Melamchi Flood Disaster in Nepal

Damage and Risk Quantification with Drone Survey, Satellite-Based Land Displacement Analysis, and 2D Flood Modeling

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Cover photo: The affected area in Melamchi Bazar by the June and August 2021 flood events.
Photo taken by Dr. Ranjan Kumar Dahal in December 2021.

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Acronyms

ADB	Asian Development Bank
DTM	Digital Terrain Model
DSM	Digital Surface Model
GSD	Ground Sampling Distance
GIS	Geographic Information System
GPS	Global Positioning System
DEM	Digital Elevation Model
MCM	Million Cubic Meter
AOI	Area of Interest
NSSDA	National Standard for Spatial Data Accuracy
HEC-RAS	Hydrologic Engineering Center’s River Analysis System
INSAR	Interferometric Synthetic Aperture Radar
MRWDS	Melamchi River Water Diversion Subproject
NDRRMA	National Disaster Risk Reduction and Management Authority
UAV	Unmanned Aerial Vehicles
WB	World Bank

Acknowledgments

Production of the report was led by **Masatsugu Takamatsu**, Disaster Risk Management (DRM) Specialist and **Hemang Karelia**, Senior DRM Specialist, in South Asia Region Climate Change and Disaster Risk Management (SSACD). The report was prepared by Professor **Thomas Oommen** from the Department of Geological & Mining Engineering & Science, Michigan Technological University and Dr. **Ranjan Kumar Dahal** from the Central Department of Geology, Tribhuvan University with significant contributions from the drone team led by **Vikas Bhusal** from the Tri Max and the satellite team lead by **Pamungkas Bujed** from the Synspective. The team extends huge appreciation to the following peer reviewers from the World Bank for providing insightful and useful comments: **Rikard Liden**, Lead Energy Specialist; **Ximing Zhang**, Senior Dams Specialist; and **Lixin Gu**, **Rubika Shrestha**, and **Feriha Mugisha** from the Nepal Water Team. The report was greatly benefited from editorial work by **Mehsum Basharat**, and professional graphic design by **Juan Velasco** from 5W Infographic. The team would like to extend sincere appreciation to Mr. **Anil Pokhrel**, the CEO, and Mr. **Rajendra Sharma**, Under Secretary, of the National Disaster Risk Reduction Authority under Ministry of Home Affairs, Nepal for supporting the entire engagement and Mr. **Saugata Dasgupta** and Mr. **Hans G. Enggrob** from the Asian Development Bank for close coordination, information share, technical discussions, and report reviews. Special acknowledgments go to the following World Bank staff: **Atishay Abbhi**, **Sulochana Nepali**, **Sujit Maharajan** (Consultant), and Dr. **Manita Timilsina** from the Geotech Solutions International, Nepal (Consultant).

Finally, the team would like to appreciate support from **Abhas Jha**, Practice Manager of SSACD, and **Niels Holm-Nielsen**, Practice Manager of the Global Facility for Disaster Reduction and Recovery (GFDRR). The study was conducted under the "BUILDING RESILIENCE TO LANDSLIDE AND GEO-HAZARD RISK IN THE SOUTH ASIA REGION" project, in the frame of the European Union - South Asia Capacity Building for Disaster Risk Management Program funded by the European Union. The Task Team would like to express sincere appreciation to the European Union for its generous financial support to the South Asia Geohazard project.

This technical report contents are sole responsibility of the Task Team. The European Union is not responsible for any use that may be made of the information contained therein.

Foreword

Nepal is highly vulnerable to climate change and is prone to disasters caused by natural hazards. With its unique geography, the country remains exposed to several climate risks such as glacial lake outburst floods (GLOF), floods, and other water-related hazards triggered by torrential rain enhanced by snowmelt during monsoon season. Millions of Nepali population and infrastructure are estimated to be at risk from climate change. The National Disaster Risk Reduction and Management Authority (NDRRMA) was established in 2019, with a mandate to coordinate and implement activities related to disaster risk reduction and management in Nepal.

On June 15, 2021, the Melamchi River experienced massive flooding and caused disastrous damage downstream. Over six consecutive days, the region reported around 200 mm of rainfall. The massive downpour coupled with rapid snowmelt 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, roads, and the headworks of the Kathmandu Valley Water Supply Project financed by the ADB, and it may take up to several years to recover from the economic impacts.

The NDRRMA quickly responded to the disaster, arranging timely site visits and sourced inputs from experts, which were crucial for effective hazard response and recovery planning. In close collaboration with the NDRMMA, the World Bank urgently provided support to the disaster with a series of activities including a drone survey to identify all damaged houses, map out inundation areas, and record the changes in topography caused by massive erosion and deposition. These quick and focused data collection and analysis in the area with difficult accessibility allowed for prioritization of resource allocation and understanding of remaining flood risks, as highlighted in the report.

Based on the data and information gathered and shared, the NDRRMA was able to focus on efforts needed for hazard awareness, dissemination, and disaster risk reduction planning in the region. The findings of the World Bank activities were also presented in two-hybrid workshops with policymakers and partners including ADB and ICIMOD.

The NDRRMA appreciates the timely efforts and resources mobilized by the World Bank to contribute to the response efforts and in helping understand disaster risks in a complex mountain setting.

Anil Pokhrel

Chief Executive

National Disaster Risk Reduction and Management
Authority (NDRRMA), Ministry of Home Affairs

Government of Nepal

Executive Summary

This is a technical case study report demonstrating monitor, assess, and quantify high-mountain geohazard risks for government agencies based on the flooding and landslides in Melamchi Watershed in Nepal. On June 15, 2021, the Melamchi River experienced massive flooding and caused disastrous damages in the downstream. The event led to several casualties and destroyed houses and critical infrastructure, including the headworks of the Melamchi River Water Diversion Subproject (MRWDS) funded by the Asian Development Bank (ADB). Further investigations identified that a landslide formed a natural dam in the proximity of the confluence between Pemdan Khola and Melamchi River. The natural dam blocked the Melamchi river and pooled water upstream. The natural dam eventually breached and abruptly released water, causing an outburst of flooding. The overall situation was intensified by the heavy rainfall and possible glacial lake outburst. A second flooding event equally severe as the first one was observed on August 1st. Following the flooding, the World Bank initiated three activities to support the National Disaster Risk Reduction and Management Authority (NDRRMA) and other governmental agencies to plan for future actions. These activities include: i) an Unmanned Aerial Vehicle (UAV)/drone-based survey to document the damage from the event, ii) flood modeling to understand the conditions generated by the event and to estimate the future risk to the community, and iii) satellite-based Synthetic Aperture Radar (SAR) analysis to identify location vulnerable to landslides in the region.

The drone survey was carried out from July 6th to August 30th, 2021 and covered a river stretch of approximately 100 km. The survey provided timely documentation of the damages from the event that could be used to calibrate and validate the flood modeling. The products derived from the drone survey include georeferenced orthorectified images, 3d-point cloud, Digital Terrain Model (DTM), and approximate estimates of erosion and deposition along the channel. The flood was modeled using Hydrologic Engineering Center's River Analysis System (HEC-RAS) as a two-dimensional

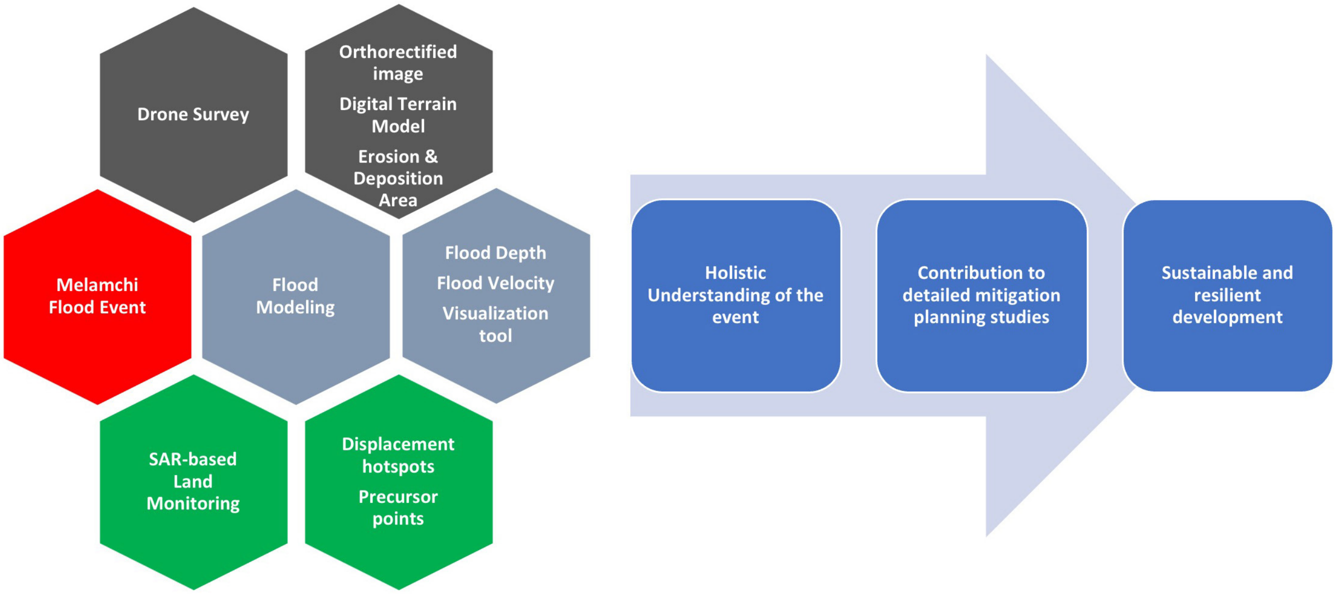


Figure 1: *Diagram illustrating the flow of post-flood disaster risk management engagement.*

non-Newtonian flow with the rainfall data collected from the Global Precipitation Measurement (NASA), and a high-density mix of water and debris (10% debris in water) was selected for the final non-Newtonian dam breach model. The modeled flood compared well with the flood extends mapped from the drone survey. Comparing the modeled flood velocity with the erosion and deposition regions identified from the drone imagery showed a strong correlation. The average flood velocity was ~3 times more for the erosion region than the deposition.

Sentinel-1 satellite Synthetic Aperture Radar (SAR) data was then used to perform Interferometric Synthetic Aperture Radar (InSAR) analysis to map land displacement. InSAR analysis was carried out using the data from April 2017 to June 12th, 2021. The results from the analysis assisted in identifying several hotspots within the area of interest that are vulnerable to ground movement. The SAR work highlights the benefit of cutting-edge research to disaster risk managers and relevant authorities as a new geohazard risk management practice.

The area of interest and study focuses were decided based on close coordination with NDRRMA who responded to the disaster immediately after the June flood and needed accurate damage and risk information. The World Bank team also worked closely with the ADB team who focused on the detailed damage assessment and risk mitigation planning of the headworks of the MRWDS through data share, technical discussions, and mutual report reviews. The field investigation conducted by the ADB team was useful for the World Bank team in validating the flood modeling and satellite-based SAR observations. The close coordination and data share with partners equipped the government and other stakeholders with useful quantitative information to better understand the complex and disastrous flood event that occurred in the Melamchi River and provided a basis for future risk reduction and management. Figure 1 conceptualizes how the studies will be helpful in the resilience planning effort in the Melamchi Watershed.

Introduction

On June 15, 2021 the Indrawati basin consisting of the Melamchi, Yangri, and Larke rivers was struck with heavy rainfall causing disastrous flooding in the downstream area of the Melamchi River. Based on the National Disaster Risk Reduction and Management Authority (NDRRMA), 17 causalities and at least 23 were reported missing due to landslides and floods caused by this event. It also led to the destruction of houses and infrastructure in several rural municipalities, including the damage to the headworks of the MRWDS Project that supplies drinking water to the people in Kathmandu Valley. The Project is a National priority project for the Government of Nepal to alleviate the acute water shortage in Kathmandu Valley and reduce the incidence of disease caused by poor water quality. Figure 2 shows the area of interest.

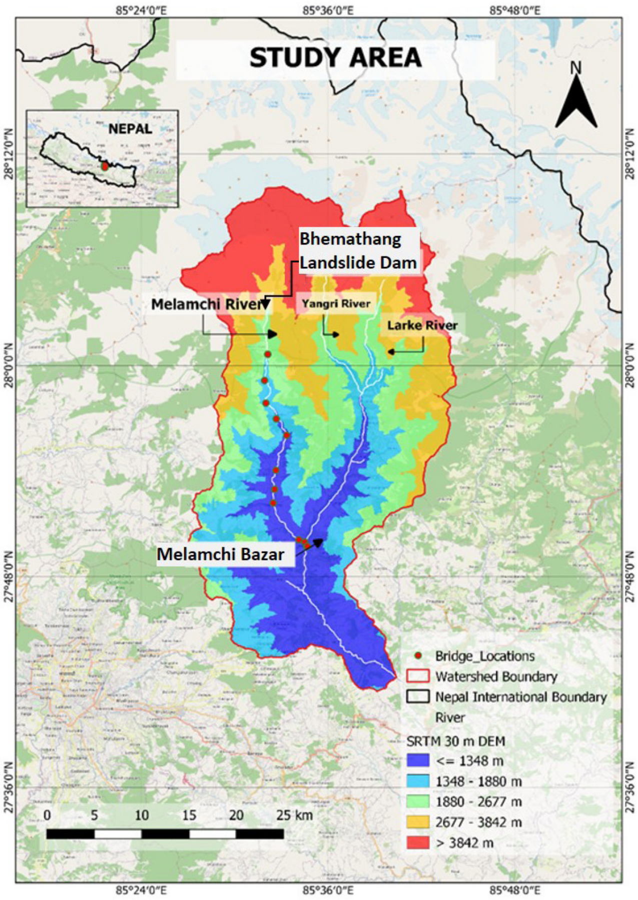


Figure 2: *Location of the Melamchi Watershed in the Sindhupalchowk District 60 km Northeast of Kathmandu*

According to the Department of Hydrology and Meteorology (DHM), Melamchi and Indrawati basins started receiving rainfall starting June 9th, 2021. The highest hourly precipitation on June 10th was recorded at 22 millimeters (mm); by June 11th, it had increased to 37 mm per hour. On 14 and 15 June, some rainfall was recorded at around 10 mm per hour. On June 11th, Sermathang recorded more than 100 mm of daily rainfall. Collectively, during the 6-day interval, the station had received more than 200 mm of rainfall. The intense rainfall and rapid snowmelt resulted in the erosion of glacial deposits in the headwaters of the Pemdan Khola (meaning creek in Nepali), Yangri River, and Larche River. Early investigations documented the formation of a landslide dam and its subsequent collapse in Bhemathan (situated in Langtang National Park). A past landslide formed the natural dam in the proximity of the confluence between Pemdan Khola and Melamchi Khola on Melamchi Watershed, as shown in Figure 3. The natural dam blocked the Melamchi River and pooled water upstream temporarily and was abruptly released, causing an outburst flood. The large volume of water was released downstream, destroying the riverbank settlements, bridges, and road on its way to Melamchi Bazar and causing heavy coverage of a thick deposit of mud and debris to the town downstream. The overall situation was intensified further by heavy rainfall runoff with snowmelt, possible glacial lake outburst, and moraine erosion in the Pemdan Khola region, as noted by ICIMOD and the Nepal Engineers' Association. The high-speed flow of water hyper-concentrated with debris (glacial deposits in the headwaters of the Pemdan Khola and fan, talus, and lake deposits in the Bhemathan area) likely eroded the channel and riverbank throughout the stretches, causing numerous riverbank collapses and landslides. A second flood event occurred on 1st August 2021, possibly due to heavy rainfall and erosion of the sediment deposited as a results of the first Landslide Dam Outburst Flood (LDOF) event.

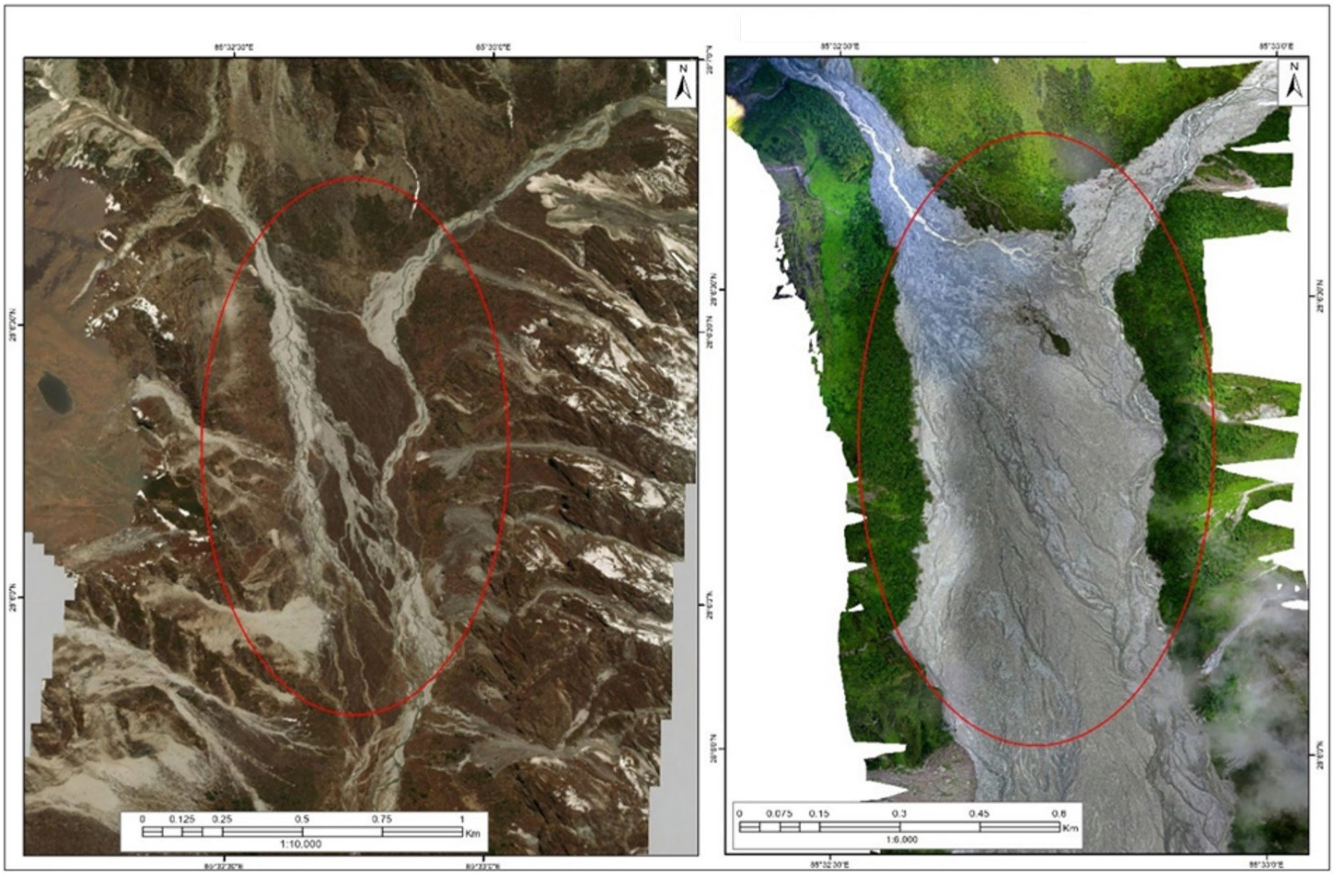


Figure 3: *Comparison of the pre-event satellite image with the post-event drone image at Bhemathan*

Goal and Scope of the Studies

Following the June 15th flood, referred to as the "Melamchi Flood", the World Bank initiated the drone survey as per the request from the NDRRMA to support the Gov in understanding the cause and damage of the disaster. While reviewing the progress of the drone survey with NDRRMA, we identified further needs to understand the cause of the complex flood, and evaluate remaining geohazard risks in the watershed. Therefore, the SAR analysis and flood modeling were initiated with an agreement with the NDRRMA. The eventual goal of the initiative was to help Gov plan the reconstruction and mitigation actions in this region by providing:

- Urgent support to NDRRMA and key stakeholders
- Coordinate, collaborate, share data, and discuss findings with interested parties, including the ADB expert team tasked to carry out a disaster damage assessment of the headworks of the MRWDS and the University team on flood zoning in the Melamchi Bazar area
- Support the GoN for preparing preliminary recovery plans

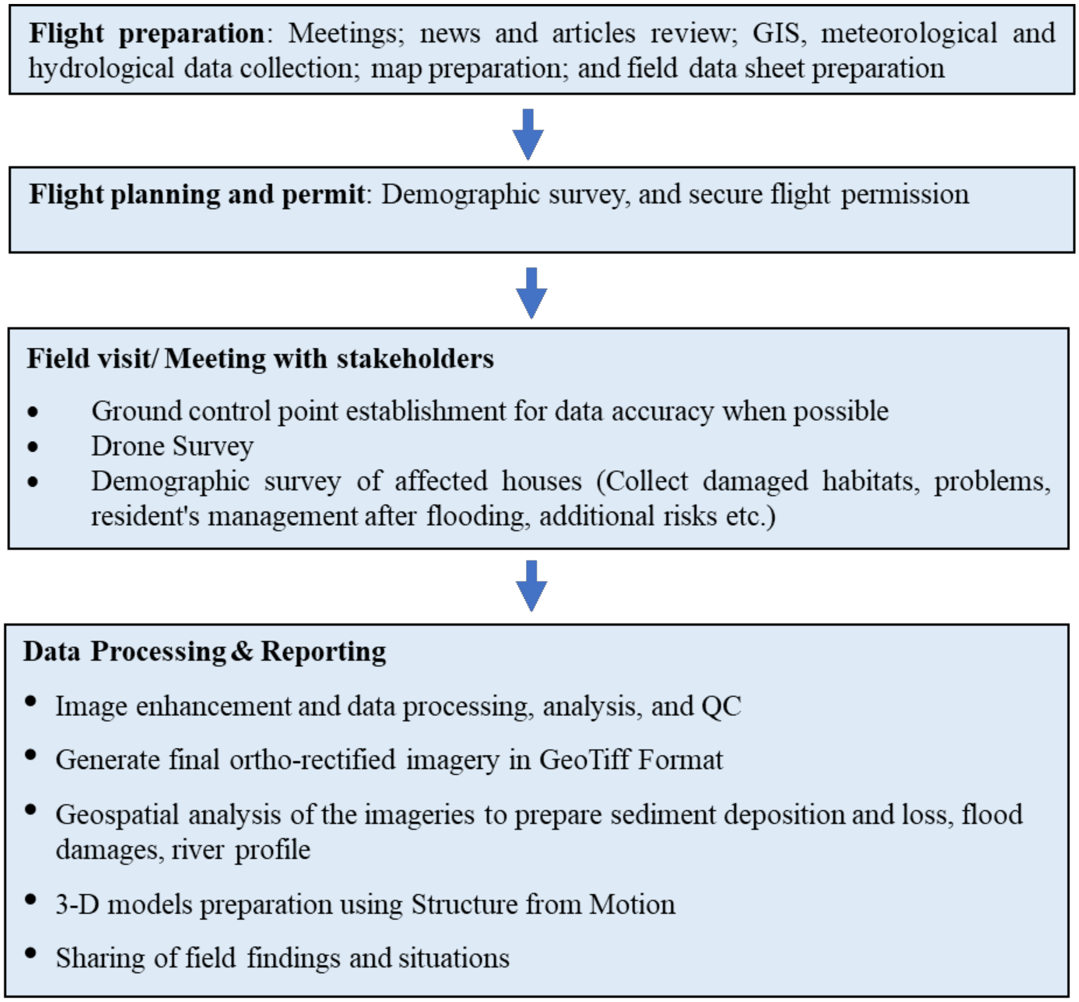
To address these goals three activities were conducted i) an Unmanned Aerial Vehicle (UAV)/drone-based survey to document the damage from the event, ii) flood modeling to understand the conditions generated by the event and to estimate the future risk to the community, and iii) satellite-based Synthetic Aperture Radar (SAR) analysis to identify location vulnerable to landslides in the region. These three activities complement each other as the drone survey helps to document the post-flood site condition, flood modeling utilizes drone data for validation and provides a valuable tool for flood risk reduction and planning, and the SAR analysis helps to evaluate historical and future landslides and its risk to the area.In addition, this report includes a section on field observations conducted by the NDRRMA. This report summarizes these activities and includes important lessons for future events similar to Melamchi's that hazard planners and policymakers can use.

Drone Survey

The purpose of the drone survey was to document the damages from the floods and landslides and develop a high-resolution ortho-rectified mosaic imagery and Digital Terrain Model (DTM) at Sindhupalchowk, Melamchi, Helambu, and Panchpokhari flooding area along the river basin. Due to their lower operational risks, and ability to remotely capture high-resolution imagery, drone-based surveys are effective for post-disaster documentation in remote areas such as Nepal where access is a critical challenge.

The schematic showing the method followed by the drone team is presented in Figure 4.

The drone survey was undertaken by Trimax IT Infrastructure & Services Pvt Ltd with DJI drones between July 6th and August 14th. After prior data collection, the drone team used several drones to capture the photographs from the area (Figure 5). The team collected ground control points to geo-reference the photos accurately when possible. The spatial extent and flight period of the drone surveys are presented in Figure 6.



Flight preparation: Meetings; news and articles review; GIS, meteorological and hydrological data collection; map preparation; and field data sheet preparation

Flight planning and permit: Demographic survey, and secure flight permission

Field visit/ Meeting with stakeholders

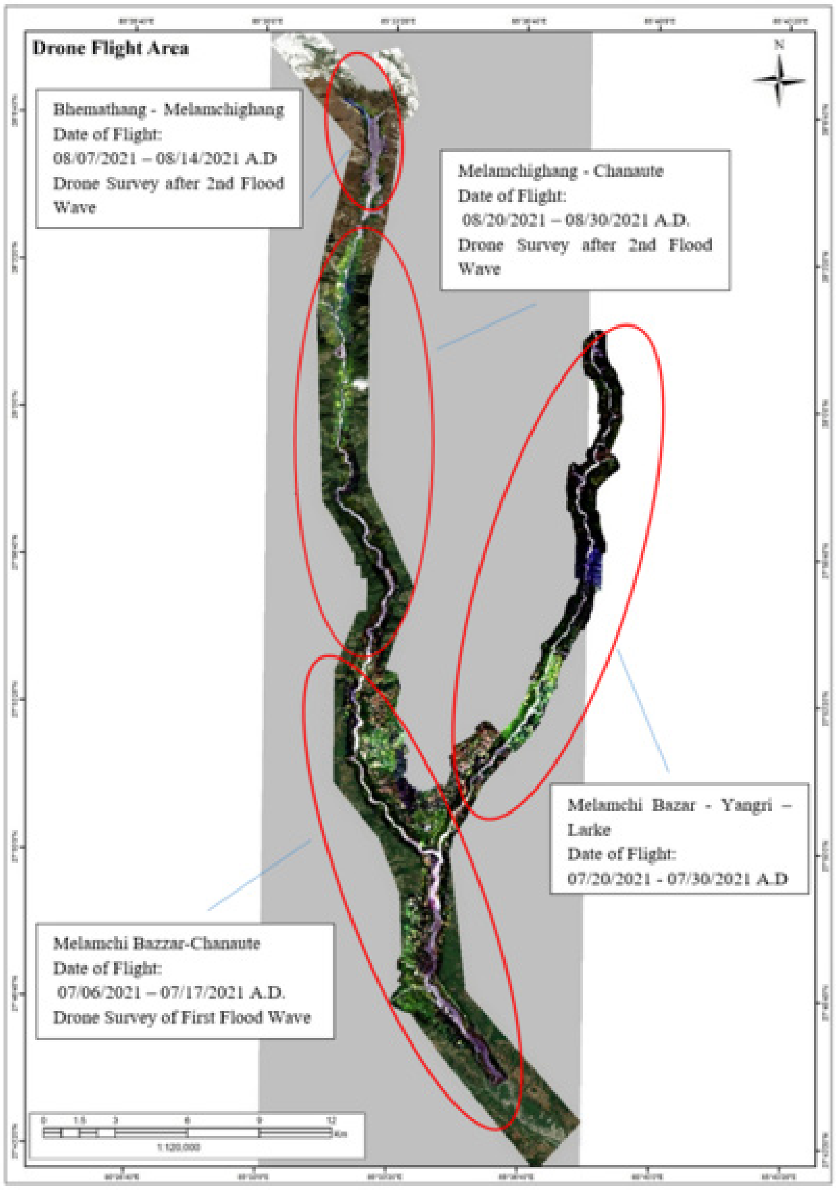
- Ground control point establishment for data accuracy when possible
- Drone Survey
- Demographic survey of affected houses (Collect damaged habitats, problems, resident's management after flooding, additional risks etc.)

Data Processing & Reporting

- Image enhancement and data processing, analysis, and QC
- Generate final ortho-rectified imagery in GeoTiff Format
- Geospatial analysis of the imageries to prepare sediment deposition and loss, flood damages, river profile
- 3-D models preparation using Structure from Motion
- Sharing of field findings and situations

Figure 4: *Schematic of the method for the drone survey*

***Figure 5:** Team capturing data using the drone, damage at Melamchi Bazar from the drone image, and the steep hilly terrain where the drone was used to document the damages and to collect post-flood topographic data*



Drone Flight Area

Bhemathang - Melamchighang
Date of Flight:
08/07/2021 – 08/14/2021 A.D
Drone Survey after 2nd Flood Wave

Melamchighang - Chanaute
Date of Flight:
08/20/2021 – 08/30/2021 A.D.
Drone Survey after 2nd Flood Wave

Melamchi Bazar - Yangri – Larke
Date of Flight:
07/20/2021 - 07/30/2021 A.D

Melamchi Bazzar-Chanaute
Date of Flight:
07/06/2021 – 07/17/2021 A.D.
Drone Survey of First Flood Wave

***Figure 6:** The spatial extent and flight period of the drone surveys*

The data collected using the drone was analyzed using remote sensing and photogrammetry software. Results from the drone footage indicated a significant change in the river pattern at Bhemathan (Figure 7). The drone imagery was also useful in identifying several landslides along the river triggered by the toe undercut by the debris flow. The one observed at Bhemathan was the largest and had dammed the upstream portion of the river.

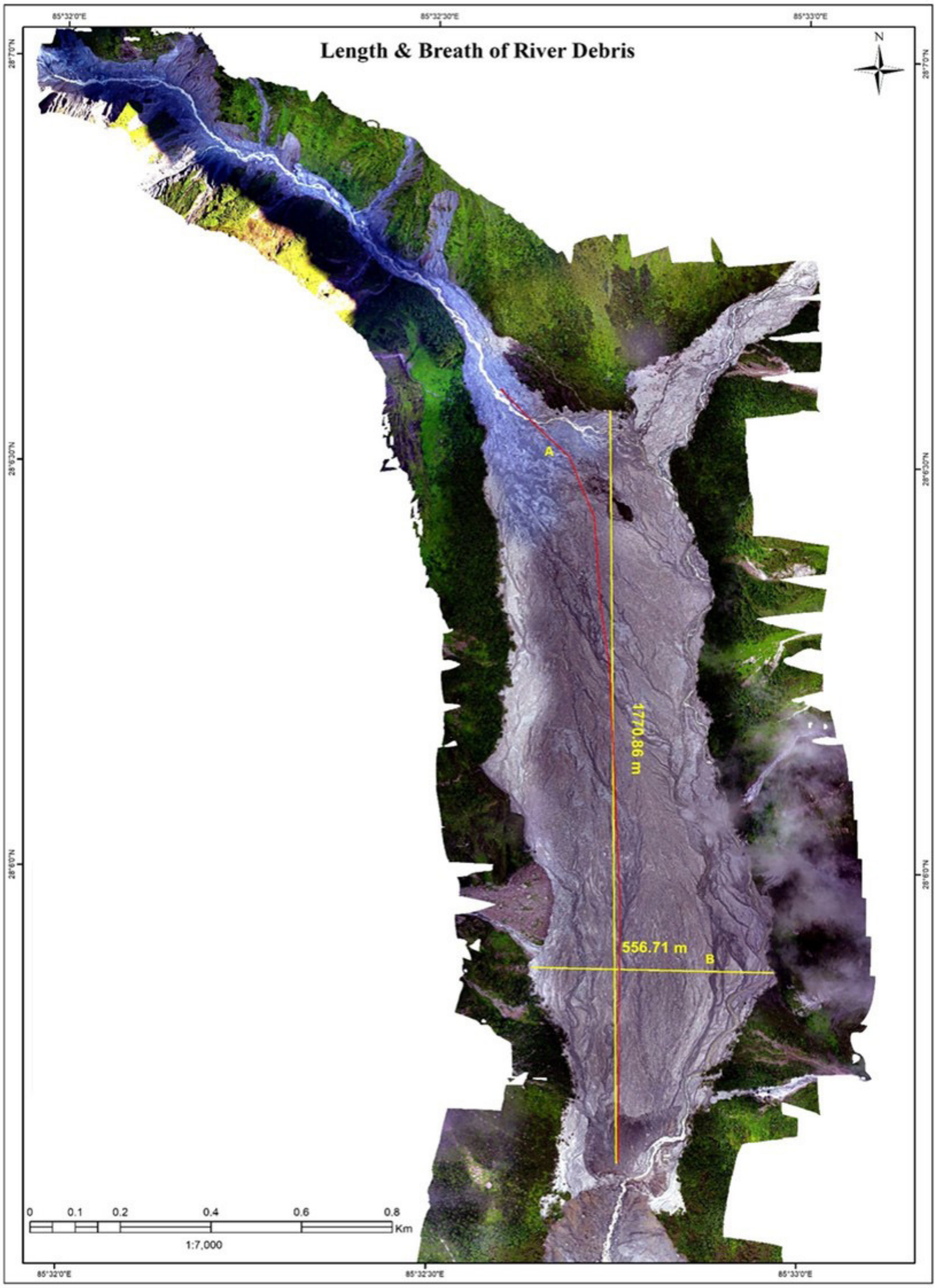
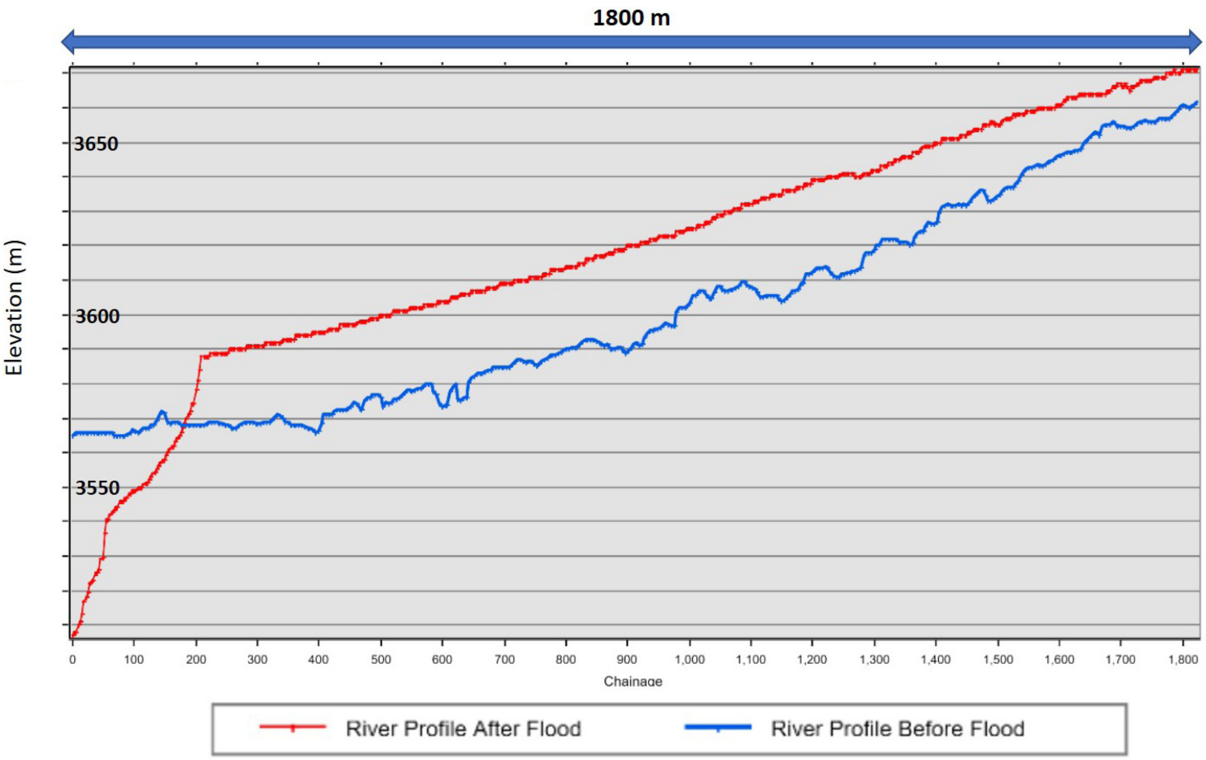
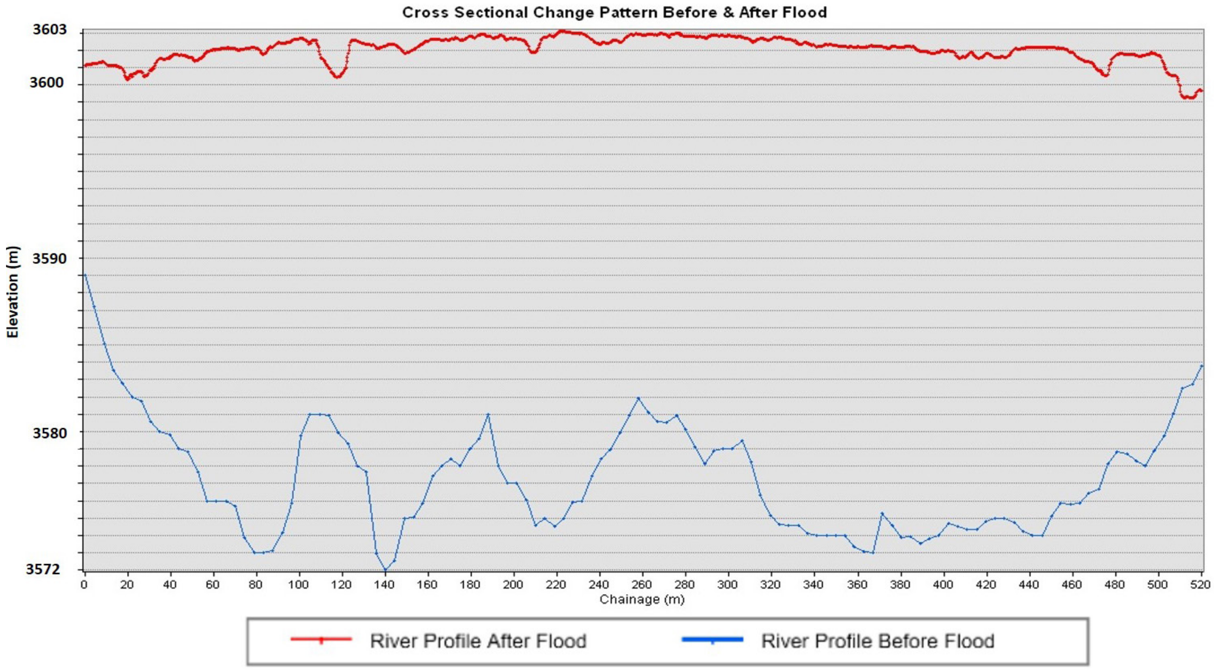


***Figure 7:** Approximate dimensions of the landslide deposits obtained from the drone imagery*



7a) *longitudinal section showing the river profile before and after the flood*



7b) *cross-section showing the river profile before and after the flood. Before-flood DEM source is WDRF (5m spatial resolution), and the after-flood DEM source is drone data (50 cm spatial resolution) as part of this project*

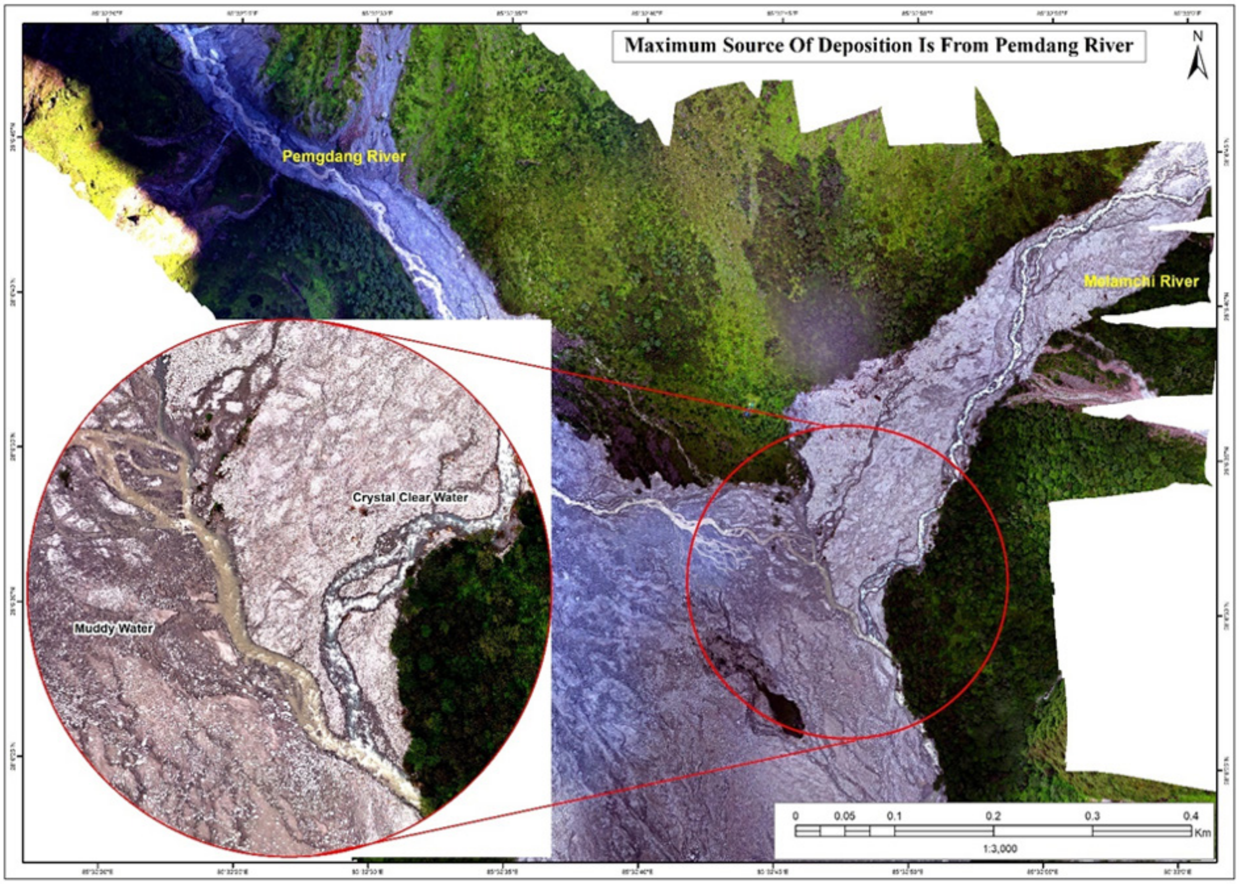


Figure 8: *Drone image showing the muddy and clear water from Pemdan Khola (west) and Melamchi River (east).*

The difference in the color of the water (muddy vs. clear) from Melamchi River and Pemdan Khola at its confluence near Bhemathan indicated that most of the deposition occurred from the Pemdan Khola (Figure 8).

The drone survey data was used to estimate the erosion and deposition volumes. It was made possible by generating longitudinal profiles along the river on the pre- and post-flood DTMs. During this exercise, caution was implied to avoid longitudinal profiles passing over wet areas as the post-flood DTM does not penetrate floodwaters. Figure 9 illustrates the longitudinal profile and the area of maximum flood extent.

In addition, the drone data and site visit information were used to develop an inventory of the damaged houses. The inventory includes information on coordinates for each damaged house, owner and resident information, building story and types, and photos. In Melamchi Bazar and Helambhu, a total of 291 and 252 houses were registered to the damaged house inventory (Figure 10).

Photos and videos taken by the drone survey team provided very clear visuals of the post-flood ground conditions along the Melamchi River, and the prepared topography based on the drone imageries were useful in understanding the massive river erosion and deposition caused by the flood. It should be also noted that the access to the upstream areas was extremely difficult because of the high altitude and limited road access. The team had to hike long distances with the survey equipment, safety gear, and other necessities to complete the survey of most areas. NDRRMA provided a helicopter ride to the drone team to access the Bhemathan area. Based on the pre- and post-flood topographic data comparison, major depositions occurred in Bhemathan (16 MCM) and the stretch between Melamchi Ghyang and Melamchi Bazar (10 MCM), while major erosion occurred in the stretch between Bhemathan and Melamchi Ghyang (26 MCM).

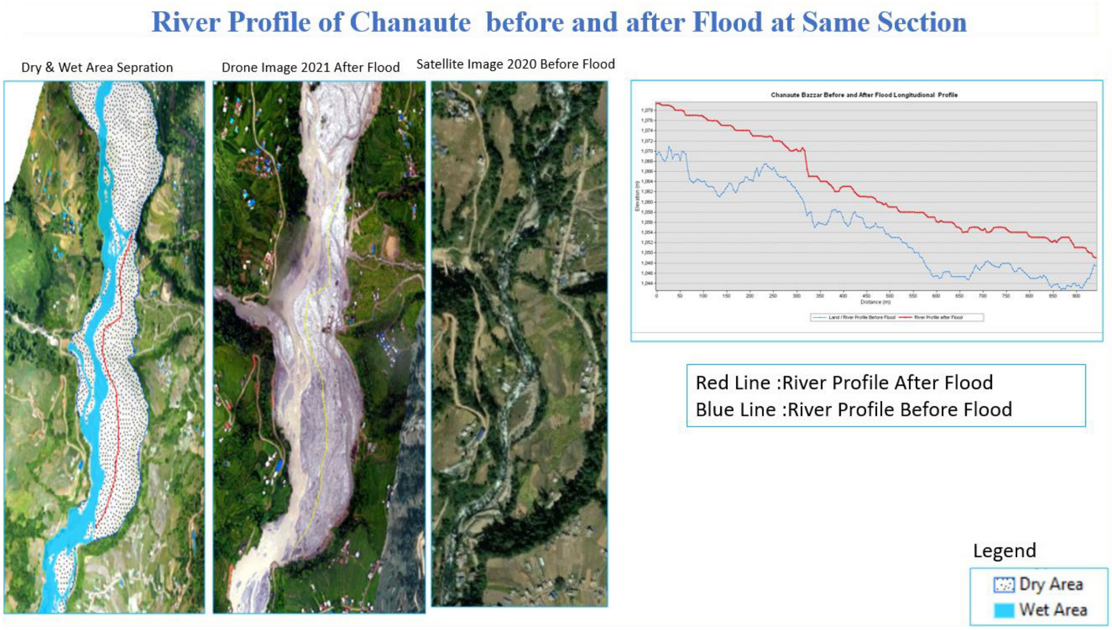
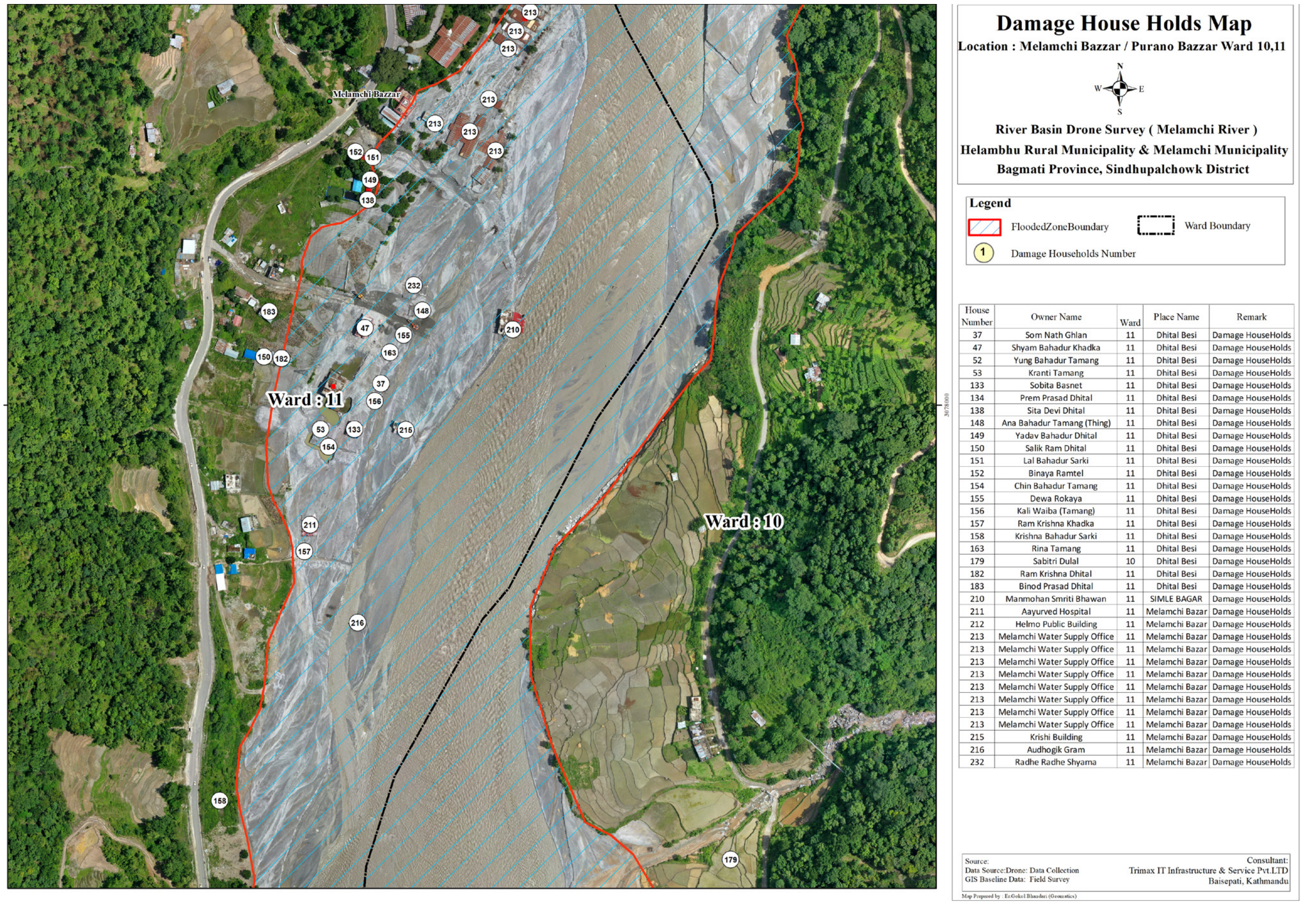


Figure 9: *This figure illustrates the area of maximum flood extent, wet area when the drone survey was conducted, profile path, and pre and post-flood elevations*



House Number	Owner Name	Ward	Place Name	Remark
37	Som Nath Ghlan	11	Dhital Besi	Damage HouseHolds
47	Shyam Bahadur Khadka	11	Dhital Besi	Damage HouseHolds
52	Yung Bahadur Tamang	11	Dhital Besi	Damage HouseHolds
53	Kranti Tamang	11	Dhital Besi	Damage HouseHolds
133	Sobita Basnet	11	Dhital Besi	Damage HouseHolds
134	Prem Prasad Dhital	11	Dhital Besi	Damage HouseHolds
138	Sita Devi Dhital	11	Dhital Besi	Damage HouseHolds
148	Ana Bahadur Tamang (Thing)	11	Dhital Besi	Damage HouseHolds
149	Yadav Bahadur Dhital	11	Dhital Besi	Damage HouseHolds
150	Salik Ram Dhital	11	Dhital Besi	Damage HouseHolds
151	Lal Bahadur Sarki	11	Dhital Besi	Damage HouseHolds
152	Binaya Ramtel	11	Dhital Besi	Damage HouseHolds
154	Chin Bahadur Tamang	11	Dhital Besi	Damage HouseHolds
155	Dewa Rokaya	11	Dhital Besi	Damage HouseHolds
156	Kali Waiba (Tamang)	11	Dhital Besi	Damage HouseHolds
157	Ram Krishna Khadka	11	Dhital Besi	Damage HouseHolds
158	Krishna Bahadur Sarki	11	Dhital Besi	Damage HouseHolds
163	Rina Tamang	11	Dhital Besi	Damage HouseHolds
179	Sabitri Dulal	10	Dhital Besi	Damage HouseHolds
182	Ram Krishna Dhital	11	Dhital Besi	Damage HouseHolds
183	Binod Prasad Dhital	11	Dhital Besi	Damage HouseHolds
210	Manmohan Smriti Bhawan	11	SIMLE BAGAR	Damage HouseHolds
211	Aayurved Hospital	11	Melamchi Bazar	Damage HouseHolds
212	Helmo Public Building	11	Melamchi Bazar	Damage HouseHolds
213	Melamchi Water Supply Office	11	Melamchi Bazar	Damage HouseHolds
213	Melamchi Water Supply Office	11	Melamchi Bazar	Damage HouseHolds
213	Melamchi Water Supply Office	11	Melamchi Bazar	Damage HouseHolds
213	Melamchi Water Supply Office	11	Melamchi Bazar	Damage HouseHolds
213	Melamchi Water Supply Office	11	Melamchi Bazar	Damage HouseHolds
213	Melamchi Water Supply Office	11	Melamchi Bazar	Damage HouseHolds
213	Melamchi Water Supply Office	11	Melamchi Bazar	Damage HouseHolds
213	Melamchi Water Supply Office	11	Melamchi Bazar	Damage HouseHolds
215	Krishi Building	11	Melamchi Bazar	Damage HouseHolds
216	Audhogik Gram	11	Melamchi Bazar	Damage HouseHolds
232	Radhe Radhe Shyama	11	Melamchi Bazar	Damage HouseHolds

Source:
Data Source:Drone: Data Collection
GIS Baseline Data: Field Survey

Consultant:
Trimax IT Infrastructure & Service Pvt.LTD
Baisepati, Kathmandu

Map Prepared by : Er.Gokul Bhandari (Geomatics)

Figure 10: *Inventory of the damaged houses generated from the drone survey and field visit*

Flood Modeling

Developing a flood model for the area helps in evaluating future flood risks and policy planning regarding setback distances and mitigation measures. At the same time, the drone survey assisted in documenting the flood extent. Besides, a flood model is also required to determine the flood depth, velocity, and other parameters. The landslide dam breach mudflow at Melamchi was simulated in Hydrologic Engineering Center's River Analysis System (HEC-RAS) as a two-dimensional non-Newtonian flow for a rapid assessment to reproduce the flood conditions in the model.

The Melamchi Valley is typically a narrow, steep Himalayan River-Valley. The lower valley has slopes with floodplains and is more like a U-shaped valley and are the sites of settlements. The upper mountain slopes are very steep (1:6), rocky, and pointed sharp ridgelines. Elevation differences between the valley floor and surrounding ridges exceed over 1,000 m in the upper part, and the watershed has a maximum elevation of 6,192 m. For calibrating the flood model, we focused on the lower reach (i.e., from Timbu and downstream to Melamchi Bazar). In contrast, the ADB team has focused on the upper reaches (i.e., from Timbu and upstream to Bhemathan).

The Melamchi watershed was delineated using ArcSWAT (ArcSWAT is an ArcGIS extension and interface for SWAT), and the boundary of the study area was fixed. The land use was classified using Sentinel-2 satellite images using the supervised classification technique. 8 Land use classes were identified - Snow, Built-up, Water, Dense Vegetation, Rock, Barren Land, Sediments, & Sparse Vegetation. The rainfall values were collected from the Global Precipitation Measurement (NASA) due to the unavailability of data from rain gauges. HEC RAS's full 2D model was selected for the study area due to the highly dynamic nature of the flood wave. First, a rain-on-grid model was built for the watershed, and from this model, the inflow hydrograph for the final

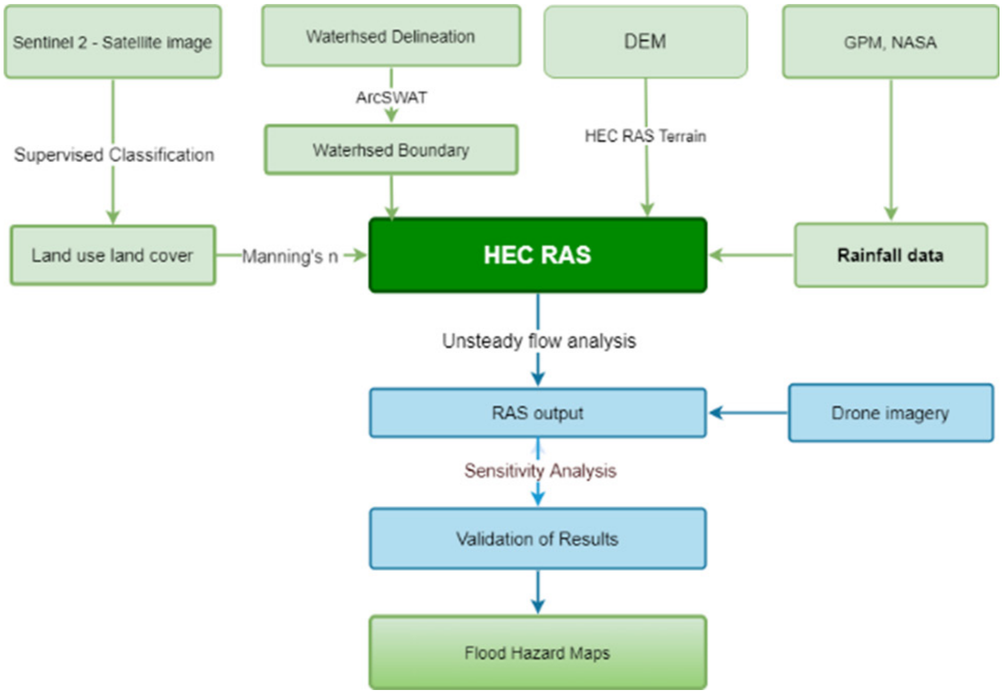


Figure 11: *Schematic showing the flood modeling methodology.*

model was extracted. After analyzing the preliminary rain-on-grid model, a refined model was constructed for the study area. This refined model was subjected to sensitivity analysis. Sensitivity analysis of the input parameters was conducted, and the results were compared with the field data and drone imagery. After the sensitivity analysis, 40 mm rainfall of duration of 1.5 hr with a high-density mix of water and debris (10% debris) was selected for the final non-Newtonian dam breach model. The terrain model was created by stacking 5 m DEM with Shuttle Radar Topography Mission (SRTM) 30 m DEM. When available, the 30 m DEM was stacked using 5 m DEM to utilize the higher spatial resolution.The model was further refined to meet the stability conditions (courant number <=1). Flood hazard, depth, velocity, and flood extend maps were generated, which were subsequently used to analyze the hazard to the community. A schematic showing the methodology followed for the flood modeling is shown in Figure 11.

Hydrograph extracted from the rain-on-grid HEC RAS model was constructed using 40mm (GPM NASA), rainfall of 1.5hr duration. Five inflow hydrographs for the main river tributaries downstream of the landslide dam and two inflow hydrographs for flow into the dam were used for the final model. Figure 12 shows an example hydrograph.

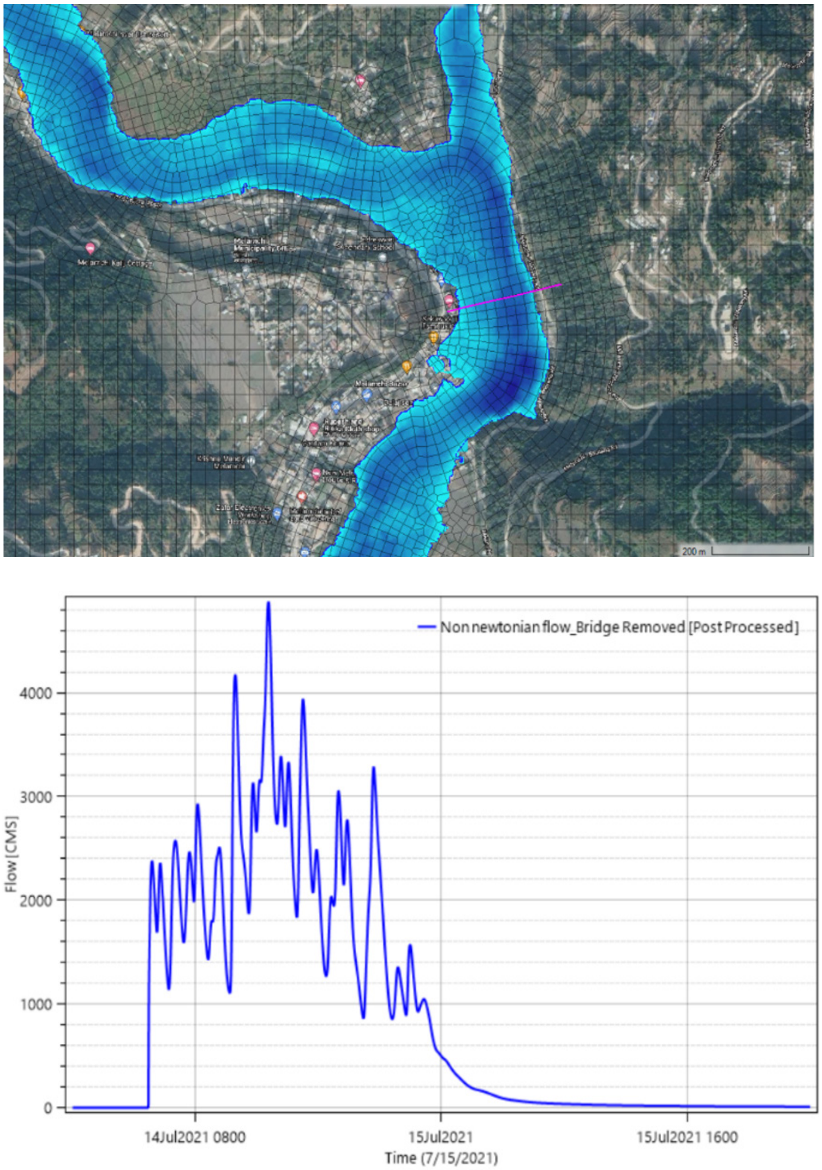


Figure 12: *Hydrograph extracted from the Rain-on-Grid model at Melamchi Bazar*

The results obtained from the HEC RAS modeling were validated against flood boundaries generated from drone surveys, and the photographs during the flood. The maximum depth and velocity map for the entire watershed are shown in Figure 13.

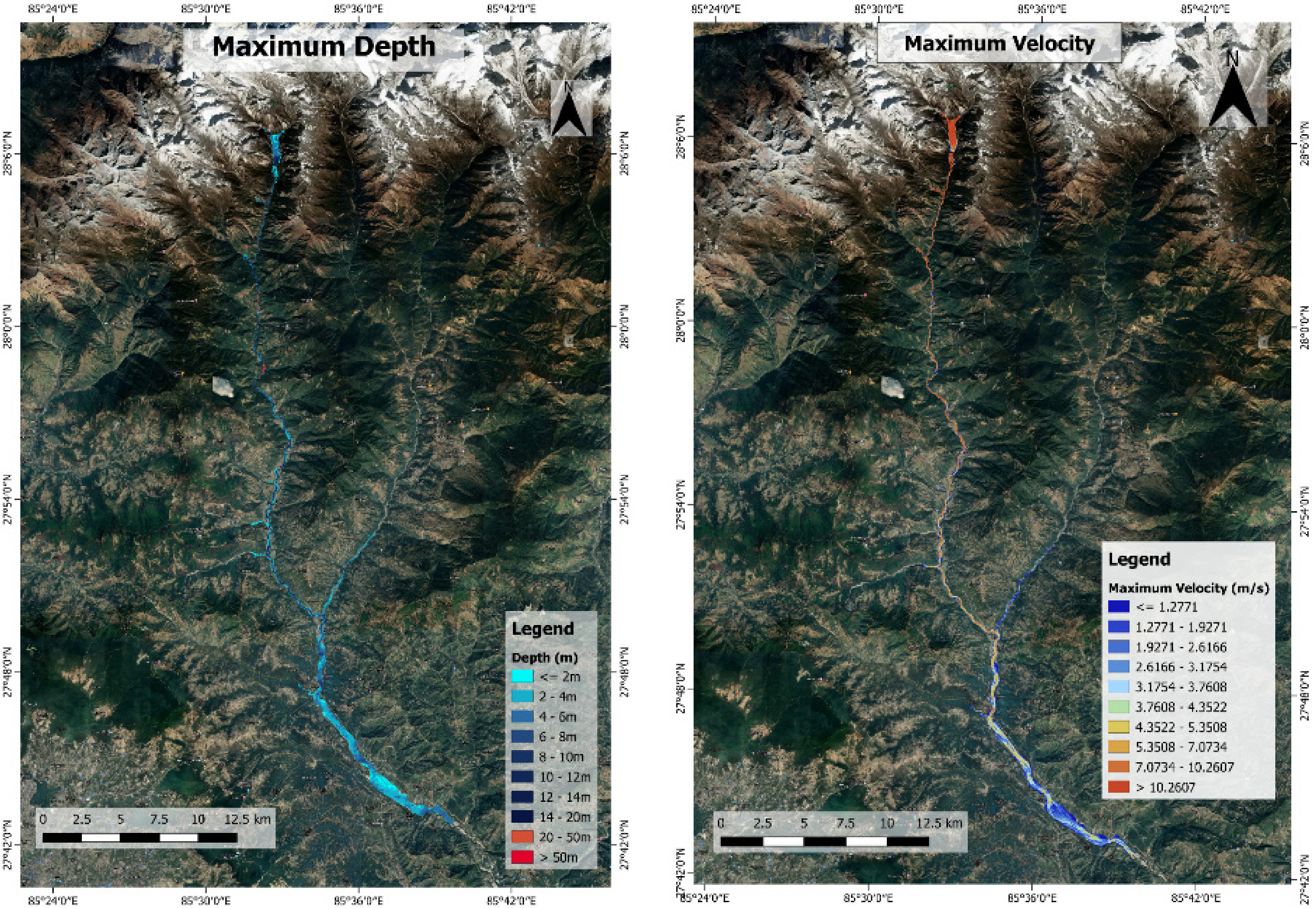


***Figure 13:** Simulated flood depth and velocity using HEC-RAS overlaid on the satellite image*

The results from the modeled flood compared to the flood extend mapped from the drone survey is shown in Figure 14. It is observed from Figure 14 that majority of the modeled flood extend matched well with the observation from drone. At site-3, the large variation between the flood extent from drone mapping and the modeled flood is a result of the observed flood extent incorrectly identified the landslide as part of the flood extent. The Chanaute Bridge (in the city Chanaute also referred to as “”Red Bridge” “) which is in the lower reach some 10 km upstream of Melamchi Bazar. ‘Red bridge’ was destroyed during the Melamchi flood. The height of the bridge from terrain (Pre-flood) was about 12 m This location was used for the modeled flood validation due to the availability of pre- and post-flood photographs (Figure 15). The modeled estimates of flood depth indicated a flood depth of 11.8m with debris, which indicates a good correlation between the modeled flood and conditions observed on the ground. The observed flood depth was used to back-calculate the peak discharge (which was estimated at 4,256 m3/s). And as this calculation was based on pre-flood cross-sections without considering elevated bed levels due to sediment deposition during the event itself, the estimated peak discharge may have some uncertainty and could be on the higher side.

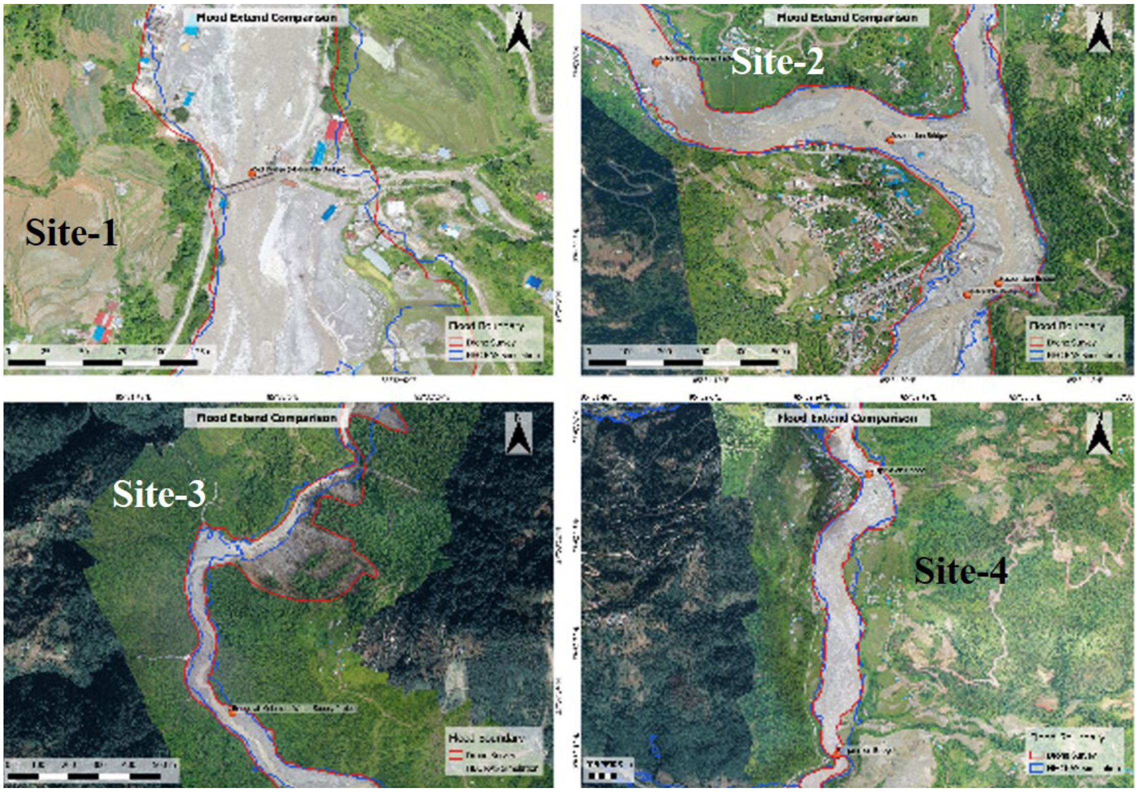


Figure 14: *HEC-RAS modeled flood compared to flood extend mapped from drone survey (red line: observed, blue: modeled)*

Figure 15: *A comparison of the pre- and peak-flood photographs from the Chanaute (Red) Bridge location*

Based on the simulated result, the areas with sediment deposition had an average velocity of 6.5 m/s, whereas the areas that experienced erosion had an average velocity of 16.2 m/s. The simulated velocity profile along the river (Figure 13) was consistent with the observed erosion and deposition pattern in the main channel (Figure 5). The results of the HEC-RAS, i.e., flood depth, velocity, and water surface elevation, are generated as a single kmz file that can be easily visualized on Google Earth.

The flood event was more complex in reality than how it was simulated in the study. The riverbed might have been gradually increasing during the flood due to the massive deposition to exacerbate the flooding. In other places, the riverbed might have been lowered by erosion, while such rapid topographic change within a flood event was not considered in the simulation.

Post-flood simulation utilizing the topographic data from the drone survey was tested but not completed because of uncertainty in the riverbed elevation underwater when the drone survey was conducted. To improve the accuracy of the topographic data prepared by the survey, a trail of the hydraulic simulation was conducted as well. For example, wet area during the drone survey was delineated and excluded from the profile and transported sediment volume calculations, and topographic data were closely reviewed and revised based on the unreasonable flow pattern observed in the simulations.

Satellite-Based Land Displacement Analysis

The vast mountainous terrain and high-altitude conditions in Nepal make it difficult and costly to directly apply in-situ land displacement monitoring techniques, like installation of measurement devices as well as frequent and regular ground surveys, over the entire region of interest in the upstream area of Melamchi River. While landslides and other types of slope failures can develop under various conditions and are hard to predict, under the right circumstances, the most susceptible slopes can be identified and monitored through land displacement mapping. Synthetic Aperture Radar (SAR) data and time-series interferometric analysis-based remote sensing techniques offer an alternative to periodically monitoring slopes with susceptibility. The free-of-charge Sentinel-1 SAR satellite data from European Space Agency (ESA) provides even higher cost-effective monitoring opportunities.

Some of the goals for satellite-based land displacement mapping in the Melamchi River upstream area were to generate time-series land displacement analysis, identify displacement hotspots area to indicate slopes with susceptibility, and identify possible precursors of the recent disaster event. This task was undertaken by Synspective. Time-series of Interferometric SAR satellite imageries were

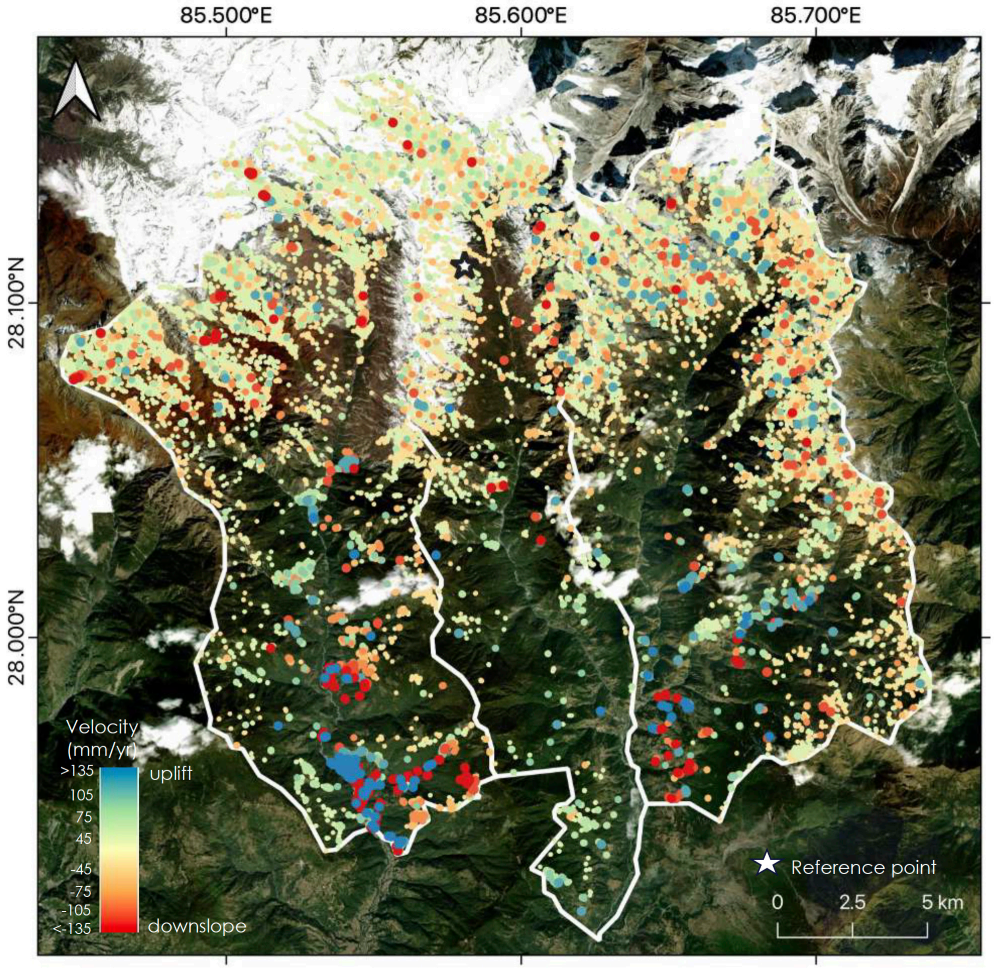


Figure 16: *Distribution of the slope-projected displacement points categorized unstable in the AOI.*

used covering the period from 2017 until the last SAR data acquisition date before the June 15th, 2021 disaster event (June 12th, 2021). Due to the influences of seasonal snow, ice melting, vegetation covers, and other SAR decorrelation factors, time-series InSAR analysis is split into several datasets (4 datasets) and skipping certain periods of data to avoid the inclusion of SAR data pairs with severe decorrelation.

Time-series InSAR analysis from Interferometric Point Target Analysis (IPTA) generated a data file containing a large number (up to a hundred thousand) of land displacement data points with uneven distribution depending on ground characteristics (vegetated ground, ground experiencing large physical change, seasonal change, will have less displacement data points density).

Time-series InSAR analysis also generated 375,912 Line of Sight (LOS) displacement data points over the 403 km^2 extent of the Area of Interest (AOI). LOS displacement data were then projected to the slope direction resulting in 350,332 along-slope displacement data points. Displacement velocity of +/- 15.62mm/year was used as a threshold for identifying instability (a positive value indicates uplift such as due to gradual sediment deposition, upheaval processes, folding, debris accumulation downstream of alluvial fan, etc., and a negative value indicates downslope movement or erosion). Using this criterion, 11.4% (39,981) of displacement data points were categorized as unstable. Figure 16 describes the distribution of these data points. Out of these unstable points, 23,431 points indicate downslope moving displacement with an average velocity of -31.8mm/year, and 16,560 points indicate uplift displacement with an average velocity of 31.27mm/year.

Both the active downslope or uplift moving displacement mainly occurs at higher altitudes (average 4,200 – 4,300 m asl). In general, displacement data density in the northern region of the AOI is higher than in the southern region.

The southern region of the AOI has vegetation covers that challenge Sentinel-1 radar wavelength (5.5cm) to reach the ground. On the other hand, displacement data density in Pemdan Khola (area of Glacial Lake) and Bhemathan old landslide dam can be deemed sufficient.

To identify slopes susceptible to landslide displacement, hotspots were determined from the SAR data. Displacement hotspots are locations with local displacement velocity higher than regional displacement velocity. Changes in the displacement time-series trend that reflect sudden/unprecedented displacements were taken as a proxy for displacement precursor. These conceptions are chosen under the presumption that a trigger factor can cause deviation inland displacement's temporal pattern, which might lead to near-future slope failure risks.

Based on the hotspot analysis, 163 hotspot zones were identified in the AOI. An ID number was assigned to each hotspot zone based on the size. A smaller ID number signifies a smaller size of the displacement hotspot zone. The smallest size of displacement hotspot zone is 50.47 m2 identified in Yangri Watershed. The biggest displacement hotspot zone is found in the Melamchi Watershed region, with a size of 60,000 m^2.

For the 163 hotspot zones, class 1-3 intensity of displacement velocity was identified. Table 1 summarizes the count of displacement hotspot zones in each intensity class of displacement velocity for the 3 watersheds of the AOI. The largest number of hotspot zone with high-velocity displacement is located in Melamchi Watershed. Compared to other watersheds, data also indicates that the downslope moving displacement hotspot zone in Melamchi Watershed has, on average, higher velocity than in other watersheds. Plotting over a map, the distribution of the 163 hotspot zones with their intensity class of displacement velocity is described in Figure 17. The displacement data were also partially presented online.

Table 1: Displacement hotspot distribution summary

Watershed	Number of zones in 3 velocity intensity classes			Fastest displacement velocity (mm/yr)	Avg. displacement velocity	
	Class 1 (<30mm/yr)	Class 2 (30-60mm/yr)	Class 3 (>60mm/yr)		Uplift	Downslope
Melamchi	43	17	**13**	-142.28	27.53	-52.47
Yangri	27	12	3	-91.49	26.40	-39.51
Larke	33	13	2	-114.63	29.37	-31.92

* Velocity indicated in negative value represents downslope moving displacement; positive represents uplift

Source: Synspective analysis (2021)

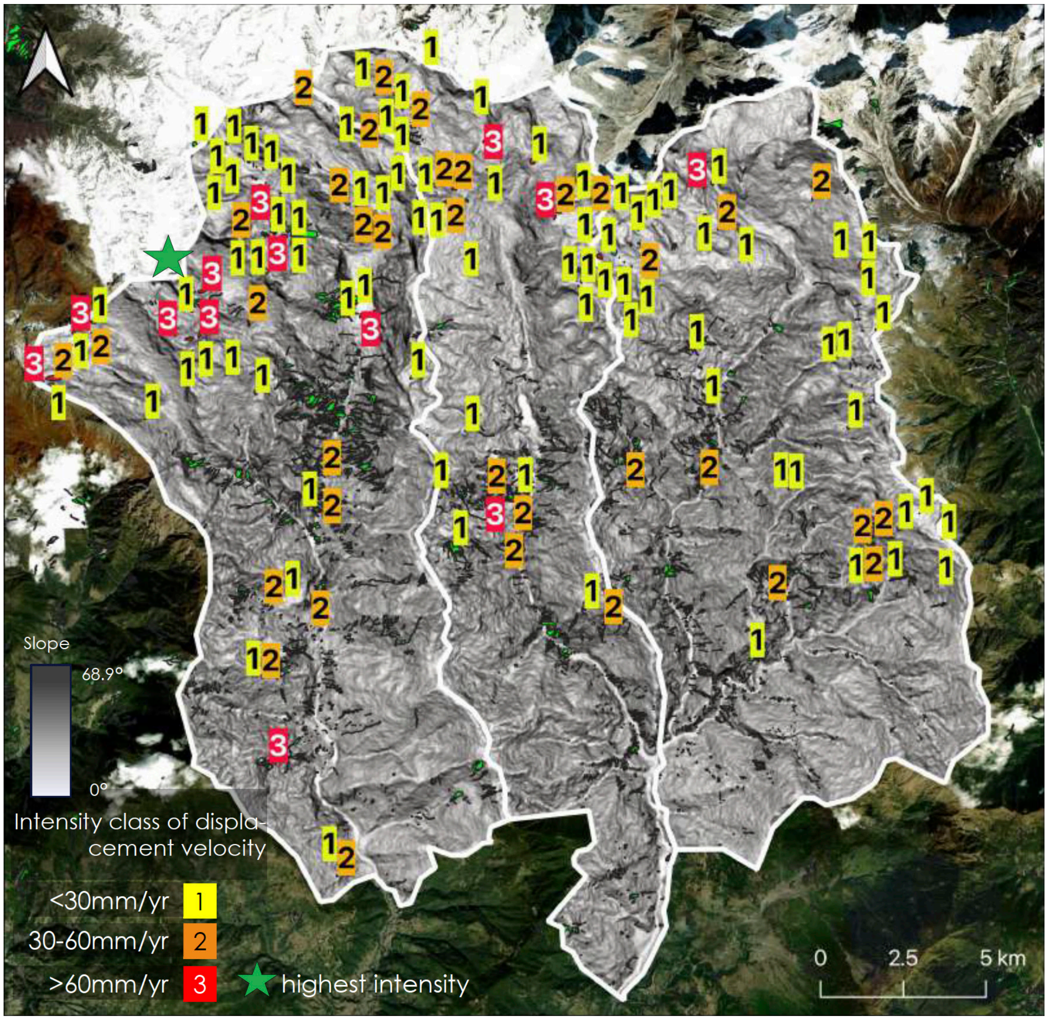


Figure 17: Distribution of displacement hotspot velocity intensity class

The displacement hotspot zones represent slope locations with high susceptibility, indicating either an area with downslope moving displacement, or deposition of debris, or bulging slope toe zone. These high priority zones can be listed for strategic actions such as mitigation and monitoring.

Further analysis was carried out at the displacement hotspot zone around the Pemdan Khola region. At the perimeter of the glacial lake in the upper reach of Pemdan Khola, the presence of both downslope moving and uplift displacement hotspot zones were identified. Subsequent analysis was carried out by overlaying the location of these displacement hotspot zones with the location of ground change during the Melamchi Flood disaster event. The result highlights that the displacement hotspot zones are co-located with locations of ground change in the Glacial Lake area. (Figure 18). These results also point to the possible hypothesis that downslope moving displacement hotspots identified in this analysis were a slow-moving type of landslide zone triggered during the Melamchi Flood disaster and became the source of debris that was transported to the lower altitude.

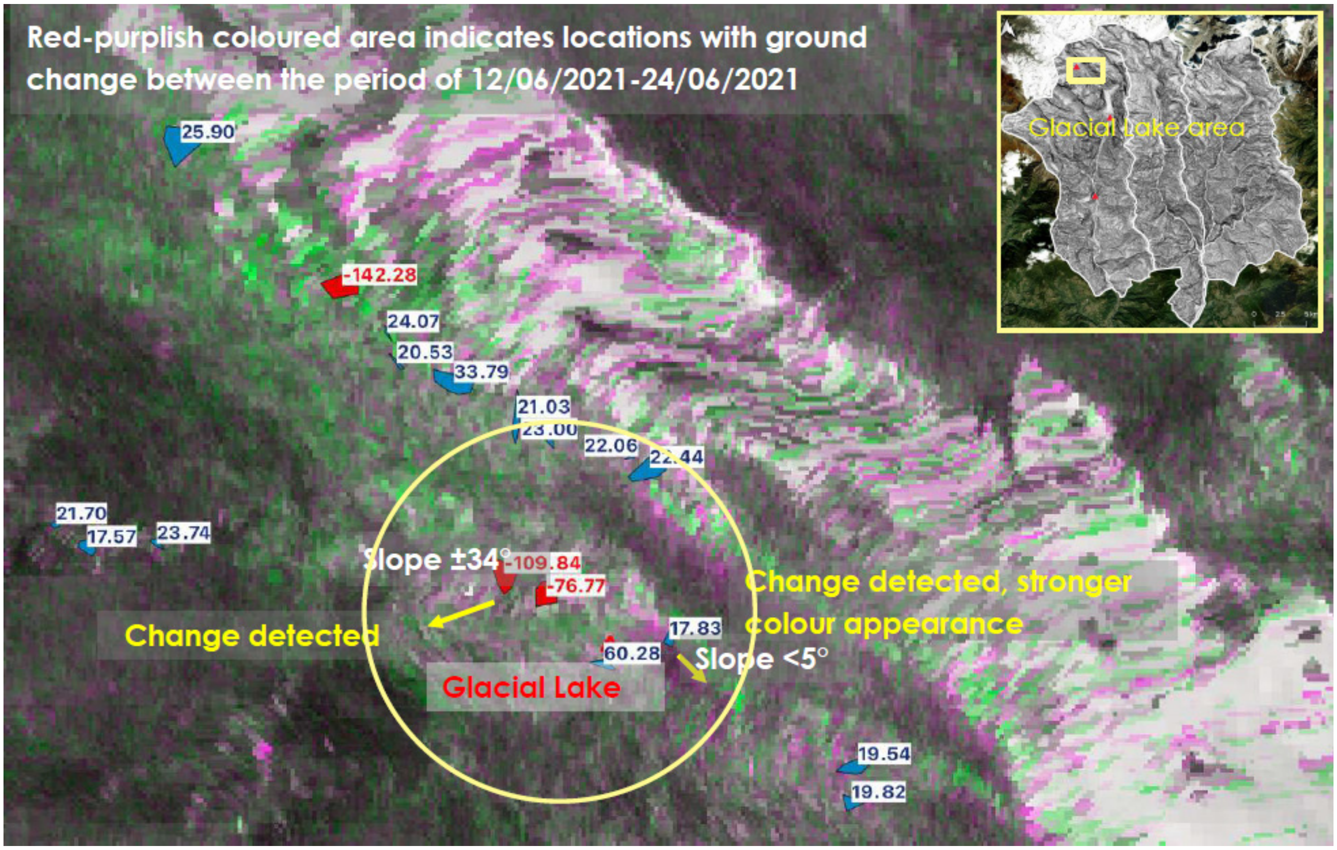


Figure 18: *Labels indicate displacement velocity (mm/yr) of hotspot zones; the red label indicates downward slope displacement and blue uplift. The red-purplish-colored area shows locations with ground change.*

Melamchi flood disaster field observations

The Melamchi flood, is a combined effect of heavy rainfall, temperature change in snow line, erosion in end moraine of Pemdan lake, possible breach of the natural dam responsible for the lake, cascading effects of natural dam breach along with erosion and series of landslides along the Melamchi River. The NDRRMA together with the ADB expert team conducted several field visits including one using a helicopter. The following section summarizes the field observations provided by Dr. Ranjan Kumar Dahal, a World Bank and Asian Development Bank expert who participated in the field visits.

Pemdan lake outwash and Bhemathan debris flow

The flood events of 2021 in the Melamchi River can be traced out from the upper catchment of the Melamchi River. On June 14-15, 2021, heavy rainfall enhanced the erosion process in the upper catchment area where permafrost is found in the deglaciated valley. As a result, on 15th of June end moraine dam of Pemdan lake (4700 m) was possibly eroded (Figures 19a and 19b) and the lake began to be emptied. The Pemdan Khola faced a flash flood, and a massive amount of boulders, gravel, and sand accumulated in the Bhemathan area. Bhemathan is an old landslide dam, and the reservoir was filled with sediment. It was well forested also. On June 15, 2021, the trees of Bhemathan were also mixed with the debris flow of Pemdan Khola. As a result, the old landslide area of Bhemathan was blocked, and flood water with debris started to flow as overtopping flow through the old landslide dam. Again, on August 1, 2021, heavy rainfall occurred. The overtopping water flow at the Bhemathan area eroded the old landslide dam abruptly (Figure 19c). A massive flash flood started to erode downstream where old glacial deposits and river channel deposits were abundant in more than 4 km stretch of the river (19d).

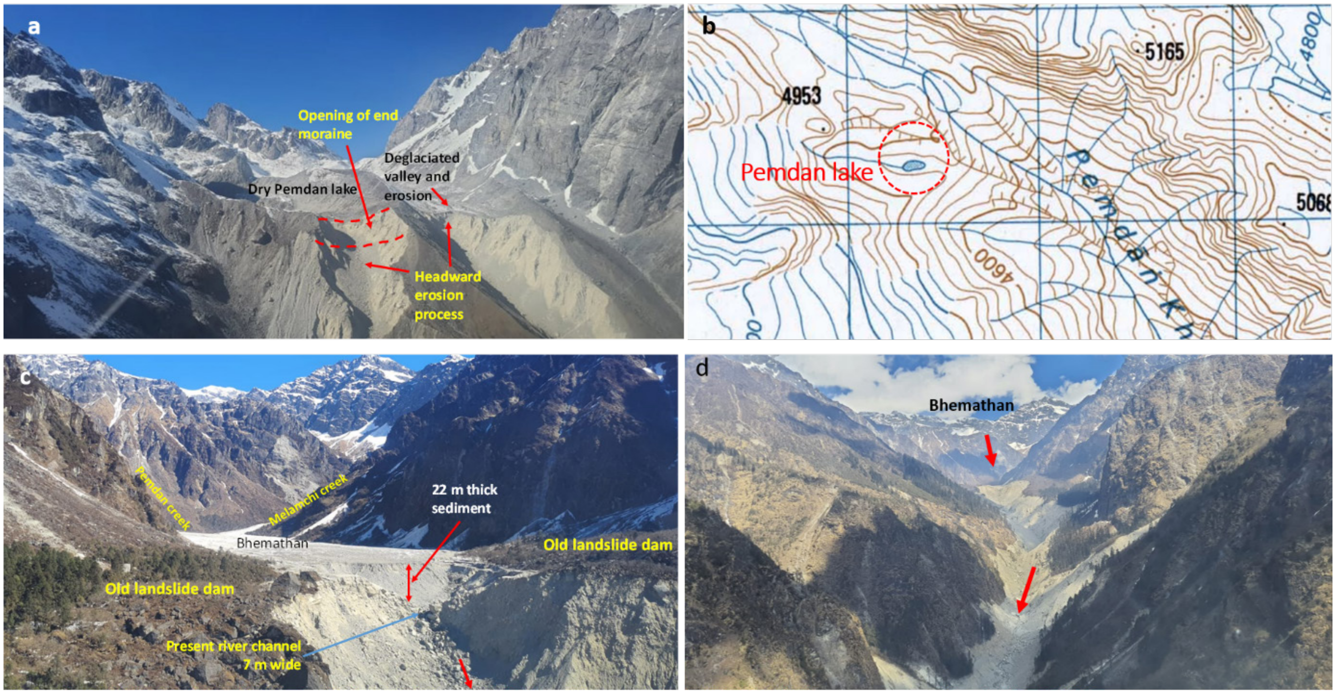


Figure 19: *Events from Pemdan Lake to Bhemathan in June 15 and August 1, 2021.*

Temporal damming of Melamchi Ghyang landslide

The Melamchi Ghyang landslide blocked the river for a few hours on June 15, 2021 (Figure 20). On June 15, 2021, hydrological data of Melamchi River at Nakote recorded this damming (lowering of water) and rising of water flow, and the gauge was washed away in this event.

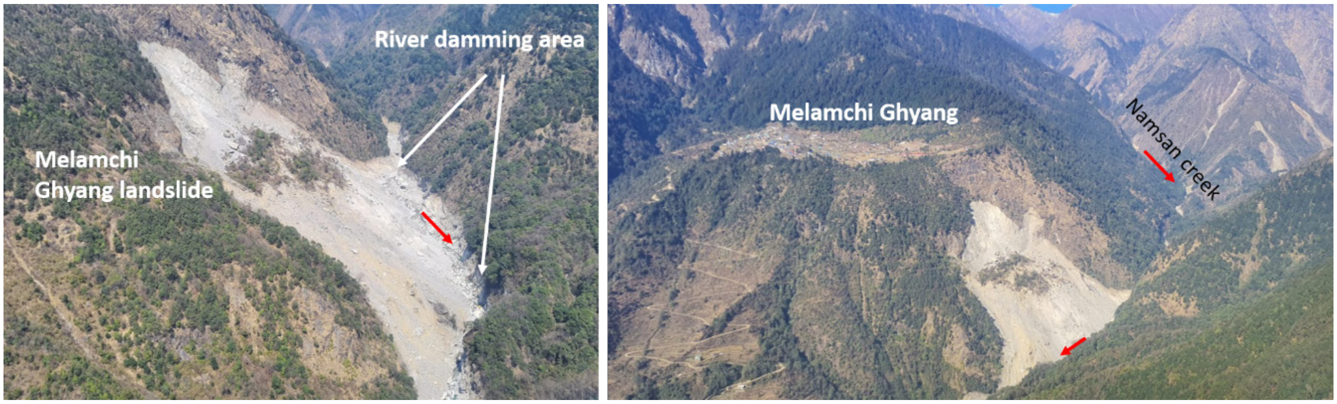


Figure 20: *Damming of Melamchi River down to Melamchi Ghyang village. From field observation, it is understood that this landslide blocked both the overtopping flood of Bhemathan on June 15 and potentially the flood on August 1, 2021 as well.*

Extreme erosion in downstream channel

Due to the sudden release of a massive amount of water from the Melamchi Ghyang landslide damming, the downstream of the Melamchi River was intensively eroded and deeply incised, and a bridge was washed away in Nakote (Figure 21).

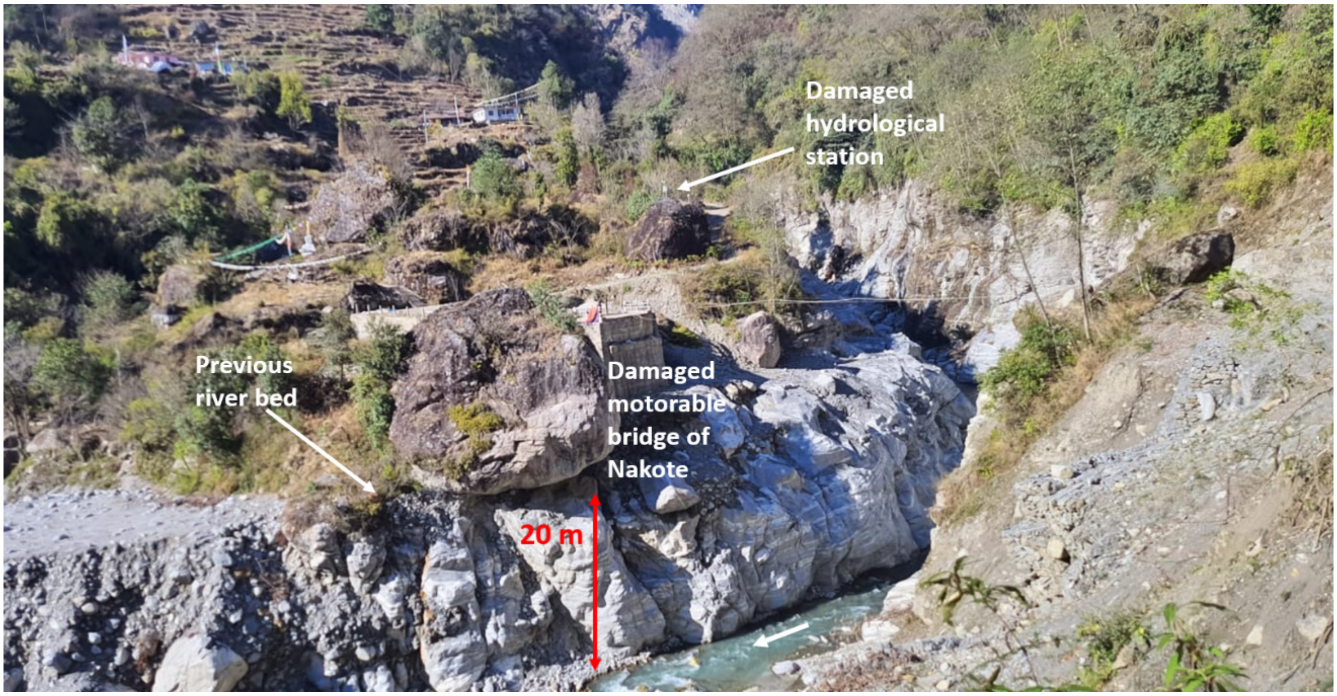


Figure 21: *Erosion into bedrock level at Nakote, site of immediate downstream from Melamchi Ghyang landslide. Only 16 days old newly constructed bridge was also washed away during the flood.*

Debris flow through the narrow gorge and buried headworks of the Melamchi Water Supply Project

The headworks area of the Melamchi Water Supply Project, with financial support from ADB, experienced severe damage, and more than 16 m of debris accumulated in this area overall. Several massive landslides have also occurred in this area. The narrow gorge just upstream of the headworks is the endpoint of the erosional channel of the Melamchi River in the 2021 flood. From the headworks to downstream, the channel experienced massive depositions. As a result, all the downstream settlements were partly buried. The effects were well observed downstream to the confluence of the Indrawati and Melamchi rivers (Figure 22).

Figure 22: *Landslide in headworks area, deep gorge and headworks area under cleaning.*

Damage in Gyalthum to Talamarang area

Massive sediment and debris deposition was observed at four (4) locations while traveling from Talamarag to Melamchi Bazar. The first location is the gorge area (Figure 23) of Bhattar Phat, where the remnant of the old chain suspension bridge was buried during the 2021 flood event. In this narrow channel, the upstream area up to Gyalthum of Helambu Rural Municipality, the sediments accumulated, huge boulders were deposited in the riverbed and buried 2nd level terraces (Figure 23). The second location was at the Thulophat area, where many huge boulders, eroded from the narrow upstream channel, were accumulated (Figure 24).

The third location is the bridge at Phatte, which temporarily blocked the sediment. The thick sediment accumulated due to the temporary ponding. At this location, downstream to the bridge area consists of mainly fine sediments, which buried cultivated lands and permanent buildings and buildings under construction.

Similarly, the fourth was at the confluence of the Indrawati and Melamchi Pul Bazar areas. The sediments with huge boulders could not pass through a narrow channel below the bridge, due to which debris reservoir was formed, and fine sediments deviated towards the Pul Bazar area (Figure 25). As a result, more than 16 m thick sediments were deposited in the area (Figure 26).

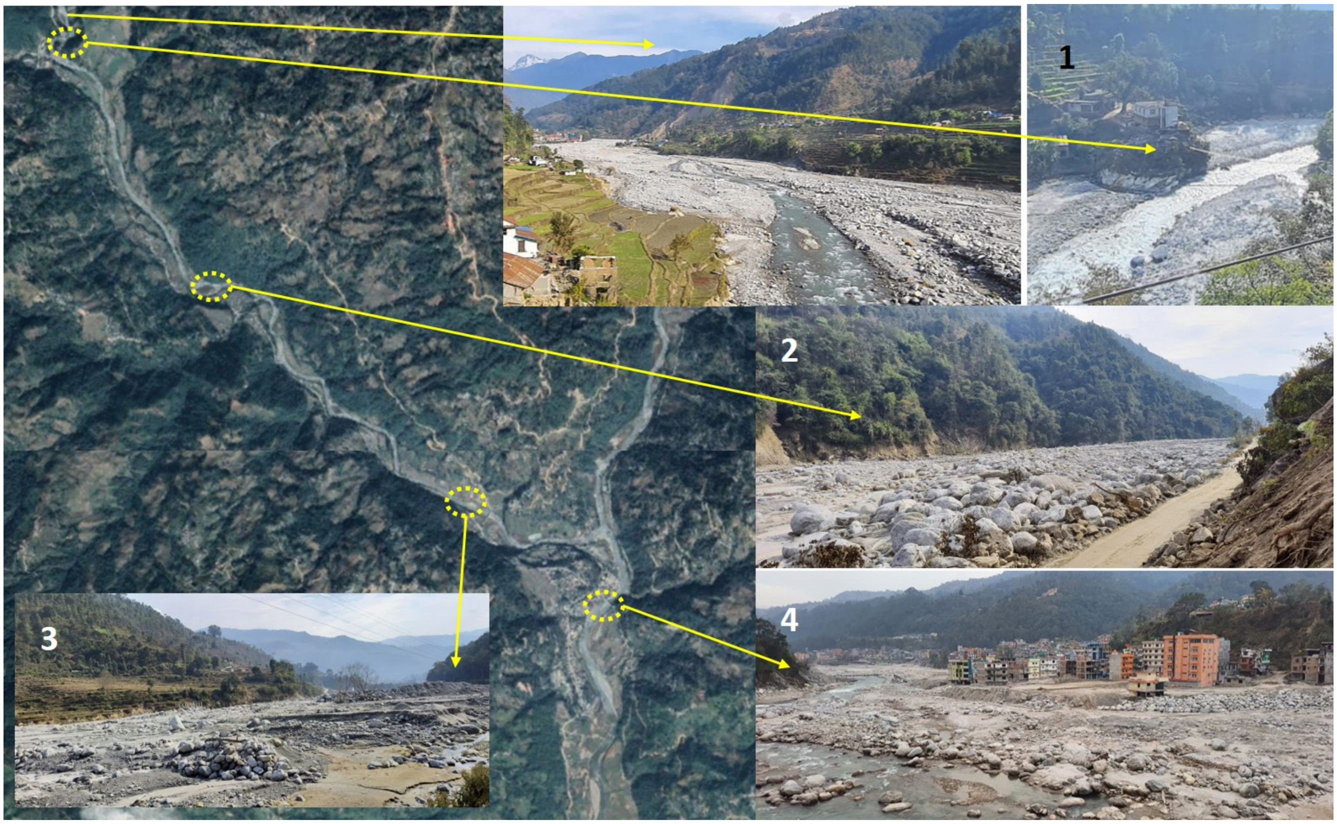


Figure 23: *Four locations (Talamarang to Melamchi Bazar section) of sediment blockage during the 2021 flood in the Melamchi River. These locations highly controlled the sedimentation process. Location 1 is Talamarang, location 2 is Thulophat, location 3 is Phatte, and location 4 is Melamchi River.*

Figure 24: *Significant deposition of debris occurred at Phatte due to a slowdown of flow caused by a downstream bridge as a blockage. Only fine sediments were found deposited downstream of the bridge.*

Figure 25: *Before and after view of damaged Melamchi Bazar. The Pul Bazar was the major obstacle, and more than 16 m of sediment was accumulated in the Melamchi Bazar.*

Figure 26: *Many buildings in Melamchi Town was covered by the debris.*

Conclusions and Lessons Learned

After the Melamchi flood in June 2021, three studies were implemented in parallel on a tight schedule based on the request from and close discussions with the NDRRMA. The implementation period of the three studies overlapped each other with regular progress meetings with the government stakeholders, and all the three teams were engaged. These studies are crucial in understanding the flood more holistically and enhanced the quality of each study. For instance, utilizing the topographic data prepared by the drone team, the flood modeling team identified key issues and helped modify the data. Using photos and videos captured by the drone team, coupled with field observations by the experts, enabled the satellite team to orient their focus and improve analysis quality. In addition, the World Bank, together with the NDRRMA organized two-hybrid workshops presenting the study results to policy stakeholders. The final workshop was attended by more than 71 participants from various government agencies and external stakeholders such as ICIMOD and NASA for sharing the findings and promoting discussions.

The three activities were critical to understanding the hazard and risks of the Melamchi Watershed. Notably, the drone-based survey provided timely documentation of the damages from the event. Such documentation is valuable to calibrate and validate models and ensure that the regional mitigation measures are sustainable. The drone survey provided a georeferenced ortho-mosaic and Digital Terrain Model (DTM) of the post-disaster condition. The ortho-mosaic helped identify flood extent, landslides, and damages to houses and infrastructure. The DTM generated from the drone survey can be used for approximate volume calculations of debris and landslide deposits and cross-section developments. The drone survey results indicate that cadastral maps can be produced quickly and easily in complex and difficult-to-access environments. However, it was observed that the drone imagery does not penetrate the water surface. Hence, any deposition or erosion quantification below the water level will be inaccurate from the drone imagery. It is important to note that the accuracy of the DTM can be limited (+/- 5m) in complex terrain when only limited ground control points can be established with high precision.

The sensitivity analysis using the HEC-RAS model identified that the landslide dam breach caused a significant elevation in the flood depth and resulted in inundating more areas of the Melamchi Watershed and surrounding places. This observation further emphasizes the need to characterize and monitor the landslide hazard in the region using technologies such as the satellite-based land displacement analysis so that the risk of such future events can be avoided. Comparing the clear water simulation and the non-/Newtonian (mud/debris-flow) flows showed that utilizing non-Newtonian conditions to model such events involving large loads of sediments better reproduced the flood event in the model. The presence of the debris reduced the flow velocity resulting in higher flood depths. The drone data was valuable for the calibration and validation of the flood simulation. Particularly the flood extents mapped from the drone were used to verify the accuracy of the HEC-RAS model. The comparison of the modeled flood velocity with the erosion and deposition regions identified from the drone imagery showed a good correlation. The deposition areas had an average flood velocity of 6.5 m/s, whereas the erosion areas had an average velocity of 16.2m/s. The results indicate that the flood velocity simulation is critical for designing mitigation measures and ensuring they would sustain the erosion and deposition mechanisms in the region. The results of the HEC-RAS simulation were distributed to the interested parties as Google Earth files for future risk reduction and visualization, making it readily accessible for researchers, policy planners, and any relevant stakeholders to plan setback distances and other relevant policies for community development.

The application of SAR satellite data and land displacement analysis emphasizes 1) the power of SAR technology and its benefit to disaster risk managers and other authorities, and 2) the adoption of the technology itself in disaster risk management practice. The role of SAR satellite data and analysis results is most suitable in circumstances in which it is challenging to obtain the onsite measurement in a timely/regular manner due to the hindrance of cost and location accessibility challenges. The adoption of SAR technology and analysis in disaster risk management practice can be considered following the conceptual scheme illustrated in Figure 27.

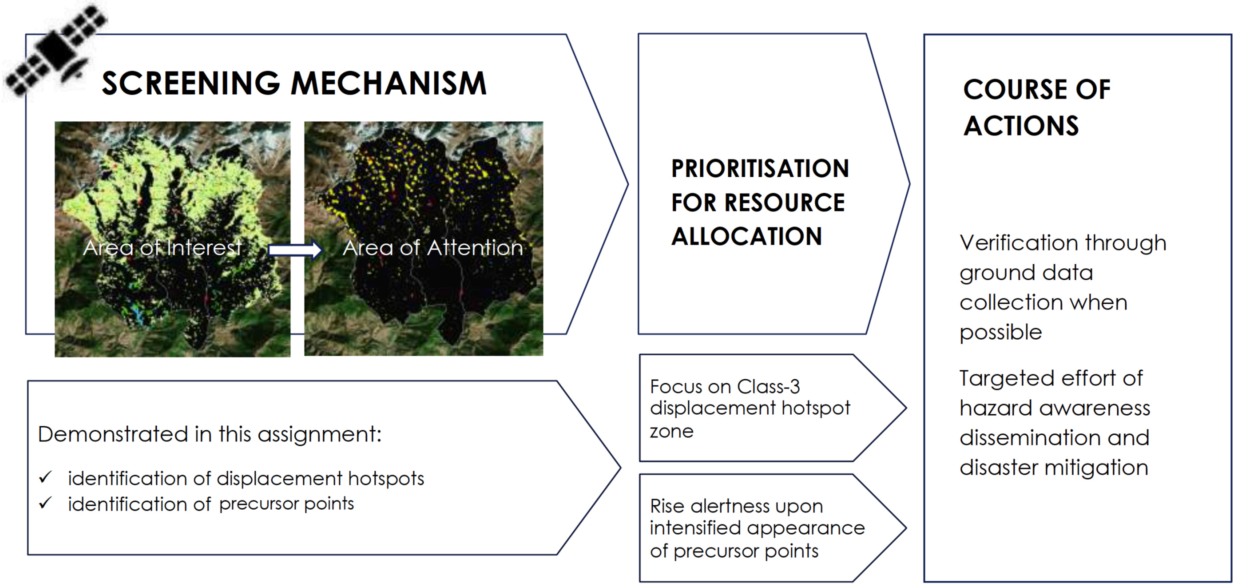


Figure 27: *Conceptual scheme for SAR technology adoption*

While this study highlights the capability of the SAR technology in providing valuable insights in slope instability-related risk management works, however, this process also has limitations that need to be acknowledged. The analysis technique itself requires expertise in executing and interpreting the analysis generated from the data processing. In many cases, it cannot be done straightforwardly, thus resulting in some difficulties. Especially in regions with geographic characteristics like the AOI in this assignment because of thick forest and snow covers, the level of difficulty in both image analysis processing and interpretation can even be higher. Post-processing additional analysis based on field observations, like the ones demonstrated in this work, needs to be done to improve insight drawing from the data and analysis results.

With the advancement in the field of artificial intelligence (AI) and data science technology, complexity and hurdles in the analysis can be minimized by automating the process and delivering the result as user friendly as possible so that the information can be quickly digested and used as supporting material in the strategic decision-making process. Considering the advancements in this area and the encouraging potential of this work seen in the initial results suggest the possible use of this technology for monitoring critical slopes. The development of the InSAR analysis in this work gives broad situational awareness regarding instability in the Bhemathan and the other critical locations impacted by the Melamchi flood and highlighted within this report

Contribution to detailed mitigation planning studies

All input and output data used for generated through the studies were shared with the NDRRMA and their partners, including the ADB expert team undertaking a detailed damage assessment of the Melamchi Headworks and Hazard Mapping of the Catchment for the MRWDS project and the University team on flood zoning in Melamchi. Melamchi Municipality has prepared preliminary plans of recovery and mitigation on the basis of Drone Survey data for this work. They utilized the topographic data prepared by the drone team and reviewed the 2D flood model setting and parameters to build their detailed hydraulic modeling. The ADB team also requested detailed InSAR land displacement data for the slope near the headworks to better understand the remaining risk of a large landslide nearby. Such close collaboration on sharing data and findings with the Gov and partners maximized the use of limited resources for understanding the disaster and remaining risks holistically, and helped improve the quality of deliverables.

Overall, this urgent support to NDRRMA through various studies proved helpful for the government agencies, partners, and stakeholders to understand the disaster better and provide a basis to prepare risk mitigation plans in the Melamchi watershed.

Application of this effort to other areas

This effort demonstrated the value of drone-based mapping, flood analysis, and InSAR analysis at a location significantly impacted by flooding and landslides. It shows the importance of drone-based data collection immediately after such an event in documenting the flood and developing post-flood topography. The post-flood topography is critical to flood modeling, understanding the revised flood hazard in the area, and assisting the InSAR-based ground displacement analysis in identifying the site conditions and validating the results. The methodology can be applied pre-event to other watersheds with high risk of such debris flow for hazard characterization. risk reduction, hazard management, and policy formulation. Pre-event drone surveys can be invaluable in developing topographic data for high-risk channels to use in hydraulic modeling. Topographic data can be prepared using the drone for high-risk river channels as a critical input for hydraulic modeling. Besides, the drone survey data can help develop a detailed inventory of houses and infrastructure at different risk levels and quantify risk scenarios.

The pre-event InSAR analysis can be invaluable in identifying vulnerable slopes and planning development measures. Often these development measures could be to avoid susceptible areas and route development through more stable terrain, which could lead to significant cost savings in maintenance and improve the reliability and sustainability of the infrastructure. Even when the project doesn’t have the flexibility to develop through stable terrain, the InSAR-based analysis can help identify the most vulnerable locations and build monitoring and mitigation measures. Such measures can reduce human casualty and increase the reliability of the development.

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