Melamchi Extreme Flood in Response to Climate Change in the Central Himalaya of Nepal

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Research Article

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Abstract

Climate change induced extreme precipitation and the associated rise in temperature have led to catastrophic floods. A flood occurred in the Melamchi River on 15 June and recurred on 31st July, 2021 in Nepal. This study has investigated these extreme flood events and their close nexus with climate. The available daily and hourly precipitation, temperature, snow depth and discharge data were analyzed. The regional flow during both flood events were estimated using 1-D hydraulic HEC-HMS model and the correlation among rainfall to the runoff and temperature with snow water equivalent were examined. The snow water equivalent was converted to the stream flow of the river. Result show that the Melamchi region found an average annual rainfall of 2610mm during 1992–2021. Specifically, Shermathang and Tarkeghang has observed the highest daily average rainfall of 26.8mm and 39.2mm during the first and 61.4mm and 66.6mm during the second flood event, respectively. The discharge found at the Melamchi Bazar was at 2893m^3/s and 1105 m^3/s in the first and second events respectively in which Kiwil, Chanaute and Melamchi were highly contributed. The peak 10m interval flood discharge during the second event at Nakote was found 285 m^3/s. The daily average discharge of Bhemathang was 357m^3/s and 76m^3/s on both events, respectively. The rainfall and runoff at the Nakote station are poorly correlated while snow water equivalent and temperature showed positive correlation during summer which indicates melting of the snow. In response to summer temperature increased, SWE and snow depth were decreased by melting. The snowmelt contribution to discharge was found 9.68m^3/s in the Melamchi River during the Summer season. The daily average snow water equivalent of the upper basin was found 672 mm which are very potential to melt out in response to increased temperature. The finding showed that precipitation is the main climatic driver while temporary damming and increasing temperature also contributes to the timing and magnitude of the of the Melamchi flood.

1 Introduction

Floods are devastating and notorious climate related disaster due to their multi-faceted attributes and large spatial extent (Gautam et al. 2022; Hirabayashi et al. 2013; Winsemius et al. 2016) which affects millions of people worldwide (UNDRR 2020; Jevrejeva et al. 2018; Sarhadi et al.2012; Dottori et al. 2018). During the past 40 years, flood has cost more than 1 trillion USD and influenced 1.65 billion individuals globally (UNDRR 2020). Specifically, fluvial flooding causes serious global economic losses and fatalities (Jongman et al. 2015; UNISDR 2018) and projected to increase in response to future climate change (Peijun 2016). Climate change alters temperature, precipitation, glacier melting and discharge of river networks (Hock et al. 2019) and fetches cascading flood havoc (Maharjan et al. 2021). Climate induced extreme precipitation event has led to catastrophic flood (Zhang et al. 2021; Pendergrass A.G. 2018 and Gualdi et al. 2013; Pandey et al. 2021; Kumar et al. 2018; Zhou et al. 2021). The warming climate and changing hydrological cycle increased the global flood risk in the future (Zang et al. 2013; Li et al. 2016; Jongman et al. 2012; Tang et al. 2020; Swain et al. 2020). Climate change not only affects flood magnitude but also shifting flood timing (Fang et al. 2022; Tabari H 2020). The flood attributing factors are mainly climate and human factors such as cloud bursts, warming induced snow melt, glacial lake outbursts and landslide damming, change in hydrological cycles, soil moisture, dam construction, land use change and river training (Bloschl et al. 2019; Bertola et al. 202; Do et al. 2020; Hodgkins G 2019). Except climate attributes, the floods are more comprehensive and cascading in nature (Gautam et al. 2022). In Landslide damming flood, large volume of water and sediments erosion leads to change geomorphology of bedrock and alluvial rivers (Lin et al., 2022). In some cases, landslides entering a channel can obstruct the river and sudden breaching give rise to knickpoints and gravel-sand waves during the flooding (Korup et al., 2006). In the Himalaya, snowmelt also has significant contribution to total runoff of the river (Li et al. 2017; ICIMOD, 2011). During summer, snowmelt water i.e amount of snow water equivalent (SWE) has positively correlated with stream flow in the rivers of Himalayas (Modi et al, 2022).

In response to climate change, South Asia is one of the global hot spots of high-risk floods (Duan et al. 2022). The flood in Pakistan and China costed 15 billion USD each in 2022 (UNISDR 2023). Large flash flood 2021 event in Rishi and Dhauli Ganga rivers and the previous Kedarnath Tragedy (Singh et al. 2022); Uttarkhanda flood in 2013 (Houze et al. 2017) and the 2021 Chamoli flood in India (Shugar et al. 2021) are shocking events in Central Himalaya. The large areas of the Hindu Kush Himalaya (HKH) region are vulnerable and flooded in every rainy season (Uddin et al. 2021; Tsering et al. 2021). The Himalayan region is characterized by a steep topography (Duncan et al. 2003; Vaidya et al. 2019); active orogeny (Roback et al. 2018) and highly susceptible to mass failure (Singh et al. 2022), thermal melting of glaciers (Fang et al. 2022), landslide and avalanche (Dhital et al. 2002; Sharma et al. 2022) resulting in Glacial Lake Outburst Floods (GLOFs) (ICIMOD 2011; Fang el al. 2022; Veh et al. 2020), river blockage and sudden Landslide Damming Outburst Floods (LDOFs) (Gao et al. 2021; Byers et al. 2021) with the large debris and sedimentation at the downstream (Bhandari et al. 2019; Adhikari et al. 2005;). Nepal is a country with the highest risk of flood and climate change related hazards in South Asia (UNDP 2009). The country is more vulnerable to multi environmental hazard of flood extreme (Sharma et al. 2018). During 1971–2016, 4160 flood events were recorded in Nepal (Shrestha et al. 2020). On May 05, 2012, a large mass of slope failure rocks blocked the Seti River in the central Himalaya that burst downslope and led to the missing of more than 70 people from downstream residence in Nepal (Dwivedi and Neupane, 2013). GLOFs occurred in Bhote Koshi during 1981 and Dudh Koshi River during 1985 in the Koshi basin (ICIMOD 2011). The Koshi Flood in 2008 is the largest flood recorded in Nepal when thousands of households, agricultural lands and billions of economies were lost (Adhikari B 2013). More specifically, the extreme precipitation during monsoon season increased extent and severity of flash floods in the Himalayan sub-basin of Nepal (Sharma et al. 2022; Talchabhadel R 2023).

Nepal receives around 80% of the total annual rainfall in the monsoon season only which result flooding in the river (Dhital Y.P and Kayastha RB 2013; Talchabhadel et al. 2018; Adhikari BR 2013). Flood led by extreme precipitation in the Himalaya is more common (Talchabhadel et al. 2023). On 15 June 2021, recurred on 31st July, 2021, an extreme flooding occurred in the Melamchi River (MF21 hereinafter) in Nepal (NDRRMA 2021; Dahal et al. 2022). The notorious Melamchi flood led to 17 casualties, 23 reported missing, left a pile of more than10m debris at Meamchi Bazar, displaced 525 households and 13 suspension bridges and severely affects the Melamchi Water Supply National Project with economy loss of more than 7.8 million USD (Pandey et al. 2021; NDRRMA 2021; Dahal et al. 2021; Sharma et al. 2022; Takamatsu et al. 2022; Pettey D 2021). The intersections between anthropogenic, hydro-meteorological and geophysical attributes have given rise to multi-hazard in the Himalayas, Melamchi flood is one of a such hazard (Lamichhane et al. 2021; Maharjan et al. 2021). The Melamchi flood first event (hereafter MF21st) has observed after rainfall, landslide damming and GLOFs in the higher reaches of the Melamchi watershed (MWSDB/Eptisa 2021) and Melamchi flood second event (MF21nd) recurred with heavy rainfall and debris deposition (World Bank/GFDRR 2021). Additionally, Melamchi watershed is highly erosive consequently sediment dynamics in the river are higher (Baniya et al, 2023). During flooding events, the regional flow contribution during the Melamchi flood are also considerable (Tirtha et al, 2023). These previous studies mainly focused on landslide damming at Bhemathang, rainfall erosivity and heavy debris in the river and their associated attributions. In this context, this study has investigated the river flow during Melamchi flood and it's nexus with climate change mainly with precipitation during flooding events and temperature induced snow melt discharge in the Melamchi River. Identification the role of precipitation and temperature to Melamchi floods could be more crucial and helpful to establish the climate change impacts on flood in the Himalaya and beyond.

2 Data and Methods

2.1 Study Area

Melamchi-Indrawati watershed consists of three main tributaries: Melamchi, Yangri and Larke in Koshi River Basin. Melamchi catchment has an area of 324 km^2 and very steep river gradient and the shortest (41km) from Himalaya origin i.e. from 5800m at its highest points to 773masl at the confluence of Melamchi and Indrawati River. The topographic variation of the Melamchi-Indrawati catchment is diverse which ranges from 629 to 6075masl and the Melamchi river stretches very steep gradient and high flow velocity, river section is narrow and deep with a slope variation of between 17–8% (Pandey et al. 2021). The mean annual flow of the Melamchi River is 9.7m^3/s and received more than daily 12mm of rainfall during monsoon season (DHM 2021). The forest is the dominant land use type in the basin followed by agricultural land and grassland. The snow/glacier land occupied 35.91km^2 which is 2.92% of total land coverage in the Melamchi-Indrawati basin (Uddin et al, 2015). Mainly, eight numbers of hydro-meteorological stations and locations from Dumredovan to Bhemathang (damming area) were covered for this study (Fig. 1; **Table 1**).

Table.1 Hydro-meteorological stations detail in Melamchi-Indrawati Watershed

SN	Name of Station	Index No	Latitude	Longitude	Altitude (m)	Remarks
1	Nawalpur	s1008	27.8130	85.6241	1653	Precipitation
2	Sermathang	s1016	27.9445	85.5951	2574	Precipitation
3	Duwachaur	s1017	27.8571	85.5663	1481	Precipitation
4	Tarkeghang	s1058	27.9993	85.5544	2596	Precipitation/Tem
5	Dhap	s1025	27.9124	85.6333	1284	Precipitation
6	Nakote Station	s 627.5	28.0108	85.5353	1750	Discharge
7	Bhaunepati	s1018	27.7924	85.5726	774	Precipitation
8	Ganjala, ICIMOD	SnowAMP	28.1545	85.5625	4962	Ppt/Tem/Snow depth

The best available daily and hourly precipitation, temperature, snow depth (Ganjala, SnowAMP), discharge (Nakote) data from the Melamchi-Indrawati basin were collected from the hydro-meteorological stations (Table 1). The Ganzala pass AWS station (Index: SnowAMP Ganja La) is located at the upper part of the Melamchi watershed at an elevation of 4962masl which was installed as part of the snow accumulation and melt process in the Himalayan catchment (Saloranta et al. 2019) and Bhaunepati (s1018) is located at the lower altitudinal region below Melamchi-Indrawati confluence at an altitude of 774masl.

2.2 Data Used

The daily and hourly precipitation data of hydro-meteorological stations of the basin during 1992–2021; gauge height and 10m interval discharge data of Nakote during flood time were collected from the Department of Hydrology and Meteorology, Government of Nepal. The hourly temperature, precipitation and best available snow depth data of Ganzala pass AWS station (Index: SnowAMP Ganja La) were collected from ICIMOD (https://rds.icimod.org). The collected data was carefully examined, cleaned, and organized to ensure accuracy and consistency. The drone survey GIS data such as flooded areas, inundated households, drone images i.e. geo-tiff, ortho-mosaic data for both flood periods were collected from National Disaster Risk Reduction and Management Authority (NDRRMA) Government of Nepal. The drone survey was undertaken by Trimax IT Infrastructure with DJI drones between July 6th and August 14th under NDRRMA. The auxiliary data such as SRTM (DEM) from NASA, USGS site and Topo sheet layers were collected from the Department of Survey, Government of Nepal. The field visit was conducted on June 15–22, 2021 on flooded sites and observed post flood scenario (Damaged households, infrastructures, river profile and flood benchmarks) and cross-sectional features of the river.

2.3 Methods

The spatial and temporal pattern of precipitation in the basin was analyzed using daily rainfall data from stations (Nawalpur, Sermathang, Duwachaur, Tarkeghang, Dhap, Baunepati and Ganjala). Hydrologic Engineering Center's River Analysis System (HEC-RAS), 1D model was used to estimate sub-basin wise (regional) flow contribution in 8 different segments of the river during both MF21st and MF21nd event. The relationship between rainfall and runoff; Temperature and SWE to discharge at upper catchment region were examined. The correlation between rainfall (Sermathang nearest station) and runoff (Nakote station) for both events was analyzed. For the MF21st, historical data on discharge and the water level was collected from the Nakote hydrological stations but for the MF21nd, the discharge and water level data were collected from Dolalghat to predict the discharge of Nakote station using the G2G correlation method (Beven K.J. and Binley A 1992; Gupta et al. 1999). Regression method was applied to the historical statistical data from both stations to develop an equation that could be used to predict the discharge and water level of the Nakote hydrological station (Wang et al. 2016; Xiong et al. 2017).

The peak discharge of both events was estimated which involved comparing real-time gauge readings to estimate peak discharge. Real time discharge of the Melamchi River at 10 min intervals during both events at the Nakote hydrological station was estimated using the gauge-to-gauge correlation. The rating equation was also applied to estimate extreme flood discharge during the flood events. Furthermore, the SCS curve number of the HEC HMS Model was applied to verify the peak discharge. This study analyzed the relationship between temperature and snow water equivalent (SWE) of the Melamchi catchment using regional equation (DHM, 2006) and then SWE was converted in to stream flow (Modi et al, 2022). The terrain processing and georeferencing technique in ArcGIS were employed to develop a flooded map and river cross sections using drone survey geo-tiff data tools. The obtained data were carefully examined, analyzed and validated as mentioned in following research flow (Fig. 2).

During post flood field observation, sample discharge in some river segments were measured using a current meter (area and velocity method). Beside it, river channel geometry, flood benchmarks at 8 different segments of the river from Dumbredovan to Bhemathang (as shown in Fig. 1) were observed to estimate the discharge in HEC-HMS model and ground truthing the results. The detail methods of regional flow estimation using HECRAS, and relationship of flood discharge with temperature induced melting (temperature-SWE- stream flow) are presented in below as follows.

2.3.1 HEC RAS modeling and flood discharge

A one-dimensional (1D) steady HEC-RAS model was used for flood analysis purpose (Basnet & Acharya 2019, Hicks & Peacock 2005, Shrestha et al. 2010). In this study, data for 8 cross sections was fetched from the field observation. The 1D is applicable for flow scenarios that vary gradually with time and distance. In the flow analysis study for different sub-basin, the continuity and momentum equations were applied (Eqs. 1 and 2).

$$Q = A*V \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\frac{\partial\left(\frac{Q^2}{A}\right)}{\partial x}+gA\left(\frac{\partial h}{\partial x}+S_f-S_0\right)=0$$

2

………………………

Where, A represents a cross-section area; Q is the water flow, *x* is a measured distance in the direction of the channel, g is the acceleration due to gravity, h is the height of the water level above the datum, S_0 is a slope of the river bed, and S_f is an energy slope.

The real time discharge of both events in Nakote hydrological stations was estimated using stage discharge relations of the following equations (Adhikari et al., 2000)

$Q = C*(h - a)^n$ ………………………(3)

Where, Q is a discharge (m^3/s), h is a water level height (m), a is a constant value representing the stage at zero discharge and C and n are coefficients. The theoretical value of probability is $p < 0.05$.

Peak discharge at Nakote station was estimated during flood events using the Soil Conservation Service (SCS) curve number (CN) method. The following mathematical equation (USACE, 2005) was used to estimate the peak discharge in Melamchi River

$Qp = (P - 0.2S)^2 / (P + 0.8S) * (1000 / CN - 10)$ ………..(4)

Where: Q_p is a peak discharge (m^3/s); P is a precipitation depth (mm); S is a potential maximum retention after runoff begins (mm) and CN is the curve number. The peak discharge (Q_p) takes into account the precipitation depth (P), potential maximum retention after runoff begins (S), and the curve number (CN) for the Melamchi River watershed.

2.3.2 Temperature, snow water equivalent and discharge

Pearson correlation was used to measure the correlation between daily mean temperature and snow water equivalents. The simple linear model was fitted with SWE and stream flow (Modi et al, 2022) to convert SWE to stream discharge of the Melamchi river using following equation (Eq. 5)

$Q = a_i\ SWE_i + b_i$……………………..(5)

Where, Q is the stream flow volume during summer months (June, July, August, Sept), i represents the SWE at a given date, a and b are the model coefficients which values are − 0.0021 and 9.693 in the region respectively. SWE is estimated using the snow depth of the region based on the following regional equation (DHM, 2006).

$SWE = 80.85 \times D + 658.47$…………….(6)

Where, SWE is snow water equivalent (mm), D is snow depth measured (m) and the values 80.85 and 658.47 is a coefficient values developed in the region.

3 Results

3.1 Precipitation extreme and Melamchi flood discharge

The Melamchi is a rain pocket zone with an annual average rainfall of the basin was 2609 mm in which Sermathang and Tarkeghang has the highest average annual precipitation showers of 3129 mm and 3452 mm, respectively during 1992–2021. During flood events, the cumulative precipitation of the basin found 102.58mm on June 15 which is lesser than the second flood event precipitation record i.e. 245.85mm. On June 10–14, the cumulative precipitation was higher compared to first flood event day. The Semathang (s1016) and Tarkeghang (s1058) contributed more rainfall with daily average rainfall of 26.8mm, 39.2mm and 61.4mm, 66.6mm on MF21st and MF21nd days respectively **(Supplementary I)**. Spatially, the precipitation patterns during flood months and event days are varied with higher in the central parts and lower in the upper and downstream regions of the basin (Fig. 3)

Figure 3 shows that the total precipitation was higher in July with a maximum of 1222mmyr^{-1} compared to June i.e. the maximum of 865mmyr^{-1}. In both months, heavy precipitation centralized in the central part of the basin instead of the upper Himalaya and lower region. During MF21st, the precipitation at Melamchi region seems lower compared to MF21nd day when the maximum precipitation was 66mm compared to 36mm on June, 15. The average river discharge during MF21st at Melamchi Bazar was 2892.7m^3/s which was 1105.21m^3/s on MF21nd day. In damming area i.e. at Bhemathang, the river discharge was found 357.2 m^3/s and 76.4m^3/s during both event days, respectively (Fig. 4)

The post flood measurement of discharge (Q = A*V) during field visit at the Chanaute and Bhaunepati sections of the Melamchi River found 17.5m^3/s and 66.75m^3/s, respectively which is considered as the non-flooding time normal discharge of the Melamchi River during monsoon season. During the both Melamchi flood event days, Chanaute (1861.9m3/s, 630.87m3/s) and Melamchi bazar (2892.7m3/s, 1105.21m3/s) area are highly affected. The flood plain area was largely expanded in middle section of the river mainly from Chanaute to Baunepati. The estimated river discharge contributed by eight different sub-basins in Melamchi river is considerable.

3.2 Rainfall and runoff relationship during flood events

The relationship between rainfall of the nearest station and discharge at Nakote on both flood event days are not well correlated (Fig. 5, 6**).** During first event, the maximum hourly rainfall 29.9mm was recorded on June-15, 5.05PM but the maximum discharge was 297.47m^3/s on June-16 at 10.05PM. Likewise during second event, the maximum hourly rainfall was 27.8mm on July-31,10.05AM conversely the maximum discharge was found 281.04m^3/s on Aug-1 at 8.05PM **(Supplementary II).** During raining at 5:05:00 PM, June 15, the corresponding discharge was found only 40.15m^3/s and constant until June 16 at 7:05:00 AM. The maximum discharge time at 10.05 PM, June-16, rainfall was surprisingly only 0.2 mm. At 12:05AM on 17th June, the rainfall again increased by 17.2mm and the corresponding discharge reached 296.24 m^3/s then after high discharge was maintained until a few hours. During MF21nd event, the corresponding discharge during the highest rainfall time at 10.05AM, July 31 was lower. After heavy precipitation at 5:05PM, July-31, discharge increased up to 281m^3/s 8:05:00 PM on Aug-1.

The rainfall and discharge are not coincided well because of heavy sediments and debris load until 4:05 PM, Aug-1. Afterward, the discharge corresponded well to the rainfall as shown in Fig. 5. In the MF21nd event, event based 10m interval peak discharge obtained from the HEC-HMS model showed 284.9m^3/s at11:05AM and followed by 118.9m^3/s at 4:05PM, August-2 when the rainfall was not much higher. Likewise, during MF21st, the peak discharge was found 7162.10m^3/s at 9.35PM, June-16 2021. However, the average daily discharge of the Nakote during June 15 and 16 were 22.12m^3/s and 161.8m^3/s, respectively.

3.3 Temperature and SWE to stream flow in the upper catchment

The average daily temperature of the area was – 2.08^{O}C with a minimum temperature of -16.45^{O}C during winter and 0.18m average snow depth was observed. The daily average snow water equivalent of the region was 672.45mm with a maximum range of 796.39mm. The relationship between daily snow water equivalent and temperature is reverse where lower temperature during winter has higher SWE and higher temperature during summer found lower SWE (Fig. 7). This reverse relationship indicates the higher snow water melting in response to higher temperature that can contributes flood in the region. The two peaks of SWE during summer in the figure indicates snow melting when the higher temperature initiates the snow melting process and increases the snow water of the region.

Table 2
Correlation between daily SWE and temperature in different seasons and snowmelt in response to baseline average temperature at Ganjala SnowAMP station

Season	**Snow Depth(m)**	**SWE (mm)**	**Tem (oC)**	**Correlation (r)**	**Snow melting**
Winter	0.15	670.82	-6.73	-0.18 (p = 0.089)	Negative
Spring	0.29	682.28	-3.76	-0.53 (p = 0.001)	Negative
Summer	0.13	668.96	2.95	0.09 (p = 0.32)	Positive
Autumn	0.15	670.47	-2.74	-0.52 (p = 0.0007)	Negative
Baseline Average	0.18	673.03	-2.08	4.07mm of SWE (0.5m snow depth) was melted during the Summer	

The higher temperature during summer has positively correlated with SWE. In response to baseline average temperature changed from – 2.08 to 2.95^{O}C, 4.07mm SWE and 0.5m snow depth was decreased from the catchment by melting which is equivalent to 9.68m^3/s river discharge. Except in the summer season, all the seasons showed negative correlation in between temperature and SWE. During winter, the temperatures are lower but higher the snow depth and snow water equivalent but instead during summer the temperature increased but snow depth and SWE decreased that indicates that snow was melted and converted to stream flow during summer. The daily and seasonal relationship shows that snow water equivalent is fluctuating in response to temperature change in the basin. Both of the snow melting and snow formation mechanism in the Himalayan basin affects to the downstream flow and discharge of the river.

4 Discussion

4.1 Melamchi flood extreme and climate change

Climate change increases the frequency and intensity of extreme precipitation event and associated rises in temperature which ultimately trigger hazards like cloud bursts, flash floods and retreating snow and increases the volume of snow water equivalent (IPCC 2013). The Melamchi extreme flood of June 15 and the following days were attributed to several multiple anthropogenic and climate factors (Maharjan et al. 2021). As the Melamchi region is located on the windward side, it is a pocket area for high precipitation in Nepal. The average annual precipitation of the Melamchi basin found 2609.8mm during 1992–2021 which is higher than the national average precipitation of 1857.6 mm (DHM 2021). The maximum average rainfall during flood days (June 15, July 31) and Months (June and July), 2021 was 39mm, 66mm and 865mm, 1222mm respectively which is more intense than the national average monthly and daily records (Karki et al. 2018). The cumulative effects of sub-basin rainfall especially higher rainfall of Tarkeghang and Sermathang were most cited for flood alert worked for Melamchi disaster (NDRRMA 2021). As experienced in the Melamchi flood, the intense rainfall initiates the landslide, damming and comprehensive flood composite in the Himalaya (Talchabhadel et al. 2023). The average annual temperature in Himalayan regions is increasing in trends. In Nepal, temperature has increased at the rate of 0.06^{o}Cyr^{-1} (Shrestha et al. 1999); 0.04^{o}C yr^{-1} (Sharma KP 2009), 0.03^{o}C yr^{-1} (CBS 2016), 0.03^{o}C yr^{-1} (Baniya et al. 2018) which effects on hydrological regime and triggered flood hazard mainly in the Himalaya. In Melamchi Bazar, the average river discharge on MF21st and MF21nd found 2892.7m^3/s and 1105.21m^3/s, respectively contributed mainly by Melamchi, Kiwil and Chanaute sub-basin.

The higher sub-basin flow contribution shows landslide river damming and GLOFs were not only responsible for Melamchi flood. Landslide damming was expected on 6-7PM, June 15 due to a sudden water level decrease from 4.7m to 3m at Nakote (DHM 2021). On the other hand, debris deposition of 8-10m with large terrace profile of the river having 1717.86m length and 556.7m width at Bhemathang observed from drone images (NDRRMA/World Bank 2021) supports that the river was dammed by a landslide at Bhemathang: upstream of the Melamchi river. However, the dam breaching discharge is still lower than regional flow contribution. The landslide damming at Bhemathang was observed for a few hours only considered as a minor blockage. A minor blockage scenario gives a peak debris discharge

(Costa 1988). The estimated basin discharge of the Bhemathang (damming area) during both flood events were 357.2m^3/s on June 15 and 76.4m^3/s on July 31 (Table 1) respectively which supports that regional flood contribution due to cloud burst was higher than the flood originated from LDOF and GLOFs. Drone images of flooded zones also supports that the river was temporary damming at Bhemathang section and breached due to river cutting, erosion and cloud burst. Consequently, large sediment was carried and deposited at the downstream regions. The middle section mainly in Chanute and Melamchi Bazar are highly affected. Altogether, 215 households in Helambu (upper section of the river) and 286 households in the Melamchi (lower section of the river) region were flooded **(Supplementary III).** In many places, debris cover in the river was more than 10m including 16m debris accumulation in Melamchi Bazar (Dahal et al. 2021).

4.2 Nexus between rainfall-runoff and temperature

The precipitation is the direct factor and temperature is the indirect factor of flood initiation and extending their hazards in the Himalayan basin in Nepal. Many literatures showed that the Melamchi flood is multifaceted and cascading in nature which has associated with several climatic, topographic, geologic and anthropogenic factors (Dahal et al. 2021; Talchabhadel et al. 2023; Pandey et al. 2021). However, precipitation is one of the main actors and alongside an auxiliary factor initiating the Melamchi flood which are also supported by precipitation extreme in Tarkeghang and Sermathang (Fig. 3), regional flow contribution (**Table 1**) and rainfall and runoff relationship (Figs. 5 & 6). The rainfall and runoff relationship in Nakote during both flood times showed that river damming, sediment load or debris flow also affected the discharge of the river rather than only cloud burst. At MF21st, river damming at the beginning and high sediment load in MF21nd lowered discharge of the Melamchi river. After damming breached during MF21st and high sedimentation in MF21nd, the discharge was increased and well coincided with rainfall (Figs. 5 & 6). River damming in Bhemathang (NDRRMA 2021) and high sedimentation during the flooding (Dahal et al. 2021) was expected through the observation of drone survey images and post-flood field observation. A sudden increase of discharge at Nakote i.e by 297.47m^3/s on June 16, 10.05PM without heavy rainfall also supports river damming and bursting at Bhemathang during flood time. The increased sediment deposition can reduce the capacity of river channels and peak flood discharge. Generally, the sediment transported fluvial discharge has linked to minor blockage (Costa, 1988), landslide and river bed alteration (An et al, 2022). The study has found that 16.9 million m^3 at Bhemathang and 70.1 million m^3 sediment at Melamchi Ghyang to Melamchi Bazar were deposited (NDRRMA 2021) which altered the original channel and river flow in the river.

During 2017 records (best available hourly data), the average daily snow depth and SWE at the upper region of the Melamchi found 0.18m and 672.45mm, respectively. During summer, snow depth and SWE has decreased by melting and contributed to stream flow (**Table 3**). Snow depth measurements provide an estimate of the snow water equivalent i.e. the depth of water produced from melting the snow for use in predicting the runoff (DHM 2006). The daily correlation shows that water equivalent has lower in higher temperature and higher in lower temperature time (Fig. 7) which indicates that higher temperature accelerates snow melt and loss through runoff in the river. In the Himalaya catchment, the snow model on climate sensitivity also showed a decrease in SWE with increasing temperature (Stigter et al. 2016). In the Himalayas, snow melts i.e. higher snow water equivalent in the region increase the water level of the glacial lakes and suddenly burst (DHM 2006). The Melamchi River has also recharged by melting water and supported the breaching of glacial lakes predicted in the upstream of the Melamchi river, however, the lake area is very small which is less than 0.003km^2 (Maharjan et al. 2021). The topographic map of the Survey Department, 1996 also confirms the two glacial lakes in the same region in Pemdam Khola, due to smaller size and very low expansion rate, which does not count as potential hazardous lakes (Bhajracharya et al. 2020). During summer, the snowmelt contribution to total runoff is significant (Li et al. 2017, Modi et al, 2022). Thus, whole region is highly vulnerable to snow melting during summer or high temperatures period. It is curious that snowmelt and runoff in response to temperature can lead to shifting timing, extend and magnitude of flood (Fang et al. 2022).

4.3 Uncertainty and validation

Melamchi-Indrawati watershed belongs to mountain terrain where plenty of hydro-meteorological stations are not available. The best available hourly data for temperature and snow depth were found only for 2017 at Ganjala Pass SnowAMP station located at 4962masl. The accuracy of the snow depth measuring instrument SR50AT-316SS in the SnowAMP has ± 0.01m. The regional equation (DHM 2006) of snow water equivalent particularly used in same region was used and regression model in between discharge and SWE was fitted to find out the a and b coefficient values in the region. The correlation between rainfall and runoff in the Himalayan River also have fluctuated due to high slope variation, sediment load, land use land cover practices, landslide damming outburst and glacial lake outburst flood. The obtained results and model parameters were validated using a one-week (June 15–22, 2021) long post-flood field visit in 8 different cross sections of the river. The fine resolution drone survey orthomosaic images and geo-tiff GIS data provided by NDRRMA; the Government of Nepal were also used (Fig. 8).

In this region of Melamchi Bazar, discharge and regional flow estimated by HEC-HMS model were also higher during both flood events (**Table 1**), high debris deposition and observed one of a severely affected area where more than 286 households in Melamchi (lower region) and 215 households in Helambu (middle region) were flooded (**Supplementary III**). The post flood field observation on same sites also supports to the results of flood severity.

In HEC RAS model 20m DEM was used in RAS mapper environment to develop required stream channels cross-sections, sun-basin layer and geometric file. According to field observed river's slope, water depth, and channel width in different cross-section points are utilized to determine the Manning's value. Manning's roughness coefficients, boundary conditions, extreme flood water levels in the downstream of Melamchi bazar were used to run the HEC RAS model. The calibrated SCS curve number method and HEC HMS model were validated using long-term observed discharge data from the Nakote station. The parameters of the model were adjusted iteratively to achieve the best fit between the simulated and observed streamflow. The curve number (CN) is a parameter which is used to estimate the amount of runoff generated from rainfall. The method uses the soil’s permeability, land use and moisture condition to determine the curve number which ranges from 0 to 100. In pre-monsoon season, CN numbers of 77 were found, a higher number indicating less infiltration and more runoff. The SCS curve number method and observed discharge of the Nakote hydrological stations were used to validate the peak flow.

5 Conclusion

This study has investigated Melamchi's extreme flood occurred on June 15 and reoccurred on July 31 and its close nexus with climate variability mainly precipitation and temperature in the Himalayan basin. The average annual rainfall of Melamchi region is found exceeded than national average rainfall during 1992–2021. During flooding, the cumulative rainfall of the basin was 102.58mm on June 15 and 245.85mm on July 31, 2021 in which Sermathang and Tarkeghang are the biggest rainfall showers. The average daily river discharge during the MF21st event at Melamchi bazar was 2892.7m^3/s which was 1105.21m^3/s on MF21nd event. The sub-basins such as Kiwil, Chanaute and Melamchi region contributed more discharge to the river during both event days. Landslide damming at Bhemathang was also expected due to the sudden water level decrease at Nakote at 6-7PM, June 15 and drone image records of a large sediment terrace setup. However, the daily average discharge at Bhemathang was 357.2 m^3/s and 76.4m^3/s on first and second flood event days respectively, which is lower than the sub-basin flow contribution. Rainfall-runoff at Nakote during both flood events showed poorly correlated due to dam breaching, high sediment transport, land use practices and human development activities. The 10m interval peak discharge at Nakote was found 7162.10m^3/s and 284.9m^3/s during first and second event days, respectively. The increased temperature response to higher melting and decreased SWE. The daily average snow water equivalent in the upper region of the basin was to be found 672.45mm with a maximum snow depth of about 1.71m which is very sensitive to increased temperature. During summer, the total snowmelt contribution to river discharge was found 9.68m^3/s in the Melamchi River. Thus, precipitation is a main and temperature induced snow melting is an auxiliary driver of the Melamchi flood.

Declarations

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Author contribution

Baniya Binod: Conceptualization, research design, data analysis, writing original draft, review and editing. Tang Qiuhong: Conceptualization, research supports, data analysis, review and editing. Adhikari Tirtha: data analysis, review and editing. Zhao Gang: review and editing. Gebremedhin Gebremeskel Haile: review and editing. Li He: data analysis, review and editing. Ram Prasad Awasti: data analysis, review and editing.

Data availability

The data is not made openly accessible. It is available for the interested researchers upon on corresponding author.

Conflict of Interest

The authors declare no conflicts of interest.

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Figures

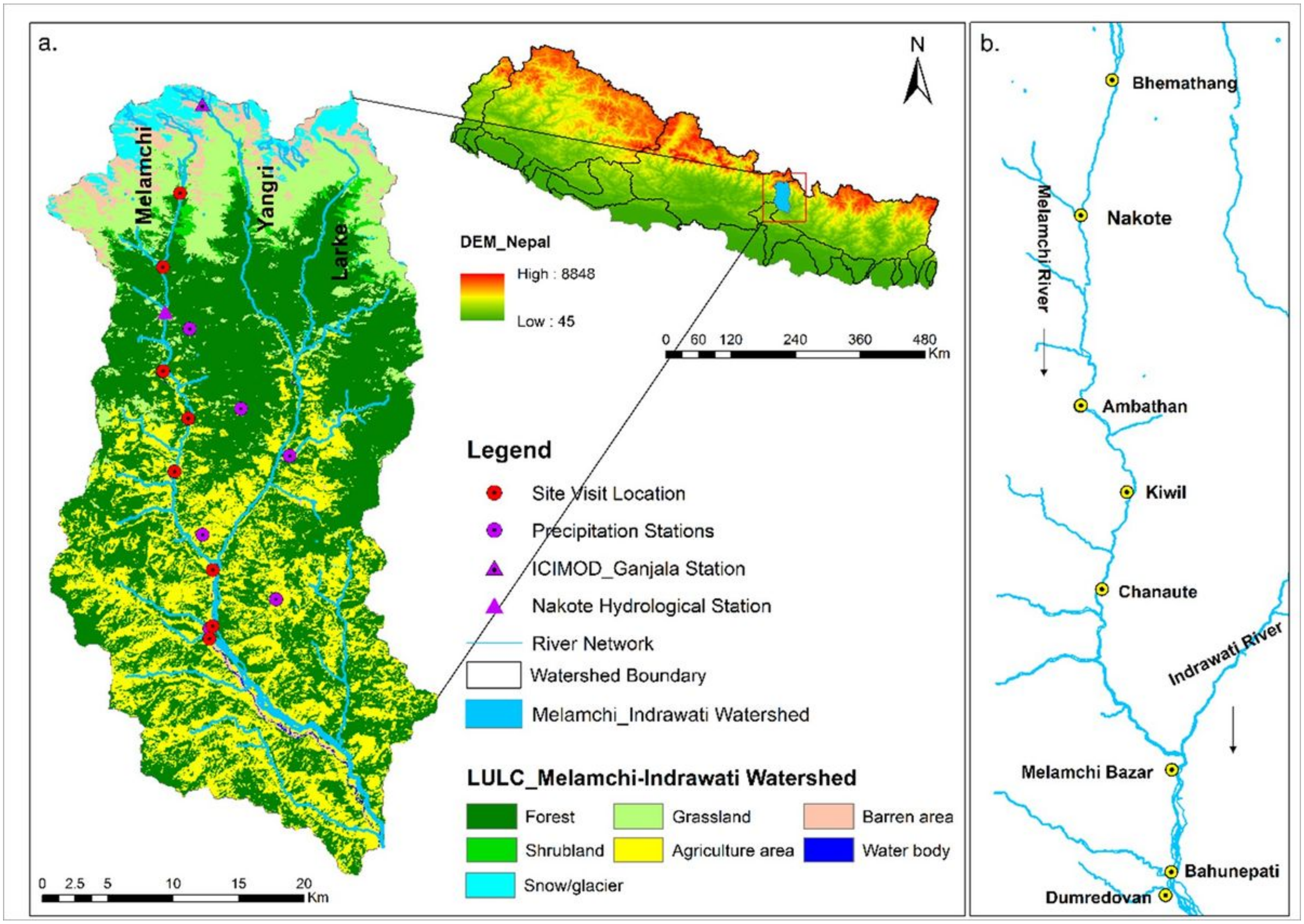

Figure 1

Study area map; a) Melamchi-Indrawati watershed locating hydro-meteorological stations, field visited sites and DEM (30m SRTM) in Nepal and b) Flood channel boundary and name of field visit sites from Bhemathan (upper section) to Dumredovan (lower section)

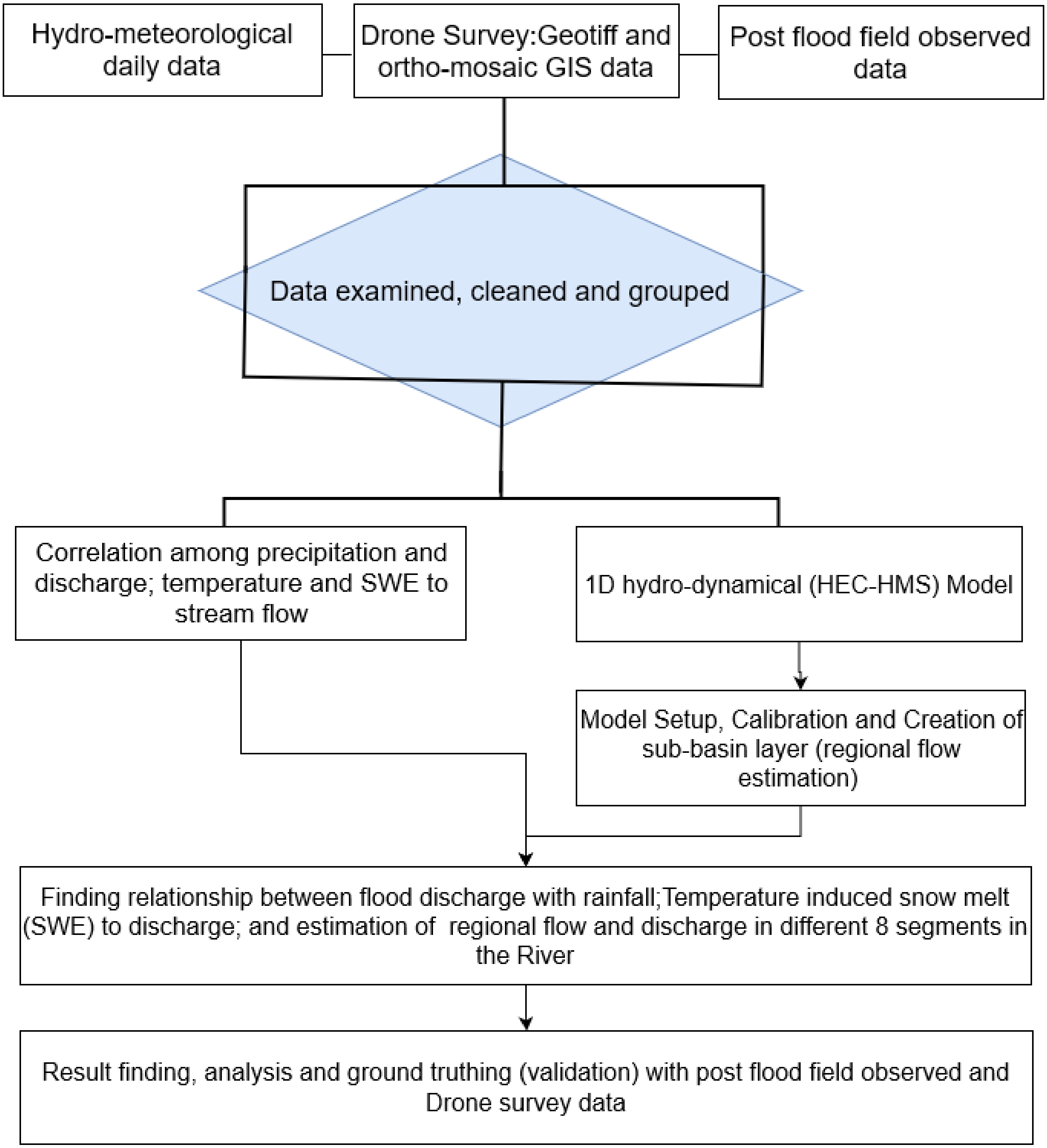

Figure 2

Research flow and methodological framework used in this study

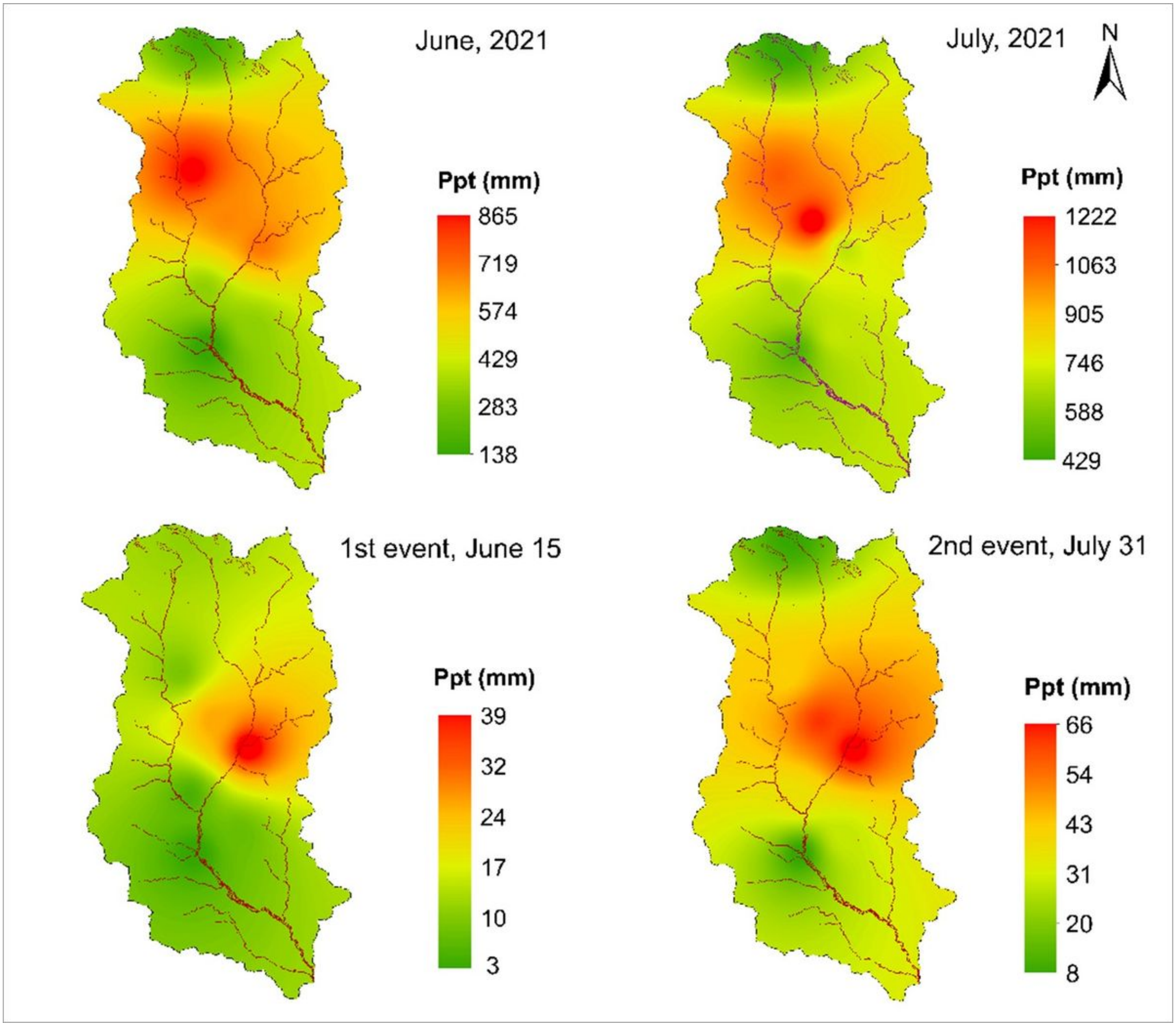

Figure 3

Spatial rainfall distribution in the Melamchi-Indrawati basin; cumulative precipitation in June-2021; July-2021; June 15 (MF21st) and July 31 (MF21nd) event day in the basin; Ppt: precipitation.

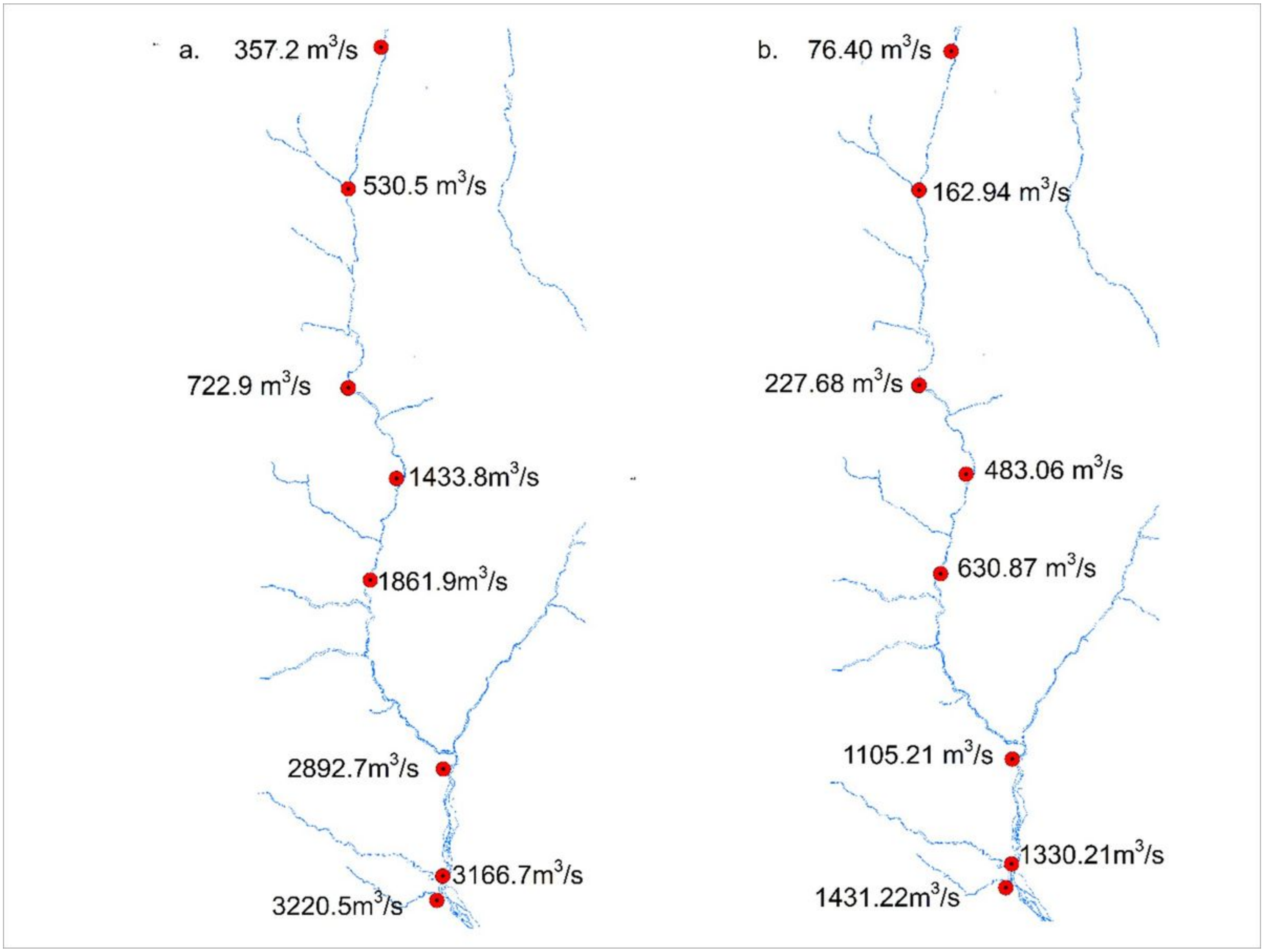

Figure 4

Regional contribution and accumulated discharge in different river section obtained from HEC-HMS Model during both a. June 15 (MF21st) and b. July 31 (MF21nd) flooding events day in the Melamchi River.

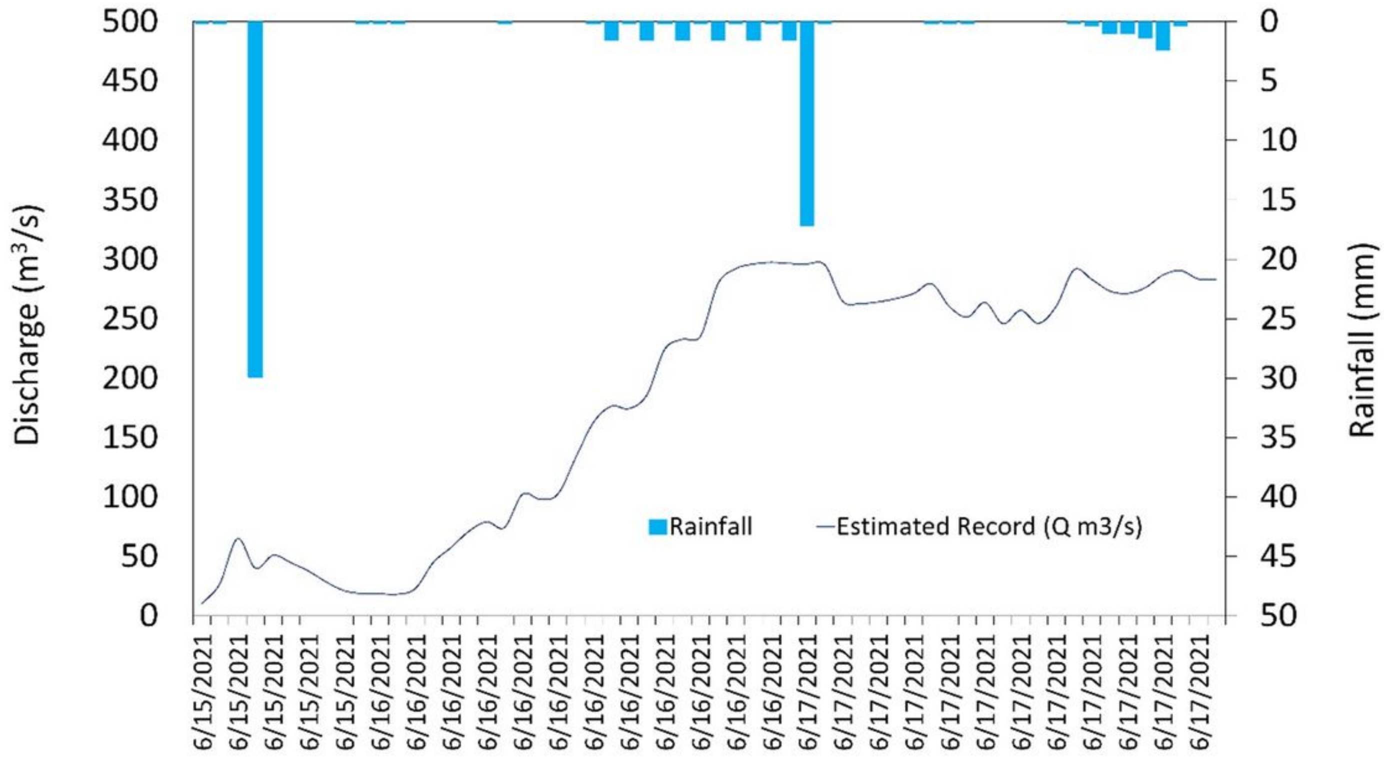

Figure 5

Relationship between hourly rainfall (mm) and discharge(m^3/s) at the Nakote during MF21st event from June 15, 2:05:00 PM to 17, 11:05:00 PM, 2021

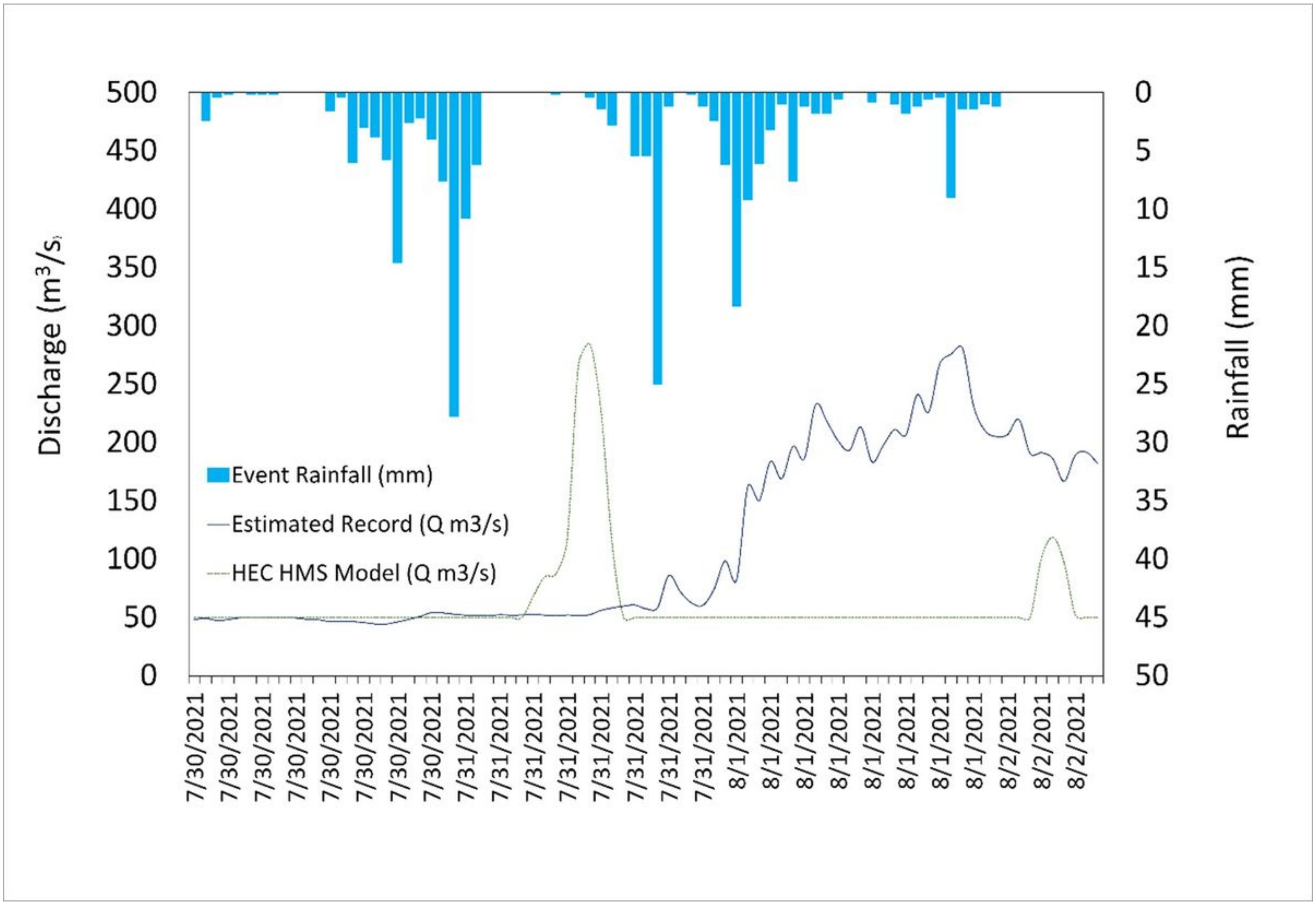

Figure 6

Relationship between hourly rainfall (mm) and discharge(m^3/s) of the Nakote during MF21nd event from July 30, 11:05:00 AM to August 2, 9:05:00 AM, 2021; blue line represents the model peak discharge at 10m interval of Nakote.

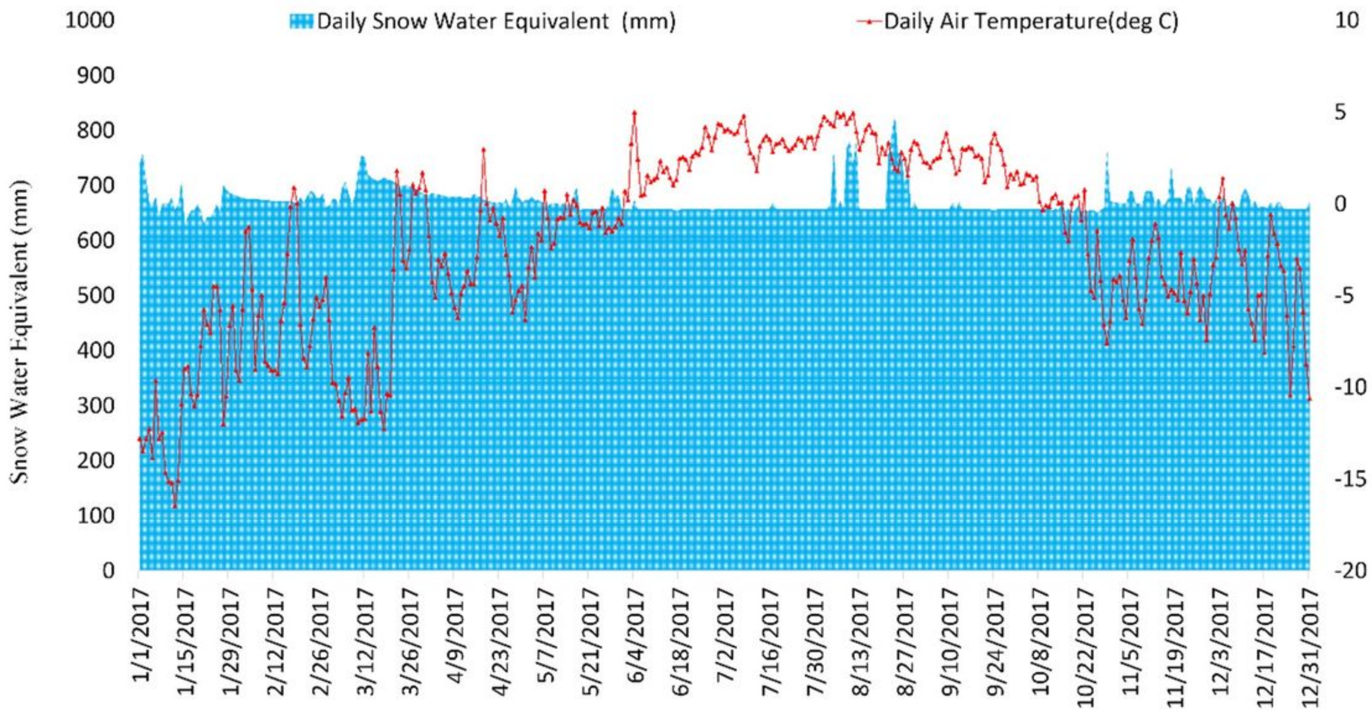

Figure 7

Relationship between daily temperature and snow water equivalent in Ganjala SnowAMP station located at 4962m altitude of the Melamchi watershed

Figure 8

3D view of Melamchi bazar flood inundation obtained from geo-tiff data of drone survey, 2021; drone survey by DJI drone of NDRRMA on August-2, 12.00PM

Supplementary Files

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