential supplies. Disruptions in supply chains led to resource scarcity, disproportionately impacting rural and remote regions. Furthermore, 2.5 million people were directly affected, with road closures compounding the challenges faced by communities already grappling with destroyed homes, compromised water supply systems, and inaccessible health facilities (Durbar, 2024).

A portion of the East-West Highway in Ward 4 of Bardaghat Municipality, Nawalparasi West District is closed in between 26th September to 28th September, due to a road sink. The 2024 September floods and landslides caused significant damage to Nepal's road and bridge infrastructure. Key highways such as Mechi, B.P., and Araniko faced closures due to landslides, floods, and road sinks. A total of 24 road sections were affected. Additionally, 44 suspension bridges sustained damage, 25 fully destroyed and 19 partially, leading to losses of NPR 1.042 billion. The combined impact underscores the need for resilient infrastructure and robust disaster management strategies (NDRRMA, 2024).

On 28th Sept 2024, three vehicles were buried in a tragic landslide at Jhyple Khola in Dhunibeshi Municipality-9 along Tribhuvan Highway. According to the Traffic Police Office in Dhading, all passengers travelling in buses lost their lives in the incident.

Figure 3 Drone footage of the aftermath of the landslide at Jhyaple Khola in Dhading, Nepal(https://eos.org/landslide-blog)

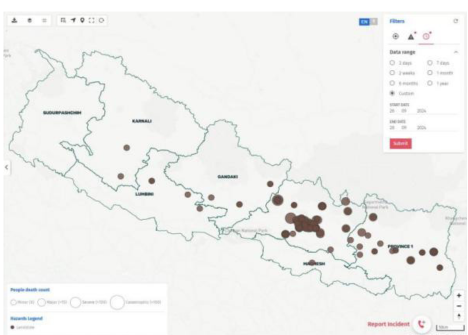

Figure 4 Landslide incidents in Nepal from 26 to 28 September 2024(www. www.bipad.gov.np)

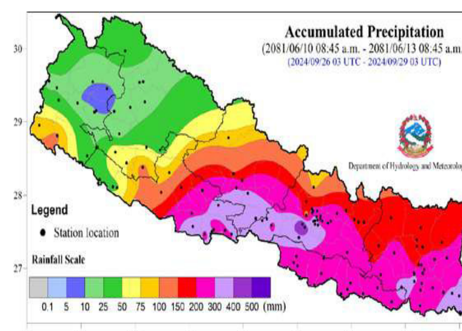

Figure 5 Map showing Accumulated Precipitation in Nepal from 26-28 September 2024 (www.bipad.gov.np)

Figure 6 Residents climb over a rooftop in Kathmandu on September 28, 2024(https://www.chinadailyhk.com/2024)

Figure 7 Bridge connecting Sindhuli and Ramechhap to Okhaldhunga damaged by the flooded Sunkoshi River, (https://english.khabarhub.com/2024)

2.2. Highway Closure

The closure patterns of Nepal's national highways during the 2024 monsoon season are characterized by significant spatial and temporal variations, as indicated by highway-specific data and seasonal trends. The analysis of closure frequency reveals that certain highways faced disproportionately high disruptions. For instance, Pushpalal Highway (NH03) recorded the highest number of closures, with nearly 200 incidents during the season. This highway is a critical route in the region but traverses highly landslide-prone zones, resulting in frequent interruptions. Then Kaligandaki Corridor (NH48) and the Swargadwari Highway (NH53) also undergo frequent disruptions (DOR, 2024).

NH03 stands out the longest total closure time (over 4,500 hours), indicating persistent and long-duration disruptions. This suggests systemic issues on this route, such as poor infrastructure, frequent natural hazards, or high vulnerability to traffic incidents. In contrast, NH08 shows a high closure time (over 3,300 hours) but low frequency. This prolonged blockage was caused by the collapse of the Ikhuwa Bridge and multiple landslides at various location along highway. In comparison, highways located in the Terai region experienced relatively fewer closures, predominantly attributed to localized flooding events rather than landslides. The data demonstrates a strong temporal correlation between cumulative rainfall and the occurrence of road closures. Notably, during September, intense and sustained rainfall likely exceeded critical thresholds for slope stability, resulting in widespread failures along multiple road sections.

The observed disparity in closure occurrences underscores the need for targeted interventions to enhance highway reliability, especially for those routes experiencing frequent interruptions.

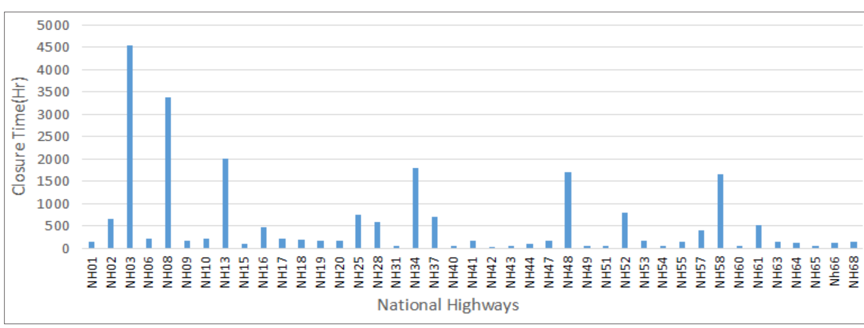

Figure 8: Total Closure Duration of National Highways in Nepal in Monsoon 2024

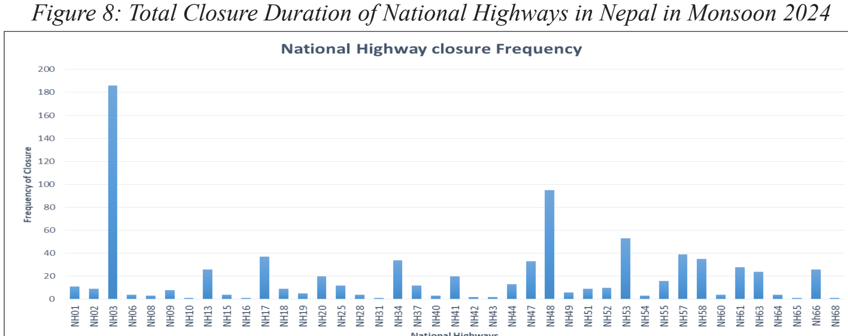

Figure 9: Frequency of National Highway Closures during Monsoon 2024 (DOR, 2024)

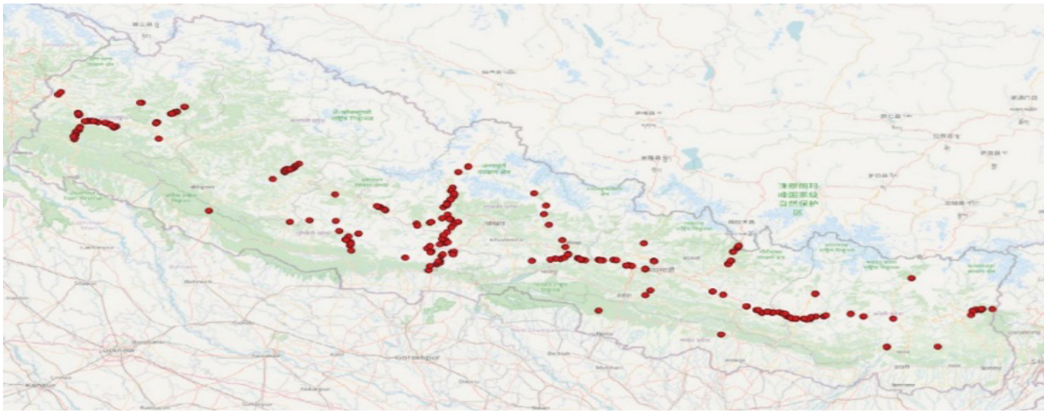

Figure 10 Road Closure Mapping of Nepal in Monsoon 2024

The monthly distribution of closure hours underscores the seasonal dynamics of disruptions. In May, closures were negligible, aligning with the pre-monsoon period. However, by June and July, closure hours sharply increased, reflecting the onset of intense rainfall. September emerged as the peak month for road disruptions, which may be due to the high rainfall month in 2024. This spike correlates with the seasonal maximum rainfall, which overwhelmed drainage systems and triggered large-scale landslides and floods. Highways such as NH03, NH48 were particularly affected during this period, with multiple closures lasting several days. In October, closure hours dropped significantly, indicating the monsoon's retreat as shown in Figure 11.

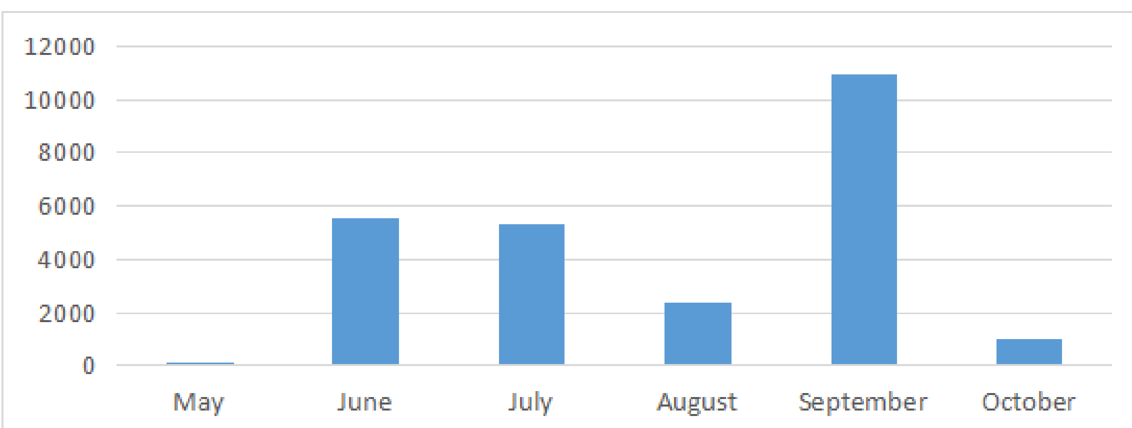

Figure 11 Monthly Highway Closure Pattern in Monsoon 2024

The infrastructure damage includes 41 road sections, contributing to an estimated total complete repair and maintenance cost of NPR 27.98 billion. The floods and landslides from September 26–28, 2024, have severely impacted key highways across Nepal, leading to widespread road closures and infrastructure losses. This natural disaster has disrupted transportation networks essential for connectivity, trade, and the movement of goods and people, particularly in Koshi, Bagmati, and Karnali Provinces (NDRRMA, 2024).

2.3 Relationship between National Highway closure and Maximum Rainfall

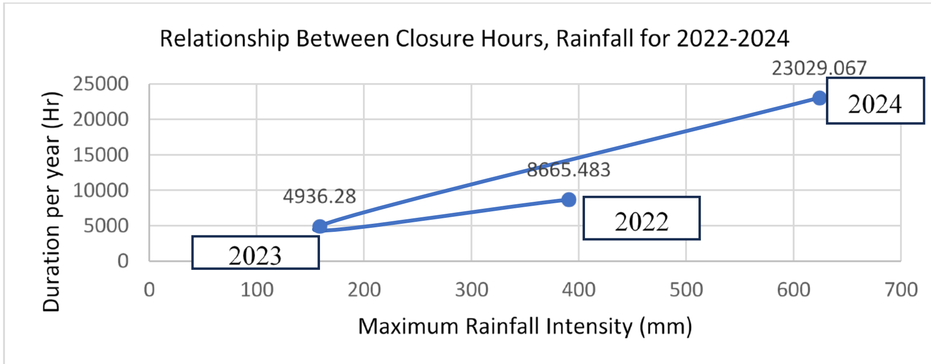

Figure 12 Closure duration with respect to Maximum Daily Precipitation per annum

In 2022, the highest 24-hour precipitation in Nepal was recorded at Chisapani in Kailali district, with 390.7 mm on November 17th (Season, 2022). In 2023, the weather station in Diktel, Khotang recorded the highest daily precipitation ever recorded in Nepal, with a reading of 158.6 mm (DHM, 2023). Nepal experienced 11% lower-than-normal rainfall in 2023, with the heaviest rainfall occurring in August, which was 14% above normal. The highest daily precipitation recorded in Nepal during 2024 was 624 mm at the Dodhara weather station in Kanchanpur district on July 8, 2024. Another extreme precipitation event occurred in late September, with Kathmandu recording 323.5 mm of rainfall in 24 hours.

An analysis of national highway closure hours in Nepal during the monsoon seasons of 2022, 2023, and 2024 revealed significant fluctuations. In 2022, there were 8,665.483 hours of national highway closure over the year. In contrast, 2023 experienced a considerable reduction in closure hours, possibly attributed to a less intense monsoon or effective mitigation efforts. The year 2024 witnessed the highest closure hours, indicating severe disruptions to highway accessibility due to monsoon-related hazards This pattern underscores the variable nature of monsoon-related hazards and their impact on Nepal's highway network. Further research is crucial to identify specific factors influencing these variations and to implement robust strategies for mitigating the impact of these hazards.

2.4 Impact on Human Life Loss

The monsoon of 2024 has been particularly devastating, resulting in 246 lives lost, 15 individuals missing, and over 17,000 people rescued. Tragically, about 3,000 homes have been damaged or destroyed, along with over 100 kilometers of roads and more than 50 bridges rendered unusable (Volunteers Initiative Nepal, 2024). One of the factors of road crashes is road and environmental conditions, which contribute around 34% globally, and also have a significant share in Nepal(Tiwari & Luitel, 2023).

According to a situation report by the National Disaster Risk Reduction and Management Authority (NDRRMA), the disaster caused extensive damage to homes, infrastructure, and agricultural land, affecting a total of 16,243 families. A total of 60 households in Yangwarak Rural Municipality-3, Panchthar, have been shifted to safer places due to increasing landslide risks as the monsoon continues in the eastern part of the country (https://kathmandupost.com).

Figure 13 Displaced Households in July 2024 Flood in Far Western Nepal (Source: bipad.gov.np)

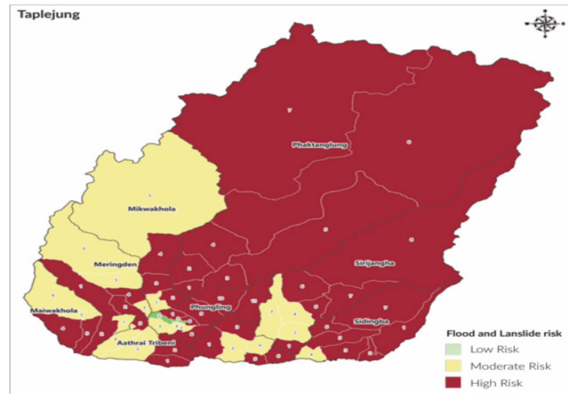

Figure 14 Risk Mapping of Taplejung District in July 2024, Nepal (Source: bipad.gov.np)

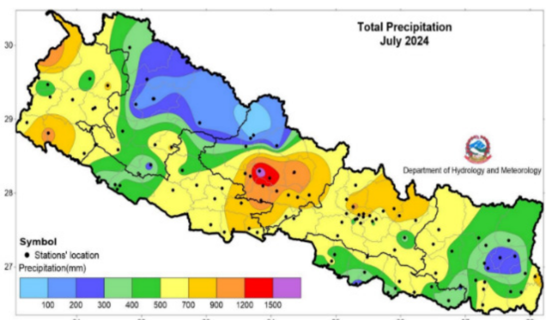

Figure 15 Total precipitation in July 2024 in Nepal (Source: bipad.gov.np)

Figure 16 Culvert collapsed at Bedkot, Kanchanpur district along East-west Highway

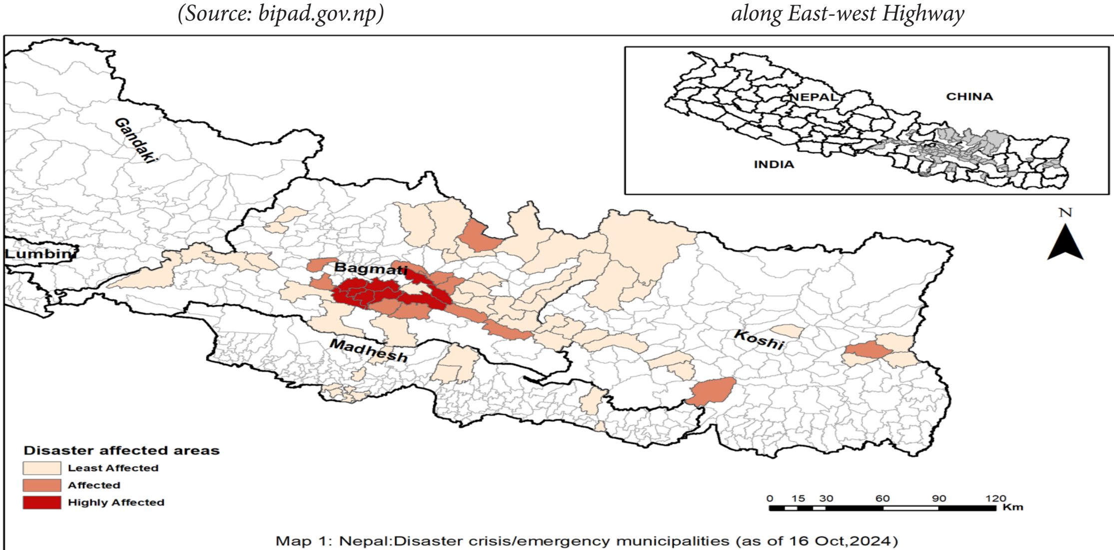

Figure 17 Disaster Disaster-Affected Areas in September 2024, Nepal

The impacts of these events extend beyond immediate losses. Damaged road networks disrupted economic activities, raised transportation costs, and delayed rehabilitation efforts. However, these challenges also underscore the need for resilience-focused infrastructure planning. The 2024 rainfall and landslide incidents serve as a critical reminder of the importance of integrating robust design principles with disaster risk reduction strategies to ensure uninterrupted road connectivity in Nepal's challenging topography (2024 September Floods and Landslides National Disaster Risk Reduction and Management Authority, n.d.)

2.5 Flood-Induced Hazards and Reconstruction of BP Highway

The BP Highway, a vital connection between Kathmandu and eastern Nepal, has been severely affected by flood-related hazards, leading to frequent closures and extensive damage. Intense monsoon rains trigger landslides and flooding along this route, disrupting transportation and local economies. Due to the continuous deterioration caused by these natural hazards, a major reconstruction project is planned, with an estimated cost exceeding NR. 9.5 billion (The New York Times Partner, Republica, n.d.).

Recurrent closures have weakened the highway's structure, with insufficient drainage and vulnerable embankments contributing to the problem. The rising intensity of monsoon rainfall further amplifies the risk. The reconstruction effort aims to incorporate measures like slope stabilization, enhanced drainage systems, and climate-resilient designs. These improvements will strengthen the highway's resilience and ensure more reliable and secure transportation, ultimately supporting economic growth and connectivity in the region.

Figure 18 Damage caused by the Roshi river at Nepalthok on BP Highway (Source: https://ekantipur.com

2.6 Assessment of Impact of Blockage

As observed, the landslide has caused significant blockage on the majority of the roads. As all the roads lack a proper database of traffic data, the sample analysis has been carried out for NH-44 Mugling to Narayanghat section. Due to unavailability of data, the database of 2022/23 provided on DOR website was used for analysis.

The total Average Annual Daily Traffic is 6384 Vehicles (including motorcycles and rickshaw). As the total blockage on the Chitwan section was 36 hours, the total blockage/impact is 30,291 vehicle-hours in 2024 The vehicle composition and occupancy on each vehicle are then used to analyze the total person hour impacted by the landslide on the mentioned road.

Table 1 Impact Assessment of Blockage (Narayanghat-Muglin-NH44)

Category	Proportion (%)	Average/Day	Assumed Occupancy	Total Person Movement	Impact (Person-hours)
Truck Category	30	3,030	2	6,060	143,319
Bus/Mini Bus/ Micro	17	1,717	20	34,340	
Car/4WD	21	2,121	2	4,242	
Utility Vehicles	9	909	1	909	
Motorcycle	22	2,222	1	2,222	

Hence, NH-44 with just 36 hours of blockage leads to an impact of 30,291 vehicle-hours or 143,319 person-hours, which also has a significant impact on the national economy.

3. Conclusion and Recommendation

The 2024 monsoon season highlighted the intensifying vulnerability of Nepal's national highway network to climate-induced disruptions, with a total of 814 closures across 41 highways, amounting to 23029 hours of cumulative road blockages. Notably, Pushpalal Highway (NH03) and Kaligandaki Corridor (NH48) emerged as the most affected, both in terms of closure frequency and duration, largely due to their alignment through landslide-prone, geologically fragile terrain. The rainfall-triggered hazards exemplified by a 624 mm cloudburst in Dodhara Chandani and over 200 mm/day rainfall recorded in 77 locations during late September overwhelmed infrastructure, exposing deficiencies in slope stability and drainage systems. The study reveals that closures peaked in September, correlating with maximum rainfall intensity and inadequate mitigation capacity. Disasters such as the July floods in Sudurpaschim and September landslides across central and eastern corridors not only compromised transportation but delayed emergency responses, isolated communities and contributed to direct human losses; at least 35 fatalities in a single landslide event at Jhyaple Khola.

As per the highway blockage impact assessment, the landslide-induced closure has caused a major disruption to vehicular movement along the Narayanghat–Mugling section (NH-44), which was taken as a representative sample for analysis and yielded 30,291 vehicle-hours impact.

Based on observed patterns and infrastructure failures, it is evident that Nepal's highway system requires a transition toward climate-resilient design, site-specific slope stabilization, and centralized real-time monitoring systems. These findings make a compelling case for integrating rainfall thresholds, geological sensitivity and infrastructure resilience into national transport planning. Without strategic intervention, the continuity of Nepal's critical road corridors will remain at high risk, with compounding socio-economic losses in every subsequent monsoon season.

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