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RESEARCH ARTICLE

Assessment of the 2021 debris flow and flood related loss and damage in Melamchi Watershed of Central Nepal

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ABSTRACT

Nepal, characterized by its youthful mountain ranges, predominantly features mountainous terrain that is geologically fragile and at high risk for prone to geodisasters. Factors such as steep slopes, intense summer rainfall, riverbank erosion, landslide and earthquake contribute to these disasters leading to a significant loss of life and property. This study aims to elucidate the 2021 debris flow and flood-related loss and damage and its impact on local livelihoods in the Melamchi Municipality and Helambu Rural Municipality of Sindhupalchok district. Data were collected through both qualitative and quantitative techniques by using household surveys, focus group discussions, key informant interviews, and field observations were carried out. The sample size was determined by using the Arkon and Colton formula. Disruption of infrastructure, extensive sediment deposition and damage across affected areas, significant erosion, river widening, landscape transformation, temporary river blockage, changes in river morphology, formation of new river channels, and the destruction of agricultural lands were observed in satellite imagery and aerial photographs and they were verified in the field. The event heavily impacted Melamchi Bazaar, claiming over 25 lives and causing substantial damage to the Melamchi Water Supply Project and the Melamchi settlement. The survey revealed that 56% of the respondents lost their agricultural land, 28% lost non-agricultural income sources, 11% lost their employment, and a few others lost other income sources. The total estimated loss of the event was USD 436 million in Melamchi and USD 62 million in Helambu Rural Municipality, including the loss and damage of houses, land, crops, and livestock. Flood and landslides are common phenomena in the Nepal Himalaya and the 2021 Melamchi event was unprecedented in terms of the loss and damage. The result of this study can help policy makers and managers with better planning to minimize the impacts of loss and damage of the geodisaster in the future.

Keywords: ***Disaster, Flood, Landslides, Melamchi Watershed, Sediment***

INTRODUCTION

Nepal lies in the central part of the Himalayas and it has young mountains and fragile geological conditions. The country is susceptible to a range of natural hazards, including landslide, debris flow, avalanche, flood glacial lake outburst flood (GLOFs), and earthquake. Factors such as the presence of fragile, fragmented rock, substantial soil and debris covering steep and rugged landscapes, climatic fluctuations, monsoons rain, and frequent seismic activity contribute to the country's vulnerability to natural disasters. Many anthropogenic causes, such as deforestation, rapid encroachments on natural habitats, and land use changes heighten the already existing hazard levels. To effectively create secure urban and mountain environments, it is essential to understand the relationship between geological and geomorphological factors along with climatic changes.

The Des Inventar and Building Information Platform against Disaster (BIPAD) websites, which catalog past disasters, reveal an increase in the frequency of disasters in Nepal in recent years. Ice avalanches entering a lake can often create a surge wave that breaches the unconsolidated terminal moraine dam (Emmer and Cochachin, 2013; Chen et al., 2017). Other potential trigger mechanisms include displacement waves from rock falls, moraine failure due to dam settlements and/or piping, the degradation of an ice-cored moraine, seismic activity, or the rapid input of water from extreme events or from an outburst flood from a glacial lake located upstream (Rounce et al., 2017a). Twenty-four known GLOF events have been recorded in Nepal, the majority occurring since the 1960s (ICIMOD, 2011). At least five additional GLOFs or glacier-related floods have been reported since then: the Koshi River flood of May 5, 2012 (Kargel et al., 2013), the Langmoche Lake flood of April 25, 2015 (Byers et al., 2017), the Lhotse glacier outburst floods of 2015 and 2016 (Rounce et al., 2017b), Imja Tsho GLOF of Imja valley, Everest region June 2016 (Lala et al., 2018), Tsho Rolpa GLOF of Rolwaling valley (Reynolds, 1999).

Since the 1980s, a number of field-based studies concerned with the causes and impacts of contemporary GLOFs have been conducted in Nepal (Vuichard and Zimmermann, 1987; Cenderelli and Wohl, 2001; Lamsal et al., 2015; Byers et al., 2017). Nearly all have taken place years to decades after the events, and there is often uncertainty as to the actual flood-triggering mechanisms involved (Lamsal et al., 2015). Debris had dammed the floodwaters directly above the village of Barun Bazaar, displacing ten families from their homes, destroying fields, and threatening to impact at least eighty families living within the immediate area if the dam suddenly failed (Shakya, 2017). The lake also threatened downstream villages, including Phaksinda, Diding, Chetabesi, Lumningtar, and other riverside communities in the Bhojpur and Dhankuta districts (My Republica, 2017). Flood devastation in Melamchi is not only because of rains (Mandel, 2021). Experts believe that the land, already weakened by earthquakes, can cause landslides with even a moderate amount of rainfall due to water seepage from the surface. Experts in geology, seismology and hydrology often discuss the impacts of the earthquake on land stability and the increase risk of landslides following seismic events. These experts includes researchers and professionals from organizations such as the United States Geological Survey (USGS), the British Geological Survey (BGS), and academic institutions with the strong geology departments.

According to the Department of Hydrology and Meteorology (DHM), the Melamchi and Indrawati basins experienced rainfall from June 9, 2021. The highest hourly precipitation on June 10 was 22 mm, increasing to 37 mm per hour by June 11. On June 14 and 15, a maximum hourly rainfall of 10 mm was recorded. Sermathang recorded more than 100 mm of daily rainfall on June 11. Over a six-day period, the station received more than 200 mm of rainfall. The intense rainfall and rapid snowmelt led to the erosion of glacial deposits in the headwaters of the Pemdan Khola, Yangri River, and Larche River. A landslide dam formed and subsequently collapsed in Bhemathan near Langtang National Park. A past landslide also formed a natural dam near the confluence between Pemdan Khola and Melamchi Khola on the Melamchi Watershed. This natural dam temporarily blocked the Melamchi River, causing an outburst flood that destroyed settlements, bridges, and roads downstream. The situation was further intensified by heavy rainfall runoff, snowmelt, possible glacial lake outburst, and moraine erosion in the Pemdan Khola region. A second flood event occurred on August 1, 2021, possibly due to heavy rainfall and erosion of the sediment deposited as a result of the first Landslide Dam Outburst Flood (LDOF) event (World Bank, 2021).

The massive downpour, coupled with rapid snowmelt from June 15, led to the erosion of glacial deposits in the far upstream of the Melamchi watershed. This phenomenon caused the formation of a landslide dam and its eventual collapse in Bhemathan. The flood event caused at least 17 casualties and damaged more than 540 houses and critical infrastructure, including bridges and roads. Recovery from the economic impacts may take several years. The effects and impacts of the floods include water depth and residence time, flow velocity, erosive capacity, sediment transport and deposition, and other associated geological phenomena (Andres et al., 2009). Increased temperature will result in an increase in saturation vapor pressure, thereby increasing atmospheric moisture and causing increased rainfall (Allen and Ingram, 2002; Dankers and Feyen, 2008). An increase in the frequency and intensity of rainfall events indicates a higher risk of flooding in the river (Duan et al., 2017).

The frequency and magnitude of floods are also affected by gradual land use change, which may exacerbate the situation (Mallakpour and Villarini, 2015). Floods are complex natural hazards that can cause massive socio-economic damage (Asgharpour and Ajdari, 2011). Increasing frequency and intensity of hydrological extremes pose threats to human life, the economy, infrastructure, and the environment of riverside catchment areas (Maghsood et al., 2018). Among the major disasters in the past decade are the Seti flood in 2012, the Jure landslide dam in 2014, the Gorkha earthquake in 2015, the GLOF in Bhote Koshi in 2016, the Barun Khola flood in 2017, the Terai floods in 2017, the tornado in the Bara-Parsa district in 2019, and the landslide and debris flow in Sindhupalchowk in 2020 (Gurung et al., 2015; Miyake et al., 2017; Geest, 2018; Byers et al., 2019; Shrestha et al., 2019; Liu et al., 2020; Yagi et al., 2021). Nepal faces flood hazards very often (NDRRMA, 2021). Nepal's Disaster Report of 2019 stated that floods and landslides are very common in Nepal and caused 213 fatalities in 2017 and 2018, responsible for national economic losses of over 11 million USD annually.

The Himalayas have steep elevation changes over short distances (Duncan et al., 2003), making landslides and avalanches highly susceptible in the upstream area (Dhital et al., 2021), with debris and slurry sediments (Adhikari et al., 2005). Floods have become one of the most serious natural disasters (Sarhadi et al., 2012; Duan et al., 2022). The nature of floods has become more cascading and widening in dimension over the years, causing significant damage (Gautam et al., 2021; Maharjan et al., 2021). The damage due to floods continues to rise. Due to heavy precipitation in the Tistung area of Makawanpur district (>500 mm in 24 hours), inundation of agricultural land and destruction of more than 67 irrigation schemes occurred (Adhikari et al., 2023). The same flood turned into a devastating debris flow event in some steep terrains, resulting in more than 60 lives lost and 52 houses damaged (Dhital, 2003). In 2021, flood events in the Melamchi River originated from heavy rainfall in the upper catchment area, which contains permafrost in the deglaciated valley. On June 14-15, 2021, heavy rainfall intensified the erosion process, possibly leading to the erosion of the end moraine dam of Pemdan Lake (at 4700 m) and the subsequent emptying of the lake. This resulted in a flash flood in Pemdan Khola, depositing large amounts of boulders, gravel, and sand in the Bhemathan area, an old landslide dam that became filled with sediment and debris. The flood also mixed the trees of Bhemathan with the debris flow of Pemdan Khola, blocking the old landslide area and causing floodwater with debris to flow as overtopping flow through the old landslide dam. Then, on August 1, 2021, heavy rainfall caused the overtopping water flow at the Bhemathan area to abruptly erode the old landslide dam, triggering a massive flash flood downstream, eroding old glacial deposits and river channel deposits along a stretch of over 4 km of the river.

Recent research by Shrestha et al. (2021) and Dahal et al. (2022) reveals that the 2021 Melamchi Flood was due to the combined effects of changing temperature, which breached the Pemdan glacial lake, creating a series of landslides and erosion in the Melamchi River basin. The outburst of the Pemdan Glacier Lake is equally important in the upstream area of the Melamchi River basin, destroying the natural dam near the Bhemathan area, which later supported erosion (Dahal et al., 2022). The study reveals that 228,309 m³ of sediment loss and 16,925,260 m³ of deposition occurred in the Bhemathang area (Dahal, 2021; NDRRMA/World Bank, 2021). A volume of 88,454,507 m³ of sediment was moved during the events (Dahal et al., 2022). The flood events in the Melamchi watershed on June 15, 2021, and July 31, 2021, were the combined effects of high-intensity rainfall, GLOFs, rainfall-induced landslides, and LDOFs in the upstream area of the watershed (ICIMOD, 2021; NDRRMA, 2021; Pandey et al., 2021). The flooding caused damage to 252 households in Helambu and 287 households in Melamchi Municipality. It also damaged many access roads and foot-trails to several settlements. The disaster resulted in 5 human casualties and 20 people missing. Furthermore, the flood debris destroyed the road network, bridges, transmission lines, the intake structure of the Melamchi water supply project, and agricultural land along its path. Additionally, the debris caused sedimentation over 10 m high in the downstream area (NDRRMA, 2021; Takamatsu et al., 2022).

STUDY AREA

The study area, which is part of the Indrawati River basin, is shown in Fig. 1. It lies within the subtropical to alpine climatic zone of the Himalayan range, spanning three central hill districts of Nepal: Sindhupalchok, Kabhrepalanchok, and Kathmandu. The basin's catchment area totals 1240 km2 with natural forest covering nearly 40% of it. Presently, less than 3% of the total basin area is utilized for farming. The study encompasses an 18 km distance, including the Helambu Rural Municipality and Melamchi Municipality, with elevations ranging from 712 to 5,747 meters above sea level. Our study mainly focuses on the areas highly impacted by the flood event of 2021, which include Timbu, Halde, Kiul, Chanaute, Gyalthum, Taramarang and Melamchi Bazaar in the Melamchi Municipality (Fig. 2). The population density of the basin was approximately 175/km² in 1998. The average annual rainfall in the basin ranges from 3,874 mm at higher-elevations (Sarmathang) to about 1,128 mm at Dolalghat in the lower elevation zone, with an average annual potential evapotranspiration of around 954 mm (WECS/IWMI, 2000). The average relative humidity is about 70%, varying from 60% in the dry season to 90% in the rainy season. Daily average sunshine is 6.2 hours per day, with variations from 3.3 hours per day in July to 8.1 hours per day in April. Major tributaries of the Indrawati River basin include Larke Khola, Yangri Khola, Melamchi Khola, Jhyangri Khola, Chaa Khola, Handi Khola, and Mahadev Khola. The Melamchi, Handi, and Mahadev River basins are significant sub-basins in the Indrawati river system in terms of water use practices.

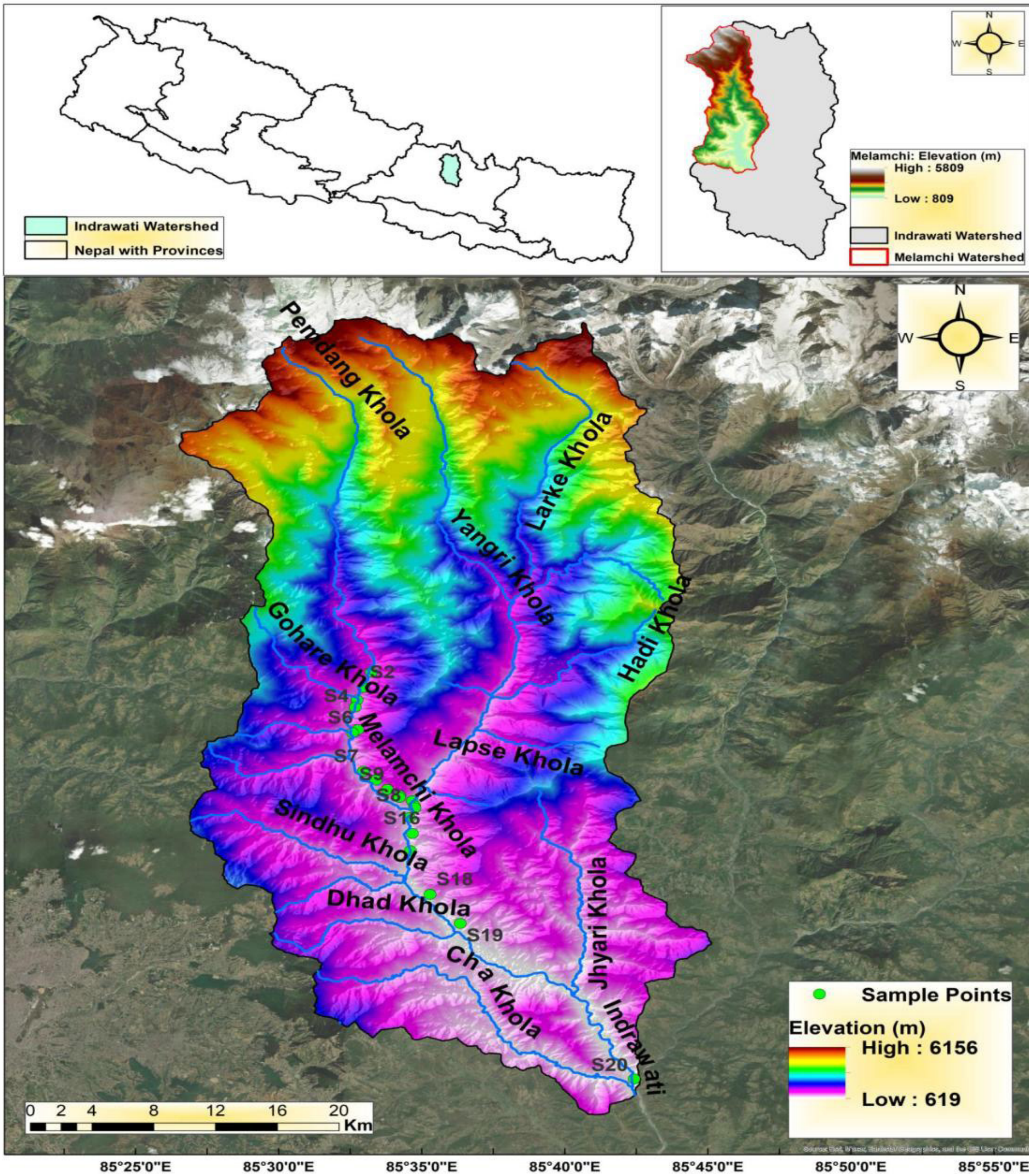


Fig. 1: Digital Elevation Model of the Study area (Melamchi- Indrawoti River basin) indicating 20 different sampling sites

MELAMCHI FLOOD

The Melamchi flood is a cascading hydrological hazard (multiple hazards co-occurring) caused by intense rainfall continuously occurring in the upstream area, which creates significant damage to the downstream regions. Climatic and anthropogenic factors are also associated with these devastating debris flow events (Maharjan et al., 2021; Takamatsu et al., 2022; Talchabhadel et al., 2023). The Melamchi flood is not solely due to rain; various other factors contribute to these events (Mandal, 2021). Thapa et al. (2022) have found that the greatest losses from the devastating flood were in the agricultural sector, which was reduced by 90.48%. According to the Department of Mines and Geology (DMG) and the National Disaster Risk Reduction and Management Authority (NDRRMA), numerous landslides occurred in the section (upstream and downstream regions of Bhemathang). The Pemdang Khola deposited 16,925,260 m^3 of sediments and debris in the initial period, with active scouring and unstable boulders being other significant issues. Among the various causes, soil slides, cloud bursts, and steep glacier moraines were major contributors to the disaster (Baskota et al., 2021). The flood resulted in the loss of many lives and significant damage to property, residential buildings, bridges, and other infrastructure. Localized rainfall triggered debris flow events, as the debris had already accumulated in the upstream area due to the fragile geological formation. The event was characterized as a cascading effect of the 2015 Gorkha earthquake. Sediments were transported over a 30 km stretch, with a high transport rate of soft sediments, and riverbed was elevated by up to 15 m in most locations (Pandey et al., 2021).

On June 9, 2021, the DHM recorded heavy rainfall, with the highest rate of 37 mm/hr occurred on June 11. This was a major factor contributing to the disaster. Fig. 3 shows the amount of rainfall received by each station from June 12 to 16, 2021, with the Shermathang station receiving only 200 mm of rainfall over the six days. Studies reveal that the landslide dam formed in the Bhemathang area was swept away and collapsed due to heavy rainfall in the upstream area, combined with snowmelt erosion in the Yangri River, Larche River, and Pemdang River. This landslide disrupted the natural flow of the Melamchi River, creating a natural dam that later burst, destroying infrastructure, settlements, bridges, and roads downstream. Other factors, such as possible glacial lake outbursts, heavy rainfall runoff, and erosion in the Pemdang River area, contributed to these events. This resulted in riverbank failures, damaged infrastructure, and landslides, leading to another devastating flood event on August 1, 2021, exacerbated by the previous events (Maharjan et al., 2021; Takamatsu, 2022; Adhikari et al., 2023). The high recorded temperatures and precipitation in June 2021 simultaneously caused glacier lake melting and heavy rainfall in the upper part of the catchment area, which later helped destabilize the steep portions of the Bhemathang area, where debris had already accumulated. Intense continuous rainfall and erosional action in the upper part resulted in a huge landslide in the Melamchi Ghyang downstream. The natural dam created by the landslide blocked the river, but the dam was later breached, causing another devastating flood event. This heavily eroded the riverbanks and led to significant deposition in the downstream area. Continuous rainfall was a supporting factor for all these cascading hydrological events and numerous landslides (Fig. 3).

Breaching and blocking of the river upstream can lead to significant disasters especially in mountainous regions like the Himalayas such events often result from a combination of climatic factors and geological activities (ICIMOD, 2021). Heavily deposited and transported materials from upstream caused significant losses and damage to livestock, property, and infrastructure in Melamchi town and damaged or destroyed riverbeds (Talchabhadel et al., 2023). Land and infrastructure near the Melamchi River corridor collapsed due to increased sediment load (Joshi et al., 2023). The Melamchi flood resulted in 23 people missing, 1 fatality, 6 injuries and 539 households damage (Adhikari et al., 2023). The flood damaged and destroyed bridges (trails and suspension), headworks of the MWSP, trout, pig, and poultry farms, and buildings were washed away, swept away, or buried with sediments (Pandey et al., 2021; Gautam et al., 2022; Dahal et al., 2023). According to the National Aeronautics and Space Administration (NASA), in the Melamchi and Helambu areas, the highest precipitation (168 mm) occurred on June 15, 2021, while the highest daily maximum temperature (20.73°C) was observed on June 9, 2021. The significant rise in temperature possibly contributed to glacier melting, creating the disaster (Source: NASA, POWER Data Access Viewer).

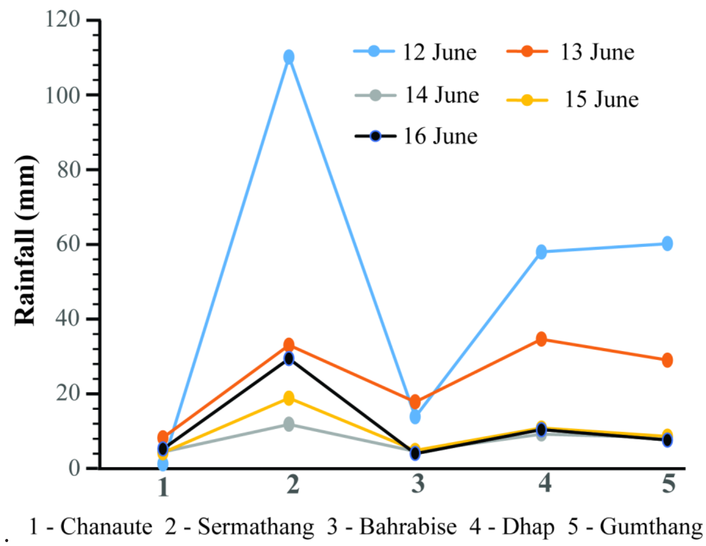


Fig. 2: Rainfall in Sindupalchowk district during June 12-16, 2021.

MATERIALS AND METHODS

For primary data, field visits were conducted in the most affected areas of the Melamchi Municipality and Helambhu Rural Municipality. For event detailing, data from residents and proxy information were used. Similarly, the catchment features of the area were studied with the help of a topographical map (Table 1). Questionnaire surveys, focus group discussions, and key informant interviews were employed. A consultation workshops, as well as informal interviews and case analyses of the events, were also conducted. Both qualitative (case analysis) and quantitative (for the total valuation of economic losses) approaches for data collection were applied. A total of 539 households were considered as survey populations (Adhikari et al., 2023). The populations were surveyed equally from upstream to downstream regions by considering low, middle, and highly affected areas due to the Melamchi Flood. The sample size for the survey was determined using the (Arkin and Colton, 1963). The sample size (n) for the questionnarie survey was determined by using the following formula given by (Arkin and Colton, 1963) at a 95% confidence level.

Sample Size(n) $= N * Z^2 * P\,(1- P) / N * d^2 + Z^2 * P\,(1-P)$

Where,

N = Total number of the affected households

Z = Value of standard variate at 95% confidence level (1.96)

P = Estimated population proportion (0.05)

d = Error limit of 5% (0.05)

Hence, the sample size (n) = 70

Table 1: Types of data used in this study

Data Type	Year	Source
Topographical Map	2021	Survey Department, Nepal
Google Earth Image	2023	Google Earth
SRTM- DEM	30 m	USGS/ Nasa Earth Data
Local level boundary	2021	Survey Department
Ancillary data	CBS 2021	CBS, Kathmandu
Field Survey	2023	Sindupalchowk District

For the secondary approaches, historical events were studied from the Bipad portal (https://bipadportal.gov.np/) as well as from situational analysis and site visits after the debris flow. Data on the losses and damages during the Melamchi Flood were collected, along with ancillary data on casualties, causes, and implications from various sources. Satellite images (before and after), Google Earth images, and digital elevation models of the study area were also analyzed. The fieldwork encompassed local household surveys, site investigations, and the collection of losses and damage data records with photographs of each Global Positioning System (GPS) location. Kobo Collector, OpenStreetMap, SRTM- DEM, Nasa Earth data and mobile phones were used during the field days. Additionally, various analyses and reviews of the events were performed. Secondary data collection involved reviewing articles, books, journals, and publications. Maps were analyzed and presented using remote sensing and Q GIS tools and techniques.

RESULTS

The overall flood-impacted area includes household settlements from upstream to downstream along the river courses, especially from the origin of the glacial lake outburst flood to Dolalghat. The disaster area along the Melamchi River comprises locations such as area affected by glacial lake drainage and snow cover, Bhremanthang, Melamcheegaun, Ribarna, Dana, Otero, Nakote, Chanaute, Thapagaun, Helambhu, Melamchi Bazaar, Thadkol, Jogitar, Dolalghat. These regions are categorized based on previous snow cover, heavy rainfall, snowmelt, erosion, and sediment deposition. In this study, we focused on the most severely impacted areas within Helambu Rural Municipality and Melamchi Municipality (Fig. 2). The study includes the roadways from the headworks to Ambathan, Timbu, Halde, Nakote, Sankathali, Kiul (Chiple Dhunga), Ganeshi, Chanaute, Gyalthum, Taramarang, Melamchi Bazaar, Sipaghat, Eklebesi, Maghitar, and Dolalghat. Specifically, sampling was conducted in the major affected areas of Timbu, Halde, Kiul, Chanaute, Gyalthum, Taramarang, and Melamchi Bazaar.For the analysis, the region from Timbu to Melamchi Bazaar, termed as the Melamchi River corridor, which was divided into three segments: upper, middle and lower. The upper and middle sections span from Timbu to Gyalthum, whereas the lower section stretches from Taramarang to Melamchi Bazaar.

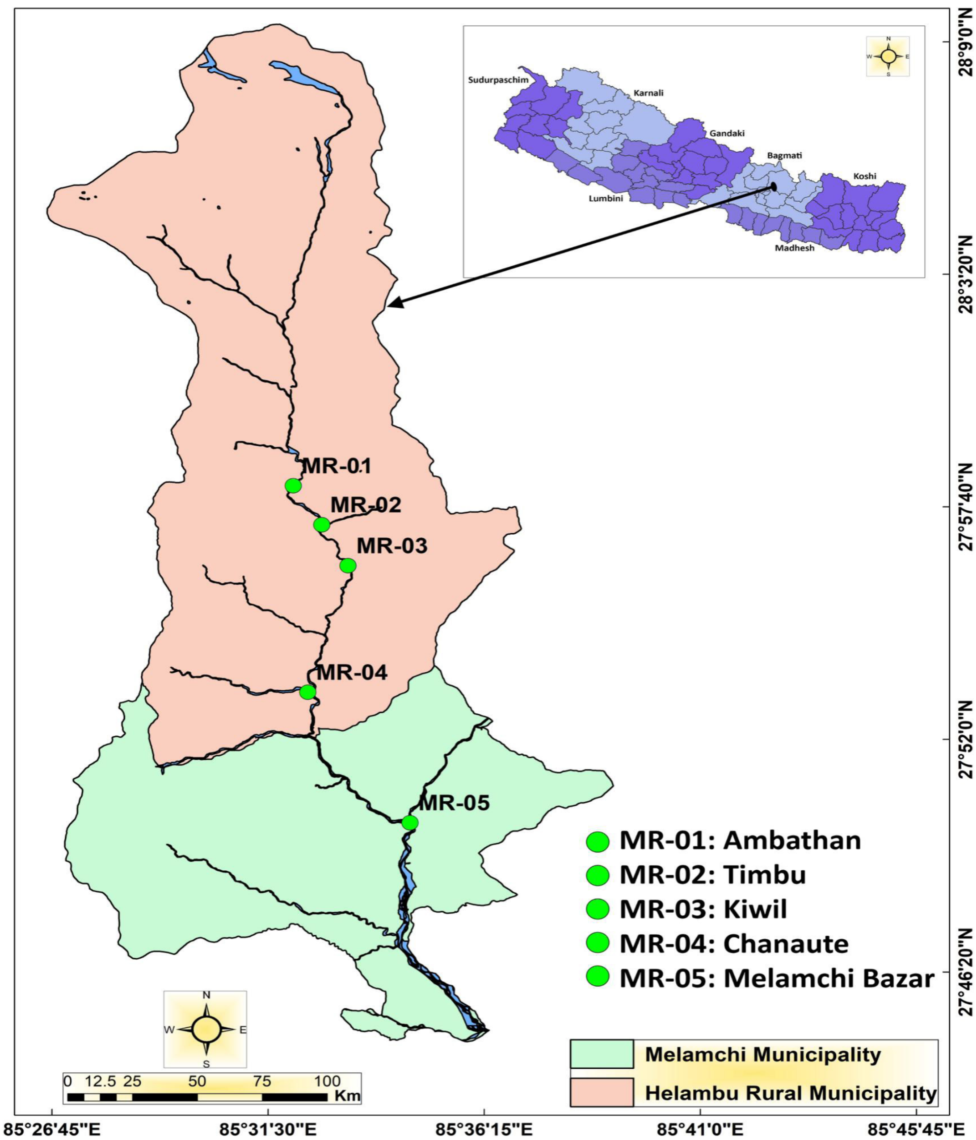


Fig. 3: Location of major affected areas in the Melamchi river Basin

Life and property along the Melamchi River corridor were heavily affected during the 15 June 2021 flood. The event lasted for about 10 hours and caused enormous loss of lives and property, including domesticated livestock and poultry, land, and physical infrastructures. At least 350 residential buildings, half a dozen bridges, and many more infrastructures were affected by the devastating debris flow events (Tables 2 and 3). The disaster caused by the Melamchi flood resulted in 5 human casualties and 20 persons missing. As a consequence, the devastating flood destroyed road access, bridge, transmission lines, schools, irrigation, FM station and heavily impacted the Melamchi Water Supply Project (MWSP). Sedimentation in the downstream area is another serious issue. The survey data revealed that among the total respondents 2.8% of the respondents were missing their family members who had gone outside for work. Some respondents reported injuries to their family members. Mental health problems were a serious issue during the flood events, affecting people in the both municipalities.

Most respondents raised concerns about clean drinking water, malaria, and dengue during the flood events in both municipalities. About 58% of people living in the Helambu area faced problems with inaccessible roads due to the flood. They were unable to go to schools or health posts for checkups. In contrast, in Melamchi Municipality, only 4% of respondents mentioned this issue. Most respondents from both municipalities (43% in Melamchi and 55% in Helambu) discussed the cultural and religious values of their ethnicity, expressing distress over the destruction of temples, churches, cremation sites, stupas, and prayer buildings. Additionally, 55% of respondents in Melamchi and 49% in Helambu agreed on the issues relating to biodiversity loss, such as the invasion of new weeds, loss of wild animals and birds from their localities, water degradation, drying of water sources, increased temperatures, reduced beauty and aesthetic values, and decreased fish diversity. Lastly, 55% of respondents from both municipalities reported considering migration due to the loss of houses, agricultural lands, lack of jobs, and other factors.

Table 2: Losses and Damaged data (Source: Melamchi Municipality and Field Survey, 2023)

Information	Number	Remarks
Houses Partially Damaged by flood	78	
Vulnerable Houses After Flood	123	
Vulnerable Houses After Flood	123	
Plots fully damaged by flood	3082 Ropani	1882 Private 1200 Public
Fully damaged business	250	Different Patterns of Businesses
Partially damaged but highly Vulnerable public infrastructure	10	
Fully damaged public infrastructure	31	
Lost livestock	120	
Fully damaged sheds of livestock	50	

Table 3: Other losses and Damaged in Melamchi Municipality, Source: Melamchi Municipality and Field Survey 2023

Infrastructure	Ward No	No.	Remarks
Motorable bridge	11	2	Fully Damaged
Suspension bridge	11 6	3 3	Fully Damaged (2) and one highly vulnerable Highly vulnerable
Lift water supply system	11 10 and 11	1 1	Fully damaged Fully damaged
House	11 6	18 1	Fully damaged (17) and one Highly vulnerable Highly vulnerable
Melamchi city park	10	1	Fully damaged
Bus Park	11	1	Fully damaged
Road	11 10 10	1 1 1	Partially damaged (Melamchi to Helambhu Road) Partially Damaged but Highly vulnerable (Indrawati Corridor Road) Partially Damaged but Highly Vulnerable (Sikharpur-Bhiotang Road)
Agricultural land	13	1	Partially damaged (community-based agricultural land)
School	6	1	Fully Damaged (3) and temaining are highly vulnerable (Terse M.V Talamarang)
Irrigation canal	10 11 7 9 and 10	1 1 3 1	Fully Damaged (Khaharekhola Irrigation) Partially Damaged (Nuhar Khola Irrigation) Fully Damaged (Sungure, Amare Thulobagar, Soldunga Irrigation) Fully Damaged
Church	10	1	Fully Damaged (Located in Simlebesi)
Electric power lines and poles	10 and 11	1	Fully damaged
Funeral house	6 10	2 1	Fully Damaged (Talamarang and Nuhankhola) Fully Damaged (located at Rampur)

Additionally, Melamchi Bajaar was severely impacted by the flash flood, which originated from two upper tributaries. This flood caused five deaths, 20 people went missing and resulted in significant loss to the Melamchi Water Supply Project. Information on the total population, number of houses, and the affected houses in the Helambu and Melamchi Municipalities were obtained from the census of 2021 and field survey. There were 4,589 houses with 8,907 males and 8,816 females in the Helambu rural municipality, and 10,811 houses with 20,073 males and 21,097 females in the Melamchi municipality. The total number of affected or damaged houses in the Helambu Rural Municipality was 252, while in Melamchi it was 287.

Stratification was done based on the spatial distribution, meaning that each sampling area was taken as a stratum. The stratified random sampling method was used to determine the household survey of three sections of the affected river corridors: Upper, Middle, and Lower. As mentioned already, Timbu to Gyalthum represented the Upper and Middle sections, whereas Taramarang to Melamchi Bazaar represented the Lower sections. The sample size of the households to be surveyed was determined as $n/N \times 69$, where n is the sample of affected households of the selected study sites and N is the total number of affected households in the entire study sites (Table 4).

Table 4: Number of Sampled households in Study sites, Source (Field Survey 2023)

Study Sites	Helambhu	Melamchi	Total
No. of total households	252	287	539
No. of samples	33 (47%)	37 (53%)	70 (100%)

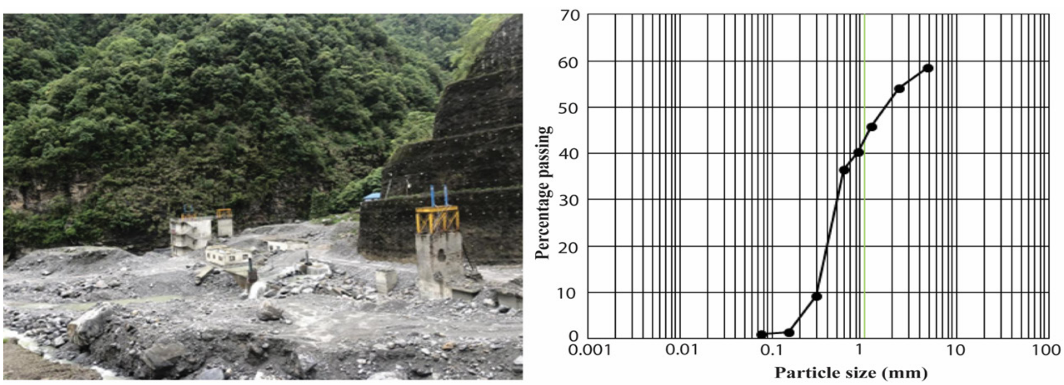
The total surveyed respondents from Helambu Rural Municipality and Melamchi Municipality represented 47% and 53%, respectively. The majority of the respondents were aged between 40-60 years. Among the respondents, 55% were men and 45% women. Most of the respondents depended on agriculture, and some were self-employed. A few were entrepreneurs engaged in the fishing business and trout farming. However, it is important to mention that all these businesses collapsed after the flooding events in Melamchi. The Melamchi flood destroyed many infrastructures, schools, agriculture, tourism, businesses, and many other sectors. A total of six bridges (Motorable bridge, bailey bridge, suspension bridge, Pedestrain bridge, Arch bridge and Truss Bridge) were damaged during the flood events in the Melamchi area. Since trout farming and tourism were the main sources of revenue generation, the flood events caused most of these businesses to collapse, leading to unemployment. According to Melamchi Municipality data, there was a loss of USD 417,840,665.03 in houses, USD 17,845,821.75 in land, and USD 91,230.66 in livestock, with a total loss of USD 435,777,717.44. In Helambu Rural Municipality, the losses were USD 4,084,343 in houses, USD 16,188 in livestock, and USD 19,844,170 for crop loss, ensuring a total loss of USD 61,772,407 in Helambu Municipality (Parajuli et al., 2023) (Table 5). These documents also proved relevant to the household survey data. The majority of the respondents from both municipalities reported losses of agricultural land, houses, and livestock.

Table 5: Economic Valuation of Assets loss of survey respondents (Source, Parajuli et al., 2023)

Information	losses	Cost (NRs)	Cost (USD)
Total house loss	63	21,10, 05,013	1,603,638
Total land loss	16.714 hectares	43,47,13,250	3, 303, 821
Total livestock loss	Hen, Goat, Pig, Buffalo Ox, Cow	27,45,500	20,866
Total crop loss		22, 70, 197	17, 253
Total loss		65,14,08,960	4, 945, 578

The survey data revealed that 95% of the respondents felt insecure about their income as a result of the flood. Among them, 56% had lost their agricultural income, 28% lost their non-agricultural income sources, 11% lost their employment, and a few lost income-generating sources such as tourism. While surveying, some people also complained about the loss and damage to Water Mills (Ghatta) and irrigation canals. They added that this has also impacted their daily routines. Nevertheless, some respondents were facing depression and anxiety issues after the flood events. They also mentioned problems they are currently experiencing with cremation due to the high deposition of debris on the riverside of Melamchi. Both municipalities were unaware of the non-economic loss and damage in the area, which need to be revealed as soon as possible.

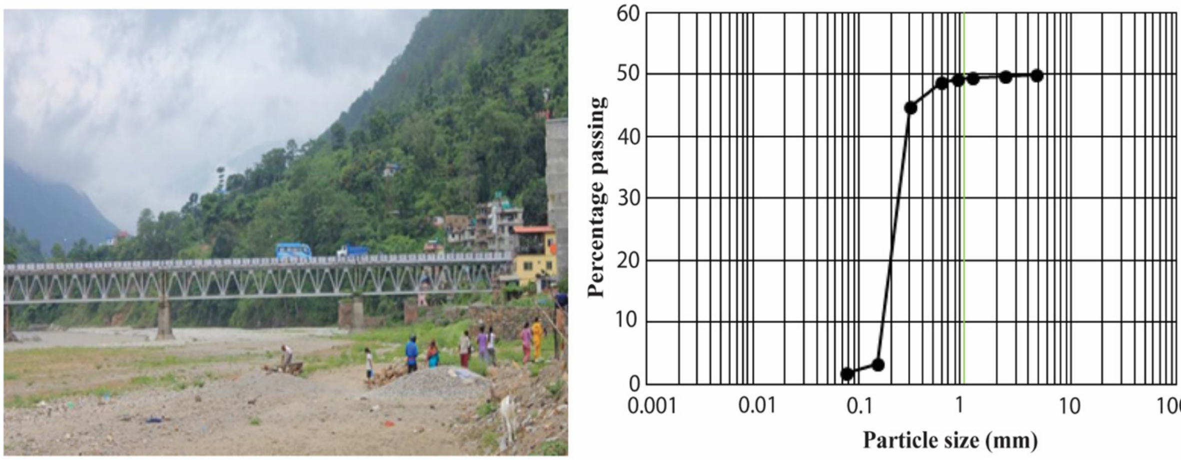
While conducting the analysis of the sample taken from the left bank of the Melamchi Khola near the head works area close to the dam. The followings results were revealed. The sample is from the high flood level debris flow deposits shows the sieve analysis curve for a sample with the following composition. Gravel 41.42%, Sand 57.65% and Silt and Clay 0.93%. Gravel: represented by the steep initial portion of the curve up to about 2 mm, indicating that 41.42% of the sample is gravel. Sand: The curve rises significantly between 0.075 mm and 2 mm, showing that 57.65% of the sample consists of sand. Silt and Clay: The smallest portion of the sample, represented by the smallest particle sizes (0.075 mm and smaller), with only 0.93% passing the sieve. The curve illustrates the cumulative percentage of the particles passing through sieves of decreasing sizes. The points on the curve are marked with percentages, indicating the cumulative passing at specific sieve sizes. This curve is typical for moderately graded soils with a mix of different particle sizes, where sand is the predominant fraction, followed by gravel, and very little silt and clay. (Fig. 4 a and b)



(a) (b)

Fig. 4: (a) Flood impacted Melamchi head works area, (b) Particle size distribution of sediment sample (Sample No. 2) collected at the head work area.

This is the analysis of the sample taken from the right bank of the Melamchi river at two previous fishponds buried sites by the debris flow of Melamchi. The materials were fine (granule to silt and clay) with some light grey quartzite boulders. The figure shows the sieve analysis curve for a sample with the following composition. Gravel 18.17%, Sand 75.65% and Silt and Clay 6.18%. The soil represented by this curve is poorly graded. It shows the significant portion of the particles within a specific size range and a lack of the intermediate size. This typically implies that the soil might not have the desirable properties for the certain engineering applications as it lacks a good mix of the particle's sizes. (Fig. 5 a and b).through sieves of decreasing sizes. The points on the curve are marked with percentages, indicating the cumulative passing at specific sieve sizes. This curve is typical for moderately graded soils with a mix of different particle sizes, where sand is the predominant fraction, followed by gravel, and very little silt and clay. **(Fig. 4a and b)**



(a) **(b)**

Fig. 5: (a) Fish Pond buried site at the Right Bank of Melamchi River above danuwar gaun, (b) Particle size distribution of sediment sample (Sample No. 20) collected at the fish pond buried site above danuwar gaun.

This is the analysis of the sample which was taken from the right bank of the Indrawoti river, at Dolalghat. The sample was appeared as a grey silty sand. The figure shows the sieve analysis curve for a sample with the following composition. Gravel 0.12% Sand 96.52% and Silt and Clay 3.36%. In this case, given the steepness of the curve around the fine particle sizes and the flattening at larger sizes, the soil appears to be poorly graded with a high concentration of the fine particles (Fig. 6 a and b)

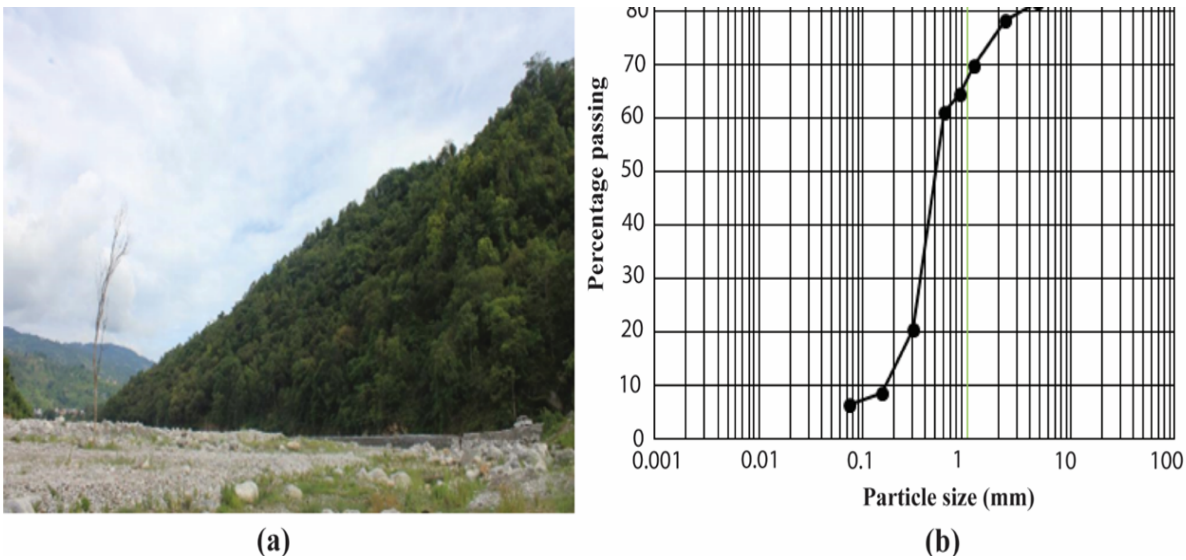


Fig. 6: (a) Flood deposit at the Dolalghat bridge, the southernmost part of the study area, (b) Particle size distribution of sediment sample collected at the Dolalghat bridge site.

Based on the field observations, interviews and surveys, the following sequences of the losses and damages were recorded along the study alignment with the specific GPS coordinates. The Melamchi Water Supply Project (MWSP) headworks area was totally damaged due to the flash flood. A huge amount of the debris flow was deposited along the site, creating high flood debris flow deposits (Fig. 7a). A few landslides were also observed near the site (Fig. 7b). Roads from the headworks to Ambathan had about 4 m of the debris flow deposits (Fig. 7c). Debris flow remanents from Timbu (Fig. 7d). Cut heights of the banks of the tributary brought much debris and partially dammed the Melamchi River (Fig. 7e). A high flood of about 5 meters from the bridge slab washed out one bridge along Ambathan road (Fig. 7f). Few houses (4-5) were buried in Halde, with debris covering the ground floor. Multiple debris flow damming was observed from Nakote to Sankathali. Electric poles were also destroyed. Here is the detailed explanation of the debris flow and the loss and damage due to the Melamchi flood.

Fig. 7: Debris flow, landslide and flood related observations between the headworks and Ambanthan, (a) Deposits seen at the road section, (b) Landslide of colluvial soil on weathered gneiss, (c) Debris flow cliff (4m), (d) Debris flow remanent at Timbu, (e) Cut height of debris at the bank of tributary, (f) Ambathan road washed out bridge.

At Kiul (Chiple Dhunga), one house was buried up to the ceiling of the ground floor at coordinates 03-57-521 E, 30-88-717 N, with an elevation of 1097 m (Fig. 8f). About 6 destroyed houses were recorded at Ganeshi, with a road ~5 meters above the cut bank also damaged. The area was unclear, and the other houses were on the river bed; boulders ranged in size from 5 cm to 1.5 to 2 m, mostly of banded gneiss. Altogether, 22 houses were buried, among them one floor was buried about 10 feet (Fig. 8d). At 03-56-868 E, 30-87-774 N, with an elevation of 1056 m, most buildings were buried up to 2 floors (~7 meters). Most houses are abandoned, and Chanaute now appears as a ghost town. Boulders' sizes range from 5 cm to 1 m, mostly of dark grey banded gneiss and quartzite, with a buried depth of about 10 meters.

Fig. 8: Debris flow, houses damaged and buried between Ambathan and Ganeshi (a) Boulder of the flood erosion at Ambathan, (b) Inverse grading of the debris flow deposits south of Halde, (c) Road on the boulder bar at Kiul, (d) Destroyed houses at Ganeshi, (e) Houses partially buried by debris flow at Halde, (f) Damaged house at Kiul.

A remanent of the bailey bridge (Rato Pul) brought down from Chanaute was left at 03-56-891 E, 30-85-510 N (elevation, 972 m) on the left bank of the Melamchi River, opposite side of the landslide at Gyalthum. There were rocks in the landslide: dark grey to grey, thin-bonded parallel laminated quartzite alternating with garnet (5 mm) schist. The disaster occurred on the 16th of Saun, at night from 11:00 PM to 12:00 AM. The depth of the deposit was 10-12 m. The flow continued for four days at a velocity of 1-2 m/minute (Fig. 9a). At 03-56-589 E, 30-85-298 N, with an elevation of 964 m, at the Melamchi Khola bar, southwest of Gyalthum, a matrix of gravel and liquefied masses was moving slowly for four days at a rate of 50-60 m/hour or 1-2 m/min, creating high dynamic viscosity with a boiling mass of debris. The debris flow must be matrix-supported sandy silt or sandy silty clay (Fig. 9b). At 03-57-175 E, 30-82-354 N, with an elevation of 905 m, at Thulo Khet on the right bank of the Melamchi River, collapsed buildings of pink color, which was a single-storeyed building (Fig. 9c). At 03-57-878 E, 30-81-686 N, with an elevation of 880 m, it is at the right bank of the Melamchi River at about 100 m long and 50 m wide bar. The bar has banded gneiss and dark grey quartzite. Boulders sizes were 5cm to 1.5 m of different variations i.e boulders to matrix (Fig. 9d).

At 03-58-532 E, 30-80-976 N, Debris flow at 858 m on the Melamchi River's right bank buried two fish ponds with fine material like granule to silt and clay having some light grey quartzite boulders (Fig. 5a). At 03-59-239 E, 30-80-485 N, with an elevation of 841 m, destroyed buildings of Danuwar Gaun were seen, buried up to 4 m, the ceiling of ground floor (Fig. 9e). At 03-59-219 E, 30-80-356 N, Granule sand and silt deposits on the right bank of the Melamchi River formed a crudely stratified 3-meter-high bar near a damaged bridge abutment at 838 m elevation (Fig. 9f)

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Fig. 9: Damaged bridge, houses, sand bar observed between Gyalthum and Danuwar gaun. (a) landslide opposite Gyalthum with baily bridge, (b) Melamchi khola bar SW of Gylthum, (c) Collapsed building at left bank of Melamchi river at Thulokhet, (d) Sand bar on top of boulder, (e) Destroyed building of Danuwar Gaun (f) Fine particles deposietd on 3m high bar near damaged bridge abutment.

At 03-59-947 E, 30-80-080 N, the Melamchi River Resort at 818 m elevation was buried by debris flow up to 6 meters, covering the ground floor and half of the first floor (Fig. 10a). At 03-60-078 E, 30-79-706N, and 823 m elevation in southern Melamchi, debris flow buried hotel houses up to 3.5 storeys (13 meters deep), leaving a flood mark on green-blue buildings. The debris was mostly silty sand (Fig. 10b). At 03-60-094 E, 30- 79- 557 N and 818 m elevation on the Indrawati River's left bank, a 15-meter-thick sediment deposit buried a two-story house. The debris flow height exceeded 2 meters, forming a flat area about 600 m long and 150 m wide near a new Bailey bridge construction site (Fig. 10c).

At 03- 59-774 E, 30- 78- 821 N having 806 m elevation on the right bank of a gully near the Armed Police Force, debris flow deposits composed mainly of crudely stratified sand and silt were observed. The thickness of the deposits was about 6 m. According to the respondents, the debris flow took place on the 1st of Asar at 5 PM, and the deposition occurred from 1:00 AM that night and continued almost the whole day on the 2nd of Asar. On the 1st of Asar, there was also flooding from the Indrawoti River, which washed out the fine and light materials. The flooding of the Indrawoti started at 5 PM on the 1st of Asar and continued through the night. The floods subsided in the Indrawoti River, but the debris flow continued in the Melamchi River. Since the power of the Indrawoti weakened, the debris flow churning by the Indrawoti and the removal was not possible, leading to sediment deposition. The deposition began at the lower reach and built up upstream. The deposition progressed from downstream to upstream. The pebbles were all angular and composed of gneiss and dark grey quartzite (Fig. 10d). At 03-59-931 E, 30-77-604 N, with an elevation of 782 m, on the left bank of the Indrawoti River near a suspension bridge. The matrix was mainly composed of angular granules and sand with silty sand. Boulders made up approximately 20%, ranging in size from 5 cm to 1 m.

At 03-59-795 E, 30-76-300 N, with an elevation of 763 m, on the right bank of the Indrawoti River about 500 m upstream from a bridge at Bahune Pati, a crudely stratified sand bed approximately 2 m thick was observed (Fig. 10e). At 03-60-888

E, 30-72-966 N, with an elevation of 732 m near Sipaghat at Eklebesi, Maghitar, on the right bank of the Indrawati River, a light brown sand bar about 30 cm thick was observed (Fig. 10f). At 03-62-589 E, 30-70-751 N, with an elevation of 709 m, at the east end of Sipaghat near a temple and bridge, there was observed an alluvial fan of the Dhad Khola, which was formed by the floodplain deposits of the 2021 Melamchi flood. Similarly, last but not least, at 03-72-463 E, 30-58-846 N, with an elevation of 630 m, on the right bank of the Indrawoti River at the confluence of the Cha Khola, in Dolalghat, the flood covered the ground floor ceiling of the house. The sediments were mainly grey silty sand, and a flood mark was also observed on the Dolalghat bridge (Fig. 6a)

Fig. 10: Buried houses, flood mark, debris flow deposits, sand bar observed below Danuwar gaun and Dolalghat. (a) Buried Melamchi river resort, (b) High flood mark on green blue buildings, (c) Houses buried on two floors on Melamchi bazzar, (d) Debris flow deposits at the transverse from Melamchi to Dolalghat area, (e) Deposits of Crudely stratified sand bed at Bahunepati, (f) 30 cm thick sand bar near Sipaghat at Eklebesi, Magitar

RESULTS AND DISCUSSIONS

This research is entirely based on field observations and aims to validate the collected information with data from the various sources, including field data, satellite images, and aerial photographs. The results show drastic changes in particle size distribution from upstream to downstream, as well as the loss and damage caused by the Melamchi flood. For the purpose of identification of clast sizes in both source and sample or in debris deposits: Block (coarse > 8 m, medium = 8-4 m, fine = 4-2 m); Boulder (coarse = 2-1 m, fine = 1-0.256 m); Cobble (256-64 mm); Pebble (64-4 mm); Gravel (4-2 mm); Sand (2-0.0625 mm); and Mud (< 0.0625 mm) scales were used. Additionally, for particle size distribution, the following scale was also used: Gravel > 2 mm, Sand (2-0.63 mm), Silt (0.63-0.004 mm), and Clay (< 0.004 mm). To determine the particle size distribution of debris flow events from the Melamchi headworks area to Dolalghat, a total of 31 collected samples of debris/soil were used and analyzed. Near the headworks area, close to the dam site, there was a significant proportion of sand followed by gravel, silt, and clay, indicating well-graded soils with a mix of different particle sizes. At the Ambathan road, results revealed that the majority of particles in the sample were fine to medium-sized with a well-graded distribution. Similarly, the sample from Halde showed that most particles were fine to medium-sized with a well-graded distribution. In Kiul, the particle size distribution displayed a range of particle sizes with a steady increase in the percentage passing as particle size increased, with the majority of sample particles larger than 0.35 mm and smaller than 2 mm. The median size was 1.2 mm, providing a central measure of particle size distribution. The sample from Ganeshi indicated a high percentage of fine particles, especially below 0.1 mm. The majority of the sample's particles were larger than 0.02 mm and smaller than 0.13 mm, with a median particle size of 0.09 mm in Chanaute. The landslide opposite Gylthum indicated a well-graded sample, with particle size distributed across a range rather than concentrated at a specific size. The sample from Thulo Khet predominantly comprised medium-sized particles between 0.1 mm and 1 mm, forming a well-graded sample with a mixture of fine to coarse particles. The sample from Danuwar Gaun indicated 20% gravel (> 4.57 mm), 50% sand (0.075 mm to 4.75 mm) with a significant rise between 0.1 mm and 1 mm, 10% silt (0.002 mm to 0.075 mm), and 0% clay (< 0.002 mm). The sample taken from the Melamchi River Resort indicated a particle size distribution curve with a significant amount of fine particles and a rapid increase in percentage passing around 0.1 mm and 1 mm. The sample from the left bank of the Indrawoti Khola at the new Bailey bridge construction site represented a well-graded soil sample with a broad range of particle sizes. Lastely the sample from the right bank of the Indrawoti river at Dolalghat area having the composition of very less amount of silt and clay nearly 0.12%, Sand 97.87% and gravel is about 0.18%. Studies reveal that the highest amount of sediment accumulation in the study area occurs during the pre- monsoon and monsoon seasons. The particle size and accumulation of debris vary in different regions due to river velocity. Thoroughly considering the above results the upper section of the sample consists of poorly graded materials having sediments size 0.1 mm to more or less > 7mm. However, in the downstream area the sediment size ranging from 0.09 mm to > 2 mm. Most of the sediment passing zone was Chanaute and Melamchi bazaar area. Due to the conjugal point of the Indrawoti and the Melamchi river in Melamchi bazaar area most sediment were passed and the river is more erosive on that zone. Due to the erosive nature of the river in the upper part huge sediments were carried out and supported the huge loss and the damage in the lower areas.

For the purpose of identification of the loss and damage on-site field visit, focus group discussions, key informant interviews, and a few alternating workshops were conducted. Land Use Land Cover (LULC) maps from before and after the flood events were also studied. Satellite images were observed. Key informants, multiple household surveys, and case analyses were also carried out in the field. According to all survey data, interviews, and technical workshops, we concluded that the devastating flood was not solely due to rain but rather resulted from multiple factors which having a multiple cascading effect. The Melamchi flood resulted from the significant cumulative impacts of a devastating flood event. The timing of the flood was also a major factor in the extent of loss and damage downstream. Communities downstream were alerted by those upstream, which significantly helped to reduce the loss and damage, allowing people to move to safer areas. Based on the responses of the informants and the data from the Department of Hydrology and Meteorology, there was a maximum amount of rainfall during those days in that area. This included earlier snowfall, temperature fluctuations, and a rapid rate of snow melting. Intense continuous rainfall in the upper area contributed to extreme rainfall and erosion towards the higher elevations. The upper part mechanism significantly destabilized the lower part of the sediments in Bhemathang. Extreme rainfall events and erosion activities in the upper reach resulted in huge landslides in the Melamchi Ghyang area downstream. The dam that had already blocked the river was later breached, causing devastating flood events. These events heavily eroded the river banks and led to significant deposition in the downstream area.

Climate change has impacted river discharge (Hock et al., 2019). The risk of floods is very high in Nepal among South Asian regions (UNEP, 2009). Sediment deposition in the Melamchi Valley was measured at 23.24 million m^3 (Chen et al., 2023). During the first event, a discharge of 2,893 m^3/s was recorded, and during the second event, it was 1,105 m^3/s at Melamchi Bazaar. The peak discharge at Nakote during the second event was 285 m^3/s. The daily average discharge at Bhemathang was 357 m^3/s during the first event and 76 m^3/s during the second event. The daily average erosivity was also high during both events. Sediment passing was high in the Chanaute and Melamchi river segments (Baniya et al., 2023). The estimated total loss was approximately USD 436 million for the Melamchi Municipality and USD 62 million for the Helambhu Rural Municiplaity (Parajuli et al., 2023).

These factors all contributed to significant loss and damage in the Melamchi area during the flood events, particularly in the middle section of the river basin. Our study has documented that the area from Timbu to Gyalthum was severely affected due to the presence of soft, weathered rocks, as well as thrusts and faults in this zone. Weak geology and a steep gradient also contributed to the issue. Moreover, the loss and damage below Melamchi Bazaar were exacerbated by an increase in river velocity at the confluence point by mixing of the two rivers and also the mixing of sediment carried by the Indrawoti River. The sediment deposition rate is also very high in the downstream area from the Melamchi confluence, which supports these facts. During the field observation, the study also attempted to correlate the downstream loss and damage with the upstream-to-downstream sediment transport phenomena, yielding satisfactory results. Moreover, the areas where large amounts of coarse sediments or debris accumulated experienced significant damage, whereas the zones where sand, silt, and clay settled caused less damage but buried much of the infrastructure. Beyond these observations, respondents revealed that there was a loss of economic assets, non-economic assets, cultural, archaeological, and aesthetic values in the damaged area. Sleeplessness due to fear of floods, gender-specific impacts, water-borne diseases, educational impacts, and psychological impacts were other forms of loss and damage experienced during the flood event.

CONCLUSIONS

Sindhupalchowk district is a zone with fragile geological conditions, characterized by numerous faults and thrusts. The area is highly susceptible to earthquakes and other natural disasters such as floods and landslides. Due to its weak geology, rugged topography, and dynamic geological settings, the region has faced numerous challenges over the years. The community experienced a devastating earthquake in 2015 B.S. and, as it was gradually recovering, an unprecedented flood in 2021 further exacerbated the difficulties in the Melamchi area. Since 2011, the municipality has experienced rapid population growth, with an annual rate of 5.2%. This growth has made the area a central hub for many businesses and services. However, the region's fate took a drastic turn after the June 2021 flood, resulting in significant loss of life and extensive damage to infrastructure. Despite the area's consistent vulnerability to various disasters—such as earthquakes, floods, landslides, fires, lightning, glacier melt, and glacial lake outbursts—several studies have facilitated a better understanding of these hazards and laid the groundwork for developing risk mitigation plans in the Melamchi watershed. It is evident that the impacts of climate change have further compounded the challenges, as seen in the significant loss of life and severe damage to homes and infrastructure. Considering various contributing factors, there is evidence that intense, continuous rainfall, steep slopes, steep river gradients, landslide dam bursts in upstream areas, fragile geological conditions, increasing temperatures, rugged topography, and frequent seismic activities likely contributed to these disasters. Cloudbursts, steep glacial slides, soil movements, and their cumulative downstream impacts were also significant contributors to the scale of the disasters. There is an urgent need for a geo-engineering investigation to collect all relevant information about the potential hazards in the area. This recommended detailed study can form the basis for mitigating and rehabilitating vulnerable areas and proposing potential locations for mitigation structures, ultimately benefiting the livelihoods of people in the region. The focus should be on prioritizing houses, roads, and infrastructure while also addressing the hardships faced by families impacted by the disaster events. It is essential to clear all debris and sediments from the area immediately and to plan for three levels of mitigation approaches: slope stabilization, resilient intake design, and river engineering works. Additionally, installing more meteorological stations near the sites and preparing for the installation and regular monitoring of early warning systems is crucial.

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