

Glacial Lakes Outburst Floods (GLOFs) modelling of Thulagi and Lower Barun Glacial Lakes of Nepalese Himalaya

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ABSTRACT

Melting of glaciers is one of the major effects of recent atmospheric warming in the Himalayas which results in the development of supraglacial lakes that coalesce to form proglacial lakes. Large volumes of water in these lakes are considered dangerous due to its unstable surrounding geomorphology. Most of the proglacial lakes are moraine-dammed and breaching of such moraine due to some triggering events may give rise to rapid release of water and sediment, often termed as Glacial Lake Outburst Floods (GLOFs). GLOFs represent catastrophic phenomenon of the Himalaya and pose a risk to downstream communities and infrastructure. Several GLOF events have been recorded in Nepal in the past few years. Since 1990s, the lake area of Thulagi has increased from 0.72 to 0.94 km² while that of Lower Barun has increased from 0.64 to 2 km² and both glacial lakes rank No. 1 in the Potentially Dangerous Glacial Lakes (PDGLs) in Nepal. In this study, NWS-BREACH and HEC-RAS model are used to assess the impact of GLOF on downstream areas. Different dam breach scenarios of 5, 10, 15 and 20 m is evaluated by NWS-BREACH model to estimate the breach hydrograph. The peak flow at the time of breach ranges from 1400 to 5400 m³/s for Thulagi and 2600 to 7900 m³/s for Lower Barun in low and high breach scenarios respectively. The peak flow estimated from NWS-BREACH is used for the flood routing in HEC-RAS to simulate peak discharge and flood height at different distances in the downstream from the lake outlet. The impact on downstream regions of the two glacial lakes is then evaluated by flood inundation map to assess the land exposed to GLOF. Nepal consists of large number of glacial lakes and only a few have been studied. Furthermore, detail field survey of the lakes and downstream areas need to be incorporated for better prediction of GLOF events.

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1. Introduction

Glaciated regions are highly sensitive to climate change [1–7] and as a result are receding in most parts of the world. However, they respond to climate change on a range of time scales usually a few decades to a century [8,9] and so are good indicators of climate change. In the past decade, the research on Himalayan glaciers has greatly improved along with which the spatiotemporal frequency and magnitude of changes in Himalayan glacial lakes have also been documented [10]. Through high emission scenarios driven projections of climate model, it has been found that 65% of ice mass of High Mountain Asia (HMA) will be lost by the end of this century [8]. This could result in an increase in the size and number of supraglacial and proglacial lakes which coalesce to form bigger glacier lakes behind the loose moraine [11,12]. GLOF consists of mixture of water and sediment which are capable of travelling tens of kilometers to more than 100 km at velocities exceeding tens of kilometers per hour and

cause serious threat with their sudden outburst due to their high magnitude discharge and long runout distance [12]. This causes loss of life and properties in the downstream regions.

According to ICIMOD [13], currently there are over 2070 glacial lakes in Nepal which were mostly formed during the second half of the 20th century as a response to increasing temperatures. Out of these 2070 glacial lakes, 21 are identified as Potentially Dangerous Glacial Lakes (PDGLs) which includes Thulagi and Lower Barun. Both of these lakes rank I in the PDGLs. Lower Barun has high hazard and high risk whereas Thulagi has moderate hazard but high risk [14]. Thulagi Glacial Lake is considered hazardous due to potential mass movements into the lake, erosion and enlargement of the outlet and presence of Tal village, major trekking route and three hydropower plants in its downstream. Lower Barun Glacial Lake is one of the largest, deepest and rapidly growing lakes in Nepal which holds large volume of water (i.e. 112.3×10^6 m³) and could also expand 25% by 2025 [10]. The risk associated with this lake is the presence of Upper Barun Lake as seen from satellite images and its unstable outlet channel. This glacial lake lacks field observation as the first reported observation was the bathymetric measurements carried out in 2015. So, this work could serve as a base for future works.

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Evaluating the dimensions of an expected flood serves to inform preventive measures. For quantitative assessment of GLOFs, hydraulic flood models are valuable tools and are also a major part in assessing GLOF hazard and planning for preventive measures [15]. In this study, GLOFs are modelled using NWS-BREACH and HEC-RAS 2-D models as these are open source models which have been successfully used in modelling GLOF inundation in previous studies [3,16–21]. Very few two dimensional (2-D) hydrodynamic models have been used to understand the hydraulic flow behavior of these events [20]. The HEC-RAS 2-D model is able to simulate GLOF characteristics i.e. multi-channel and multi-directional flows [22]. Along with this, it requires less computational effort in solving and calculating inundation depth and travel time which is a useful tool for estimating lower limit for the risk that a GLOF represents to downstream communities.

Flood hydrograph is an important input parameter which shows discharge per unit time. In this study, NWS-BREACH model, developed by National Weather Service (NWS) of United States is used to estimate the GLOFs hydrograph. It is a mathematical model for predicting the breach characteristics (size, shape, time of formation) and the breach outflow hydrograph. The model is physically based on the principles of hydraulics, sediment transport, soil mechanics, the geometric and material properties of the dam and the reservoir properties [23]. After deriving GLOF hydrograph from NWS-BREACH model, flood propagation in the downstream areas are simulated using two dimensional (2-D) capabilities of Hydrologic Engineering Center's River Analysis System (HEC-RAS) version 5.0.6. It is a hydrodynamic model developed by the US Corps of Engineers. HEC-RAS flood routine algorithm is used to generate the inundation map to determine the extent of flooding caused by GLOF in downstream region.

The aim of this study is to estimate peak flow in different dam breach scenarios, flow volume, depth at different sections and to prepare flood inundation map downstream of Thulagi and Lower Barun Glacial Lakes. In order to do this, satellite images is used to evaluate the lake area change and NWS-BREACH model is used to estimate the peak flow. Further, inundation map with flood volume and depth is used to evaluate GLOFs impact downstream.

2. Study area

Thulagi and Lower Barun Glacial Lakes ranking I in PDGLs [13] are both fed by temperate glaciers located on the Southern flank of the Himalayan range (Fig. 1). They are both located in the south of the Tibetan Plateau and adjacent to two of the world's highest mountain range i.e. Manaslu (8th highest) and Makalu (5th highest) respectively. Both of these glacial lakes are dammed by ice-cored moraine [24].

Thulagi Glacial Lake, locally known as Dona Tal, is located in western Nepal at 28°29.24'N latitude and 84°29.17'E longitude at an altitude of 4050 m a.s.l [10]. It is the headwaters of Dona Khola which is a tributary of the Marsyangdi River. The lake lies at the terminus of ~4.5 km long debris-covered Thulagi Glacier to the southwest of Mount Manaslu. There is a possibility of rock avalanche from vertical mountain slope on the right moraine about 1.5 km from the lake outlet. The Marsyangdi River is also the site of major hydropower projects such as Upper Marsyangdi (Bhulbule and Nadi), Middle Marsyangdi (Lamjung) and Lower Marsyangdi (Khaireni) and also a major trekking route.

Lower Barun Glacial Lake is located in eastern Nepal at 27°47'N latitude and 87°05'E longitude at an altitude of 4550 m a.s.l [10]. It is located

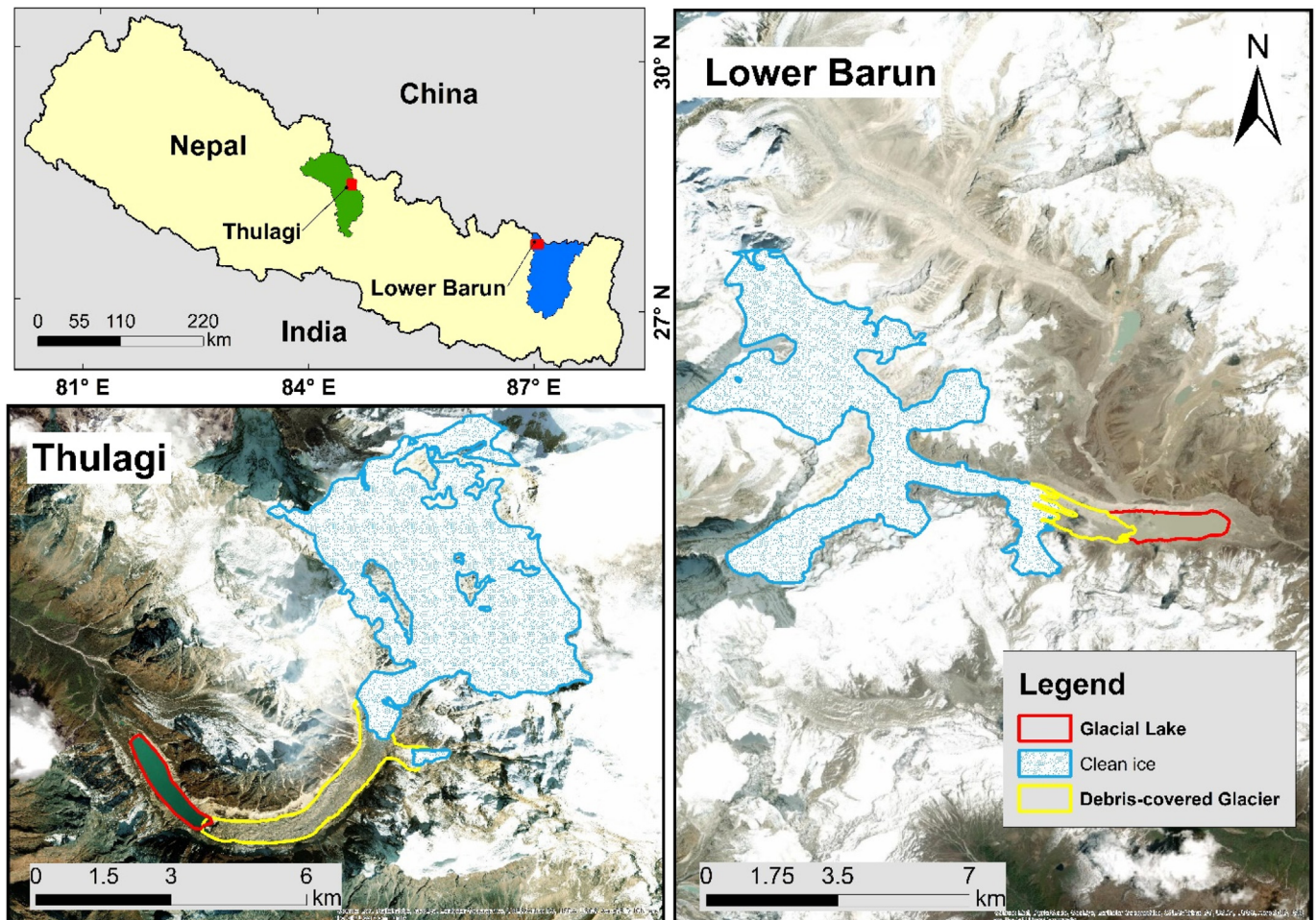


Fig. 1. Map of study area showing Thulagi Glacial Lake of Marsyangdi Basin and Lower Barun Glacial Lake of Arun Basin.

Table 1
Landsat data used for mapping glacial lake area change.

Thulagi Glacial Lake	Lower Barun Glacial Lake	Sensor	Spatial resolution (m)
20 November 1988	9 November 1989	Landsat 4-5 TM	30
26 September 2000	23 November 2000	Landsat 4-5 TM	30
19 December 2010	5 December 2010	Landsat 4-5 TM	30
25 December 2018	25 November 2018	Landsat 8 OLI/TIRS	30

southeast of Imja Glacial Lake in the upper reach of Barun River and adjacent to the mountain range of Mount Makalu. The lake lies at the terminus of ~2.7 km long debris-covered Lower Barun Glacier to the west and is dammed by ice-cored moraine to the east. There is a consistent calving of the glacier terminus into the moraine-dammed proglacial lake as seen from images of the lake along with possibilities of rock and ice avalanches from vertical mountain slope on right side of the lake. There is also possibility of cascading effect caused by lake burst from couple of lakes in the upper catchment which might increase the water volume of the lake. The glacial lake feeds into Barun River along which there is a major trekking route to Makalu Base camp and Barun Valley.

3. Materials and methods

3.1. Materials

The materials required to carry out GLOF modelling are satellite images (i.e. Landsat) and ALOS PALSAR Digital Elevation Model (DEM). The Landsat images were acquired from the website of United States Geological Survey (USGS) (<https://earthexplorer.usgs.gov/>). The Landsat images were used to map the changes in glacial lake area of Thulagi and Lower Barun Glacial Lake. Multi-temporal Landsat images of the year 1988, 1989, 2000, 2010 and 2018 were used in this study. These multi-temporal images were obtained from the data of Landsat 4-5 TM (Thematic Mapper) and Landsat 8 OLI/TIRS (Operational Land Imager/Thermal Infrared Sensor). Most of the precipitation occurs during monsoon (i.e. June to September) in Nepal as it lies in a monsoon dominated region. Due to high precipitation and cloud cover during this season, the images of the dry season were selected with a minimum of 10% cloud cover. The different Landsat satellite images used for glacial lake area change detection are mentioned in Table 1.

DEM (Digital Elevation Model) with high spatial resolution and coverage are available worldwide. Advanced Land Observing Satellite's (ALOS)

Table 2
Input parameters used in GLOF modelling.

	Units	Thulagi Lake	Lower Barun Lake
Moraine Dam Data			
Surface area of glacial lake	sq. km	0.94	2
Volume of water in glacial lake	m ³	36.1 × 10 ^{6a}	112.3 × 10 ^{6a}
Maximum depth of lake	meter (m)	76 ^a	205 ^a
Top elevation of dam	meter (m a.s.l.)	4056 ^d	4569 ^d
Toe elevation of dam	meter (m a.s.l.)	3864 ^d	4441 ^d
Width of dam crest	meter (m)	20 ^{b, c}	15 ^b
Length of crest of dam	meter (m)	305 ^c	930 ^b
Maximum height of moraine dam	meter (m)	67 ^c	128 ^b
Slope of upstream face of dam	1:z	1:4.5 ^c	1:6 ^b
Slope of downstream face of dam	1:z	1:5 ^c	1:8 ^b
Dam Material Properties			
Grain size (D ₅₀)	millimeter (mm)	20 ^c	20 ^c
Porosity	%	30 ^c	30 ^c
Cohesiveness (c)	kN/m ³	0 ^c	0 ^c
Internal friction angle (ϕ)	degree	35 ^c	35 ^c

^a Haritashya et al. [10].

^b ICIMOD [13].

^c ICIMOD [3].

^d ALOS PALSAR DEM (12.5 m).

mission Phased Array type L-band Synthetic Aperture Radar (PALSAR) yielded detailed observation of all-weather from day to night and repeat-pass interferometry from 2006 to 2011. PALSAR was one of the three instruments on the ALOS-1 that was developed to contribute to the fields of mapping, precise regional land-coverage observation, disaster monitoring and resource surveying. It was the mission of Japan Aerospace Exploration Agency (JAXA). The ALOS PALSAR DEM was accessed through 11 November 2015 from the website of Alaska Satellite Facility (<https://www.asf.alaska.edu/sar-data/palsar/>) and is of 12.5 m resolution.

3.2. Methods

3.2.1. Glacier and glacial lake mapping

Landsat images were used to analyze the variations of the Thulagi and Lower Barun glacial lakes along with their connecting glaciers (Table 1). The extent of the glacial lake and glacier were manually identified and digitized by using false-color composition of the image. Google earth images were also used as a guide to verify the interpretation results.

3.2.2. GLOF modelling

To carry out GLOF modelling, surface area of glacial lake, maximum depth of lake and the volume of water in it is required as input parameters. Along with these different characteristics of dam such as top and bottom elevation of dam, width of dam crest, its maximum height and slopes of the faces of dam plays an important role in determining the flow hydraulics over dam. The material properties of the dam affect the rate of erosion of dam material and so these are also taken as input parameters [22]. Table 2 summarizes the input parameters used in GLOF modelling of Thulagi and Lower Barun Glacial Lake. Fig. 2 shows the research design followed in this study to carry out GLOF modelling.

3.2.3. NWS-BREACH model for estimating peak discharge and dam breach hydrograph

Physically based models combine key hydraulic, structural and geotechnical properties, often simultaneously with empirical values and coefficients, to analytically or numerically predict the breaching process for an embankment. The main advantage of these is the increased accuracy. As

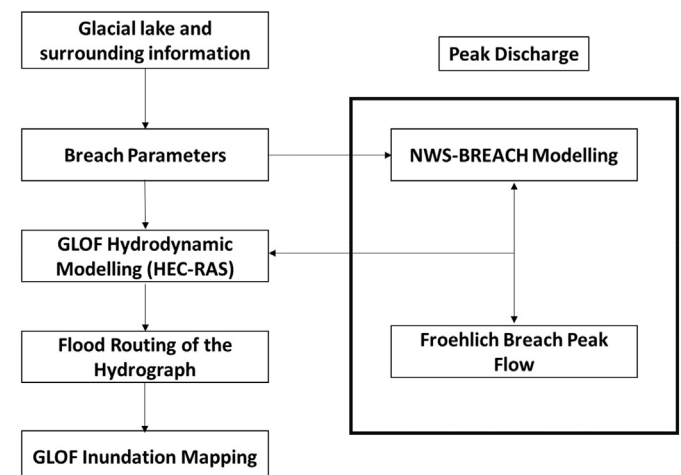


Fig. 2. Research design for GLOF modelling.

Table 3
Glacial lake area change.

Thulagi		Lower Barun	
Date	Area (sq. km)	Date	Area (sq. km)
1988	0.72	1989	0.64
2000	0.89	2000	1
2010	0.93	2010	1.59
2018	0.94	2018	2

of 2014, HEC's guidance on carrying out dam break studies recommends the use of physically based models where appropriate for determining breach characteristics, rather than parametric models [25,26].

A mathematical model, NWS BREACH model, have been used in this study for predicting the breach characteristics (size, shape, time of formation) and the breach outflow hydrograph. The model is physically based on the principles of hydraulics, sediment transport, soil mechanics, the geometric and material properties of the dam and the reservoir properties. It is developed by coupling the conservation of mass of the reservoir inflow, spillway outflow, and breach outflow with the sediment transport capacity of the unsteady uniform flow along an erosion- formed breached channel. The growth of the breach channel is dependent on the dam's material properties (D_{50} size, unit weight, friction angle, cohesive strength). For GLOF modelling, overtopping failure of the moraine dam has been carried out where a sudden collapse of the dam's upper portion in the proximity of breach development may result in the sudden enlargement of the breach. The collapse occurs due to the pressure of water on the dam's upstream face exceeding the stabilizing forces of soil shear and cohesion. When this occurs, the breach erosion ceases until volume of collapsed wedge is transported through breach channel at the same transport rate prior to collapse. The outflow hydrograph was then obtained through a time-stepping iterative solution which is clear of numerical stability or convergence difficulties [23].

3.2.4. Froehlich's model

In the past many empirical equations have been applied to estimate peak discharge from natural dam failures. Empirical formulae is the simplest approach to modelling dam-break [22] which are developed through the regression analysis of historical dam failure data [26]. Output of these equations usually comprises of peak discharge and dam failure time. In this study, we used the Froehlich's equations [27] as they have low uncertainty compared with other approaches such as MacDonald and Langridge-Monopolis equation [26,28,29]. This empirical equation requires volume at the time of outburst in m^3 (V_w), depth of water above the breach invert at the time of failure in m (h_w) and height of breach (h_b) as input parameters. The peak discharge (Q_p , m^3/s) and time of dam failure (t_p , h) were estimated as follows [27]:

$$Q_p = 0.607 V_w^{0.295} \times h_w^{1.24} \quad (1)$$

$$t_p = 0.00254 V_w^{0.53} \times h_w^{-0.9} \quad (2)$$

It was assumed that the flow reaches its peak discharge following a linear rise before decreasing to m^3/s with a same time span of rising. The parametric model uses empirical observations of previous dam failures such as breach width-depth relation, time of breach formation and breach depth to develop outflow hydrograph. However, observations of such parameters are not existent in moraine dams, rendering the parametric approach infeasible. In regard to this, the breach erosion model has some advantages over the parametric breach model since the critical properties used by the model are measurable or can be estimated within a reasonable range from a qualitative description of dam materials. So, the result from Froehlich's model was used only as a base to compare the result from NWS-BREACH model.

3.2.5. Hydrodynamic modelling of GLOF using HEC-RAS model

After deriving GLOF hydrograph, the nature of propagation of flood in the downstream areas of the lakes were simulated using two dimensional (2-D) capabilities of Hydrologic Engineering Center's River Analysis System (HEC-RAS) developed by the US Corps of Engineers. It can simulate multi-directional and multi-channel flow which are dynamic characteristics inherent to GLOF [22]. ALOS PALSAR DEM was used to create a terrain model to set up for modelling and mapping. 2-D unsteady flow calculations were then carried by providing upstream boundary conditions as estimated dam-breach hydrographs from NWS-BREACH model and downstream boundary conditions as normal depth or energy slope. Manning roughness coefficient (n) of 0.15 for both channel and floodplain was considered as Manning (n) values in the Mount Everest region were also estimated with values of 0.10–0.16 and 0.20–0.30 for the channel and floodplain respectively [29–31].

The performance of unsteady flow simulation was carried out to observe peak flow propagation, flood inundation extent and flood water depth. Manning roughness coefficient introduces uncertainty in modelling and was considered in sensitivity analysis. Finally, the flood simulation results were obtained which was then used to analyze potential impact of GLOFs on downstream areas. The potential flood stage, flood wave travel time, time to peak flood stage and their corresponding water surface elevations in downstream areas were the results obtained from flood routing using HEC-RAS. The result thus obtained was then used to produce flood inundation map and also to calculate the amount of land cover exposed to potential GLOFs.

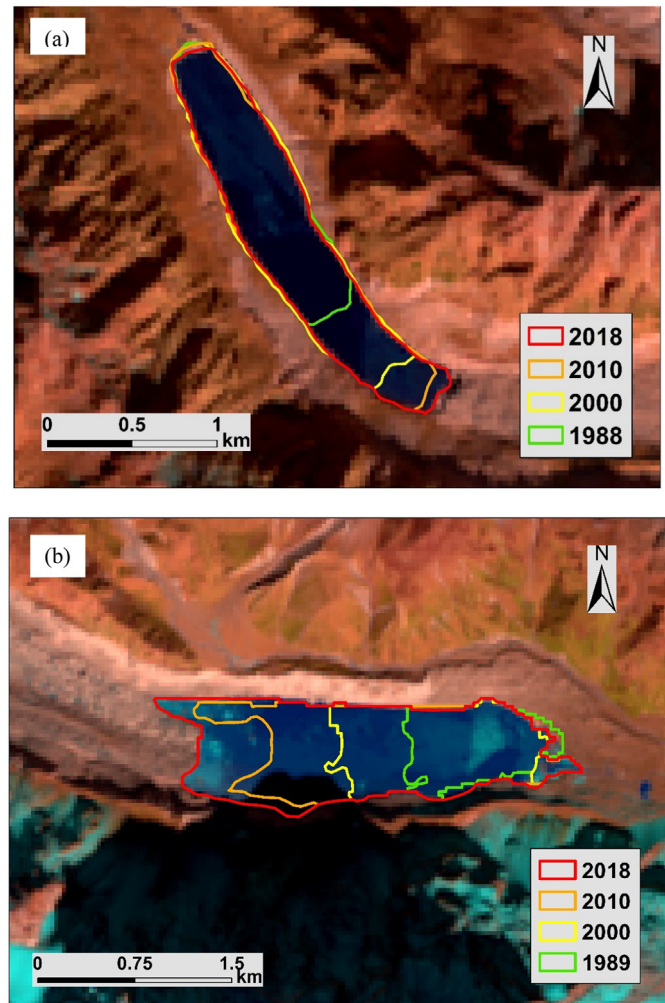


Fig. 3. Lake area change with ~8 to 10 years interval for a) Thulagi and b) Lower Barun Glacial Lakes.

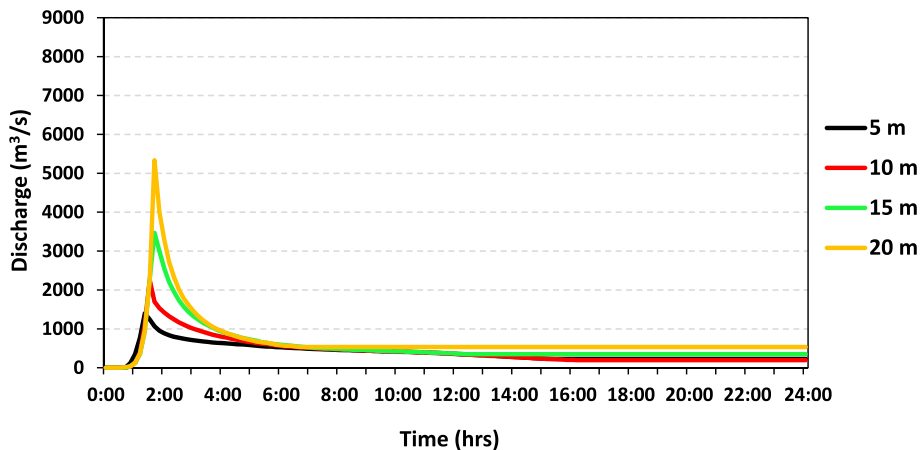


Fig. 4. Variation of peak discharge from NWS-BREACH model when the Thulagi Glacial Lake moraine breached by 5 m, 10 m, 15 m and 20 m.

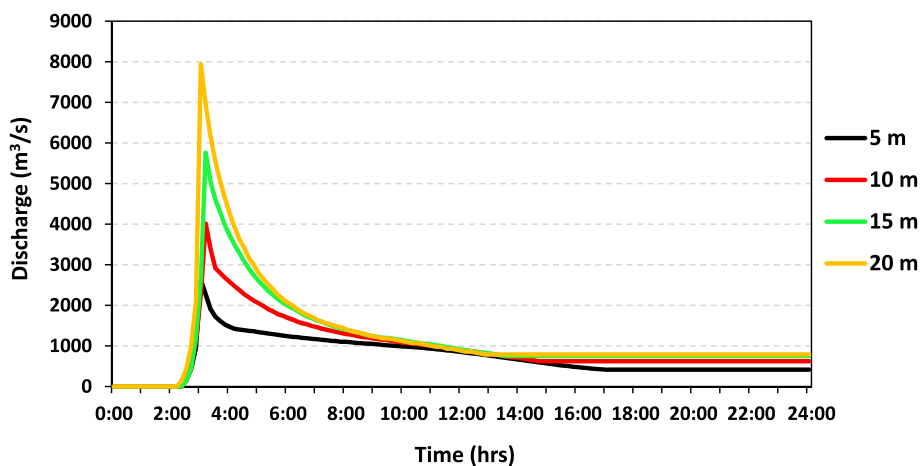


Fig. 5. Variation of peak discharge from NWS-BREACH model when the Lower Barun Glacial Lake moraine breached by 5 m, 10 m, 15 m and 20 m.

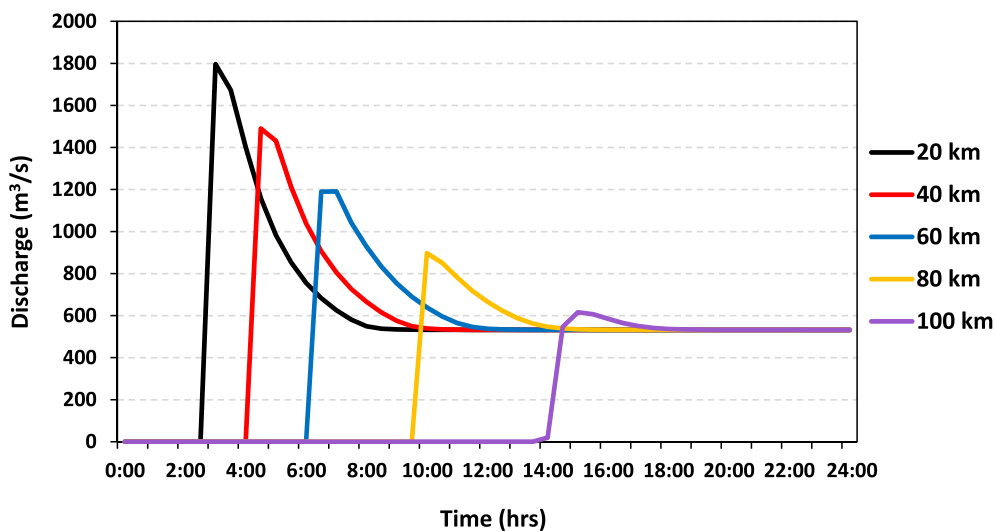


Fig. 6. Flood attenuation after 20 m moraine breach of Thulagi at various distance from lake outlet.

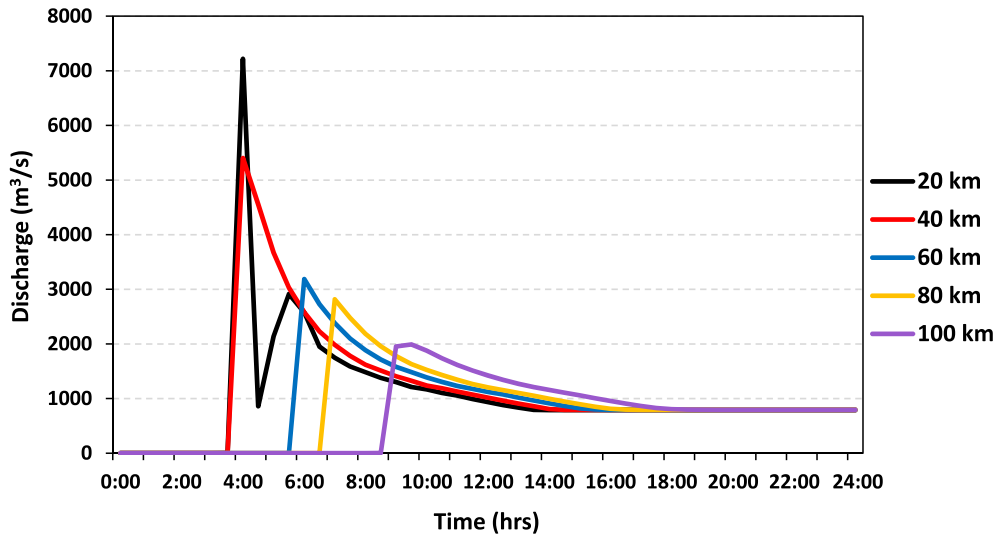


Fig. 7. Flood attenuation after 20 m moraine breach of Lower Barun at various distance from lake outlet.

4. Results and discussions

Based on Landsat images the glacial lakes area has increased within past 30 years. Within the past 30 years, the glacial lake area has increased by three times for Lower Barun Glacial Lake while the change is not so drastic in Thulagi. Thulagi Glacial Lake is fed by debris-covered Thulagi Glacier with an area of 2.7 km². This lake was 0.72 km² in 1988 and increases to 0.94 km² in 2018. Thulagi Glacial Lake started to form about 50 years ago and from 1995 to 2009, its area had increased from 0.76 to 0.94 km² with change in length from 1.97 to 2.54 km [3]. Most of the growth occurred in this lake until mid-1990s with a roughly linear trend until ~2005 and a limited change between 2005 and 2017 [10].

Lower Barun Glacial Lake is fed by debris-covered Lower Barun Glacier which is 1.4 km². This glacial lake was 0.64 km² in 1989 and increases to 2 km² in 2018. Lower Barun grew more rapidly after 2000 [10] where lake area increased by 34% from 2000 to 2017. With an average growth of 0.054 ± 0.006 km²/yr, Lower Barun has had most expansion rate than Chamlang North, Chamlang South, Dig Tsho, Imja Tsho, Lumding, Thulagi and Tsho Rolpa [24]. The growth of proglacial lake area is simultaneous with the retreat of Lower Barun Glacier. The change in glacial lake area has been shown in Table 3 and Fig. 3.

By the use of NWS-BREACH model, possible breaching time and breach peak floods were estimated for different breach scenarios of 5, 10, 15 and 20 m. These different scenarios were evaluated and breach hydrograph was estimated. The peak discharge at the time of outburst ranges from 1399 to 5334 m³/s for Thulagi (Fig. 4) and 2619 to 7936 m³/s for Lower Barun (Fig. 5). After breach initiation, peak flow achieved at 1 h 40 min and 3 h for 20 m breach in Thulagi and Lower Barun Glacial Lakes respectively. At Thulagi, peak discharge in 20 m (5,334 m³/s) breach is almost four times that of 5 m (1,399 m³/s) whereas the difference is three times between Lower Barun for 20 m (7,937 m³/s) and 5 m (2,619 m³/s) moraine dam breach. However for 10 m and 15 m breaching scenarios in both sites, 1000 m³/s difference is estimated. A similar pattern of result was obtained in ICIMOD [3], when dam breach analysis of Thulagi Glacier Lake was carried out using NWS-BREACH model where the peak flow of 4750 m³/s with 0.92 h of breaching time was derived. This result also ties well with Khanal et al. [32] wherein maximum flow at the lake outlet of Thulagi was estimated as 4736 m³/s. Lower Barun has high peak discharge compared to Thulagi as the lake area and water volume held by Lower Barun Glacial Lake is more than that of Thulagi Glacial Lake. The bathymetric survey carried out in Lower Barun showed it to be biggest and deepest with a maximum depth of 205 m among three other lakes i.e.

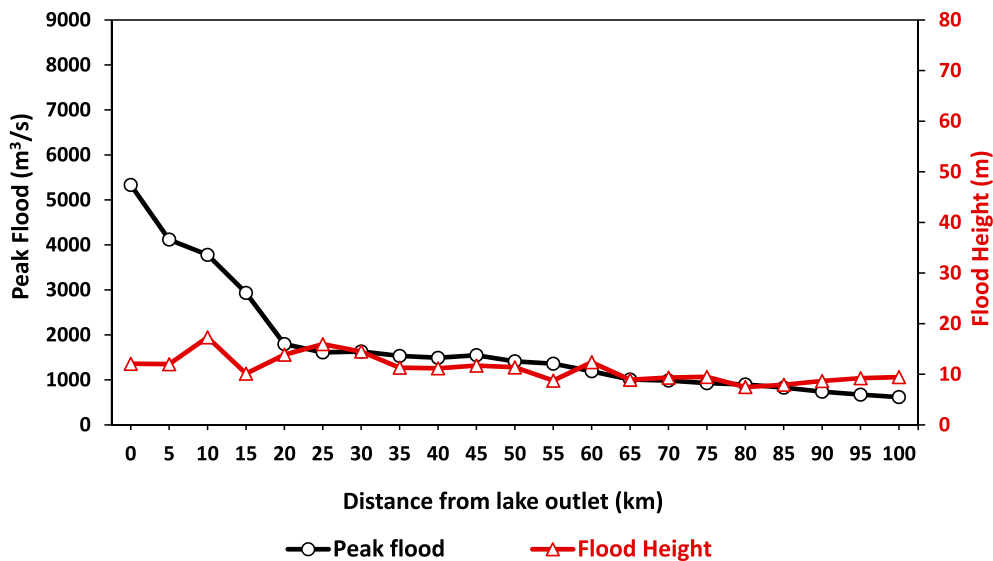


Fig. 8. Peak flood and flood height of Thulagi Glacial Lake after 20 m moraine breach.

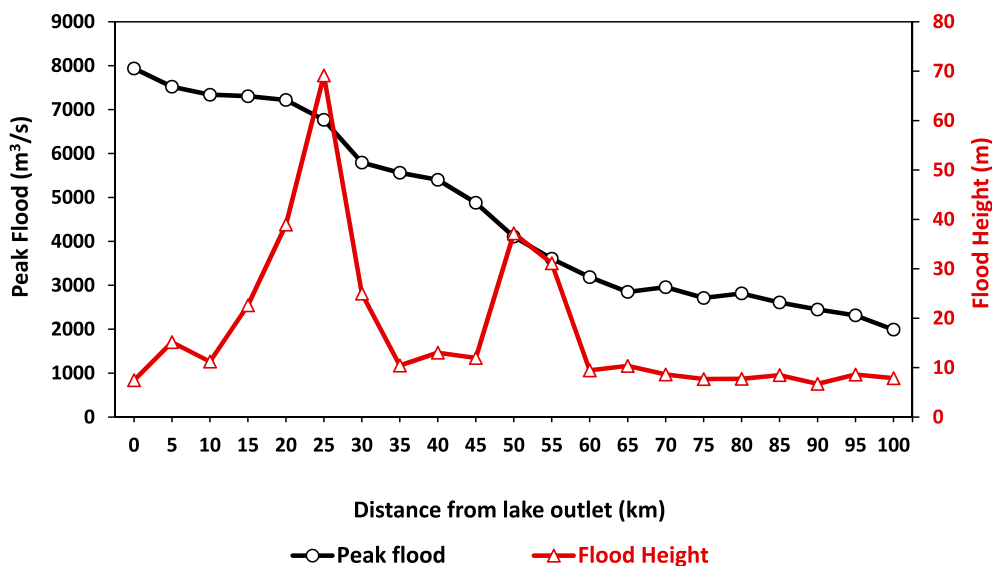


Fig. 9. Peak flood and flood height of Lower Barun Glacial Lake after 20 m moraine breach.

Imja Tsho, Tsho Rolpa and Thulagi [10]. By further comparing its result with that of Tsho Rolpa ($\sim 7200 \text{ m}^3/\text{s}$) and Imja Tsho ($\sim 5800 \text{ m}^3/\text{s}$), it can be concluded that Lower Barun has high peak discharge [3,32]. Based on previous studies, among the four scenarios “20 m breaching” was considered to be more likely and so this was used for detailed downstream impact [16,21,33].

The outburst hydrographs from NWS-BREACH were used as an input for upstream boundary in flood routing from HEC-RAS. Potential flood stage, flood wave travel time, time to peak flood stage and their corresponding water surface elevations in downstream areas were calculated. Peak flood discharge was estimated in an interval of 5 km along the 100 km downstream from dam. Cross-sections were chosen in comparatively straight and stable reaches and its multiple measurements were carried out that helped to address the uncertainty in routing a flood with immense depositional, erosional impacts and temporary debris-flow characteristics in a non-uniform channel. Dharapani, Tal, Syange and Bahundanda village with human settlement located at 14, 20, 34 and 39 km from Thulagi Glacial Lake outlet, can expect flood to arrive after 2 h 30 min, 3 h, 4 h and 4 h 30 min respectively. Similarly, Yangle Kharka and Barun Bajar located 9 and 32 km from Lower Barun Lake outlet, can expect flood to arrive after 3 h and 4 h respectively.

In Thulagi, the peak discharge is relatively lower at 20 km below the source. Peak discharge at the time of breach is $5334 \text{ m}^3/\text{s}$ while it is $1796 \text{ m}^3/\text{s}$ at 20 km below the moraine after its 20 m breach (Fig. 6). This reflects that the river reach is shallower compared to that near the source and the floods spread across a flood-plain in Tal. Whereas, there is a higher discharge at 20 km below the source in Lower Barun. The peak discharge at the time of breach is $7936 \text{ m}^3/\text{s}$ while it is $7218 \text{ m}^3/\text{s}$ at 20 km below the moraine after its 20 m breach. The appearance of another peak in the hydrograph is caused by hydraulic pooling at the very narrow intermittent cross-section (Fig. 7). This effect of hydraulic pooling is significant in downstream areas where the river cross-sections are very narrow compared to upstream areas. Appearance of such multiple peaks in an outflow hydrograph due to hydraulic pooling was also seen in Tam Pokhari [34]. These are not evident in other distances as the river cross-sections below 20 km are not very narrow.

Among the lakes, the flood routing along the downstream differs. Peak flood of Thulagi decreases sharply initially up to 20 km (i.e. Tal) then gradually decreases as it proceeds downstream as shown in Fig. 8. Similar trend was obtained in the previous studies carried out in Thulagi by ICIMOD [3] and Khanal et al. [32]. At Dharapani flood height would be around 13.7 m which will then decrease and starts to rise as it reaches Tal village at 20 km where the flood height would be

around 14.9 m. Tal village is located a few meters above the river and thus the flood depth which is more than the normal flow depth would damage the settlements as well as the lands and also has a great chance of lake formation. The flood height will then decrease and remain almost similar at around 11 m until it reaches 60 km downstream. The reason behind it is due to the reservoir dam of Upper Marsyangdi Hydropower station and flood depth more than normal flow will affect the area downstream of this hydropower due to release of large volumes of water. The dam might cause back water effect by resisting the flow from the GLOF.

Lower Barun has a gradual decrease in peak flow as it proceeds downstream. However, the peak flow decreases sharply from 20 to 25 km and again maintains a gradual decrease beyond 25 km. The flood water spreads out in flat and wide floodplain of Yangle Kharka around 9 km from the source with a flood depth of around 11.2 m. The lower end of Yangle Kharka basin consists of bedrock constriction and thus Yangle Kharka also has the chances of lake formation [35] which when released through the lower end increases the flood depth since the reach is narrow below it as shown in Fig. 9. That is why, the potential flood height reaches up to 69.2 m within the stretch of 20 to 30 km downstream from source. In spite of that, this area lies within the Makalu Barun National Park and so there is probability of less or no loss of life and property. But Yangle Kharka would receive high impacts and the trekking trail to Makalu base camp will also be affected. The flood depth remains around 10 to 13 m till 45 km and it again increases reaching up to 37.2 m at 50 km as the reach is flat, wide and meandering. However, this study lacks field assessment and so from previous studies based on hazard and risk assessment, it can be acknowledged that Lower Barun Glacial Lake has very high hazard due to the combination of its ice-cored moraine and its susceptibility to dynamic failure [14,24].

The peak discharges and flood heights were calculated using hydrodynamic models and the GLOF impacts on the downstream were also simulated. The initial peak flood is almost halved beyond 50 km from the origin of GLOF. The flood inundation maps were then obtained (Figs. 10–13) and land exposed to potential GLOFs were estimated using the Land Cover of Nepal 2010 data published by ICIMOD in April 12, 2013 [36]. The data was accessed from the website <http://apps.geoportal.icimod.org/ArcGIS/rest/services/Nepal/Landcover2010/MapServer/0>. The results of the land cover losses due to potential GLOFs from Thulagi and Lower Barun Glacial Lakes are summarized in Table 4. Around 12.8 km^2 of land cover is estimated to be exposed to GLOF up to 100 km downstream from Thulagi Glacial Lake. 34% (4.3 km^2) along the course of the river would be flooded and the rest 66% affected would include forests (1.1 km^2), shrub land (0.4 km^2),

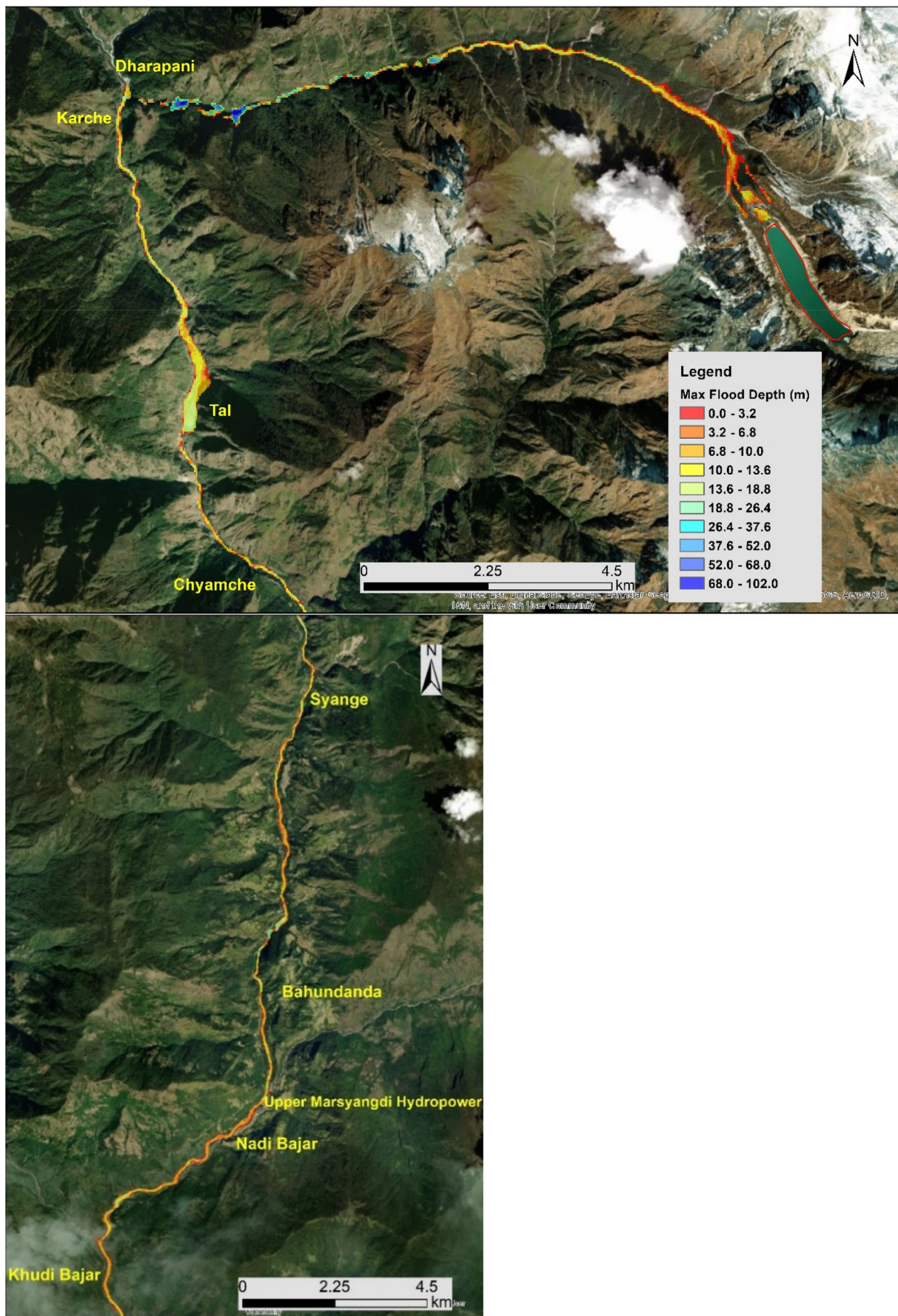


Fig. 10. Modelled inundation map along the Marsyangdi Valley, 50 km downstream of Thulagi.

grassland (1.2 km²), agricultural land (5.1 km²), barren land (0.4 km²) and built-up area (0.3 km²) (Figs. 10–11).

Similarly, from Lower Barun Glacial Lake, 17.9 km² of land cover is estimated to be exposed to GLOF where 15% (2.7 km²) along the course of the river would be flooded and the rest 85% affected would include forests (3.3 km²), shrub land (1.3 km²), grassland (1.4 km²), agricultural land (4.8 km²) and barren land (4.4 km²). Recent drainage of Langmale Glacial Lake on April 20, 2017 which is relatively smaller in area (i.e. 0.1 km²) compared to Lower Barun Glacial Lake and lying in the same catchment provides some insight to how GLOF from Lower Barun affects the downstream areas. Peak discharge of 4400 ± 1800 m³/s with total flood volume of 1.3×10^6 m³ was estimated. Using upper and lower peak velocities estimates of 4 m/s and 8 m/s, a flood hydrograph was developed at Yangle Kharka with peak discharge of 2369 m³/s and 4739 m³/s respectively. The flood had carved steep canyons, scoured river's course free of vegetation and deposited debris, boulders and sediments along the river reach from settlement of Langmale to Yangle Kharka which lies 6.5 km downstream of the lake. A 2–3 km long lake was also formed in the confluence of Barun and Arun River due to blockage by debris [35]. This shows that the disaster caused by the GLOF from Lower Barun will be much more damaging and so the downstream areas are in higher risks (Figs. 12–13).

It is difficult to verify the obtained hydraulic calculation from this research as it does not represent past events. In our work, to assess reliability of the hydraulic characteristics of flood event, it has to be compared with field evidence. However, the reliability of the model used in this work has been tested with field evidences from documented GLOF events at Keara in the Apolobamba region [19] and the Cordillera Blanca, Peru [18] and was shown to reproduce realistic flood depths and inundations. Peak discharge of the historic GLOFs in nearby drainage provides some insights to the potentially expected values for Thulagi and Lower Barun flood. GLOF that occurred from Dig Tsho Lake of the Langmoche valley in 1985 which stored 5×10^6 m³ volume of water reached a peak discharge of 1600 m³/s and had flood depth ranging from 20 to 50 m in the river channel [37]. The 1998 GLOF from Tam Pokhari released approximately 18×10^6 m³ of water with a peak discharge of about 10,000 m³/s with flood depths up to 25 m in the river channel [34]. A range of 1000–10,000 m³/s depending on size and volume of water stored in the lake seems reasonable to use for comparison with peak discharge estimates. The result obtained from this research also shows similar values in case of Thulagi and Lower Barun Glacial Lakes. Peak discharge for Thulagi with 36.1×10^6 m³ volume ranged from 1399 to 5334 m³/s and for Lower Barun with 112.3×10^6 m³ of volume ranged from 2619 to 7936 m³/s. A previous study of Thulagi Glacial Lake by ICIMOD [3] found a peak

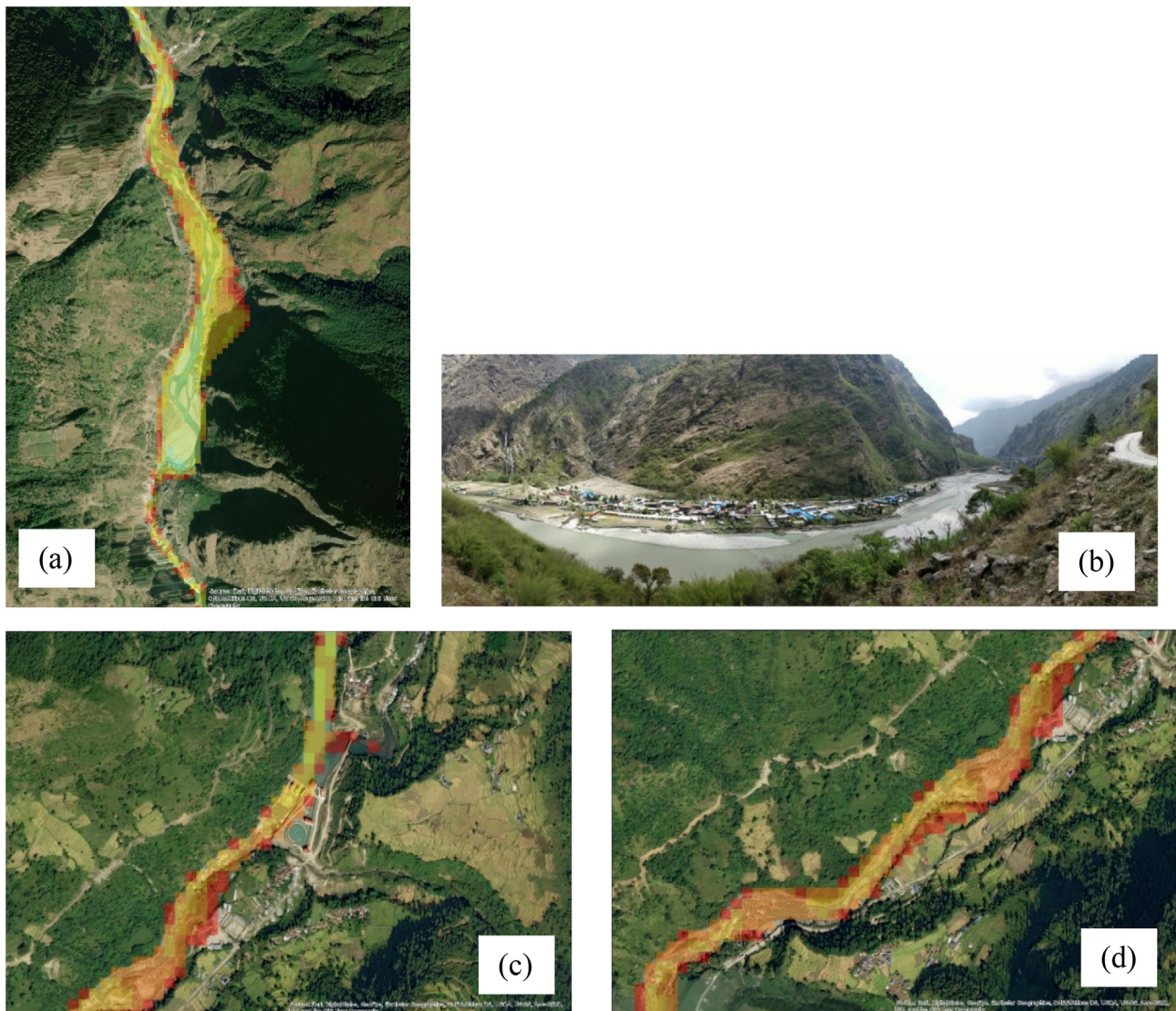


Fig. 11. Flood inundation maps a) Zoomed in view at Tal village, b) Panoramic view of Tal village, c) Zoomed in view at Upper Marsyangdi hydropower and d) Zoomed in view downstream of Upper Marsyangdi hydropower.

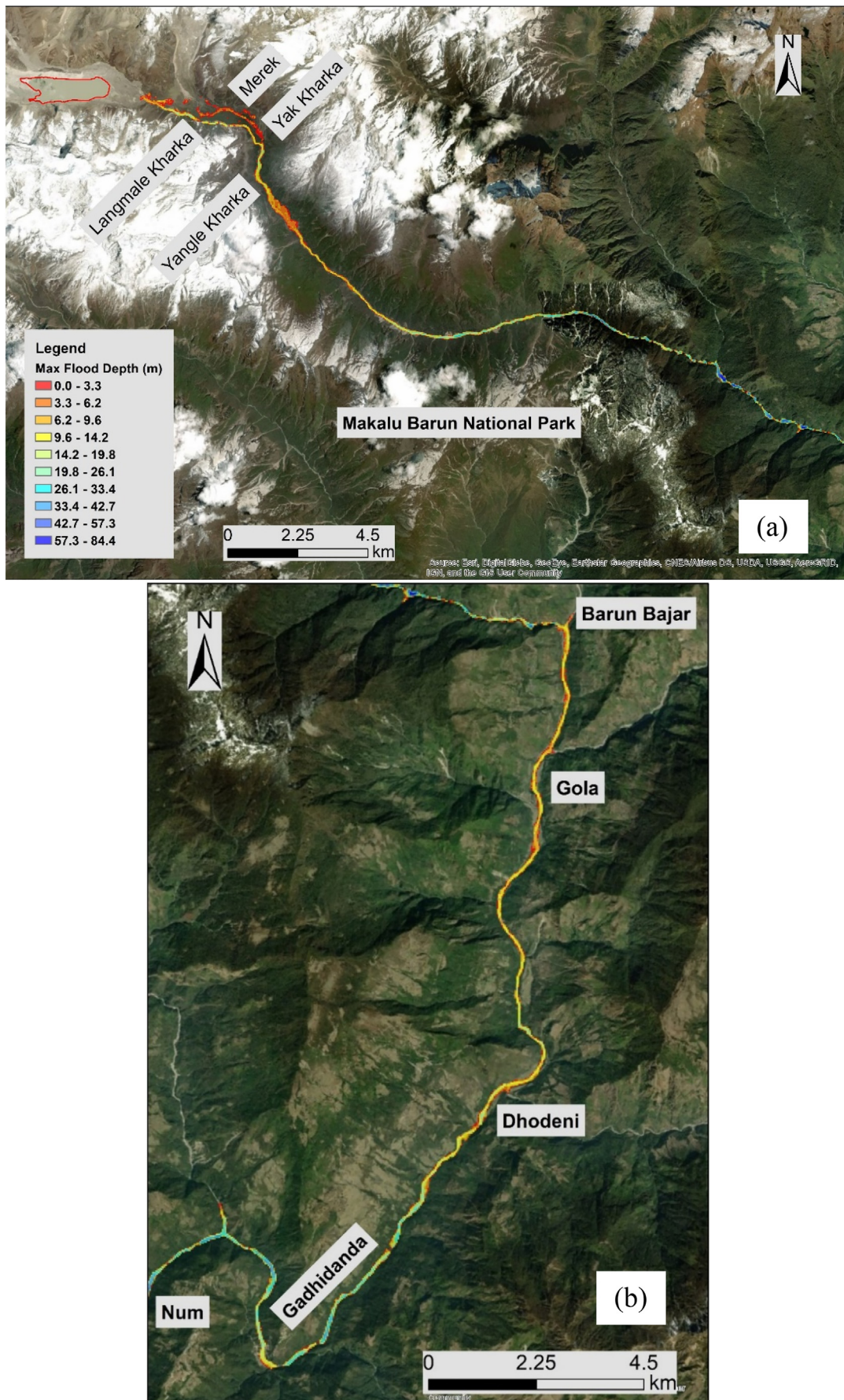


Fig. 12. Flood inundation map along the Arun Valley, a) 25 km and b) from 25 to 50 km downstream of Lower Barun.

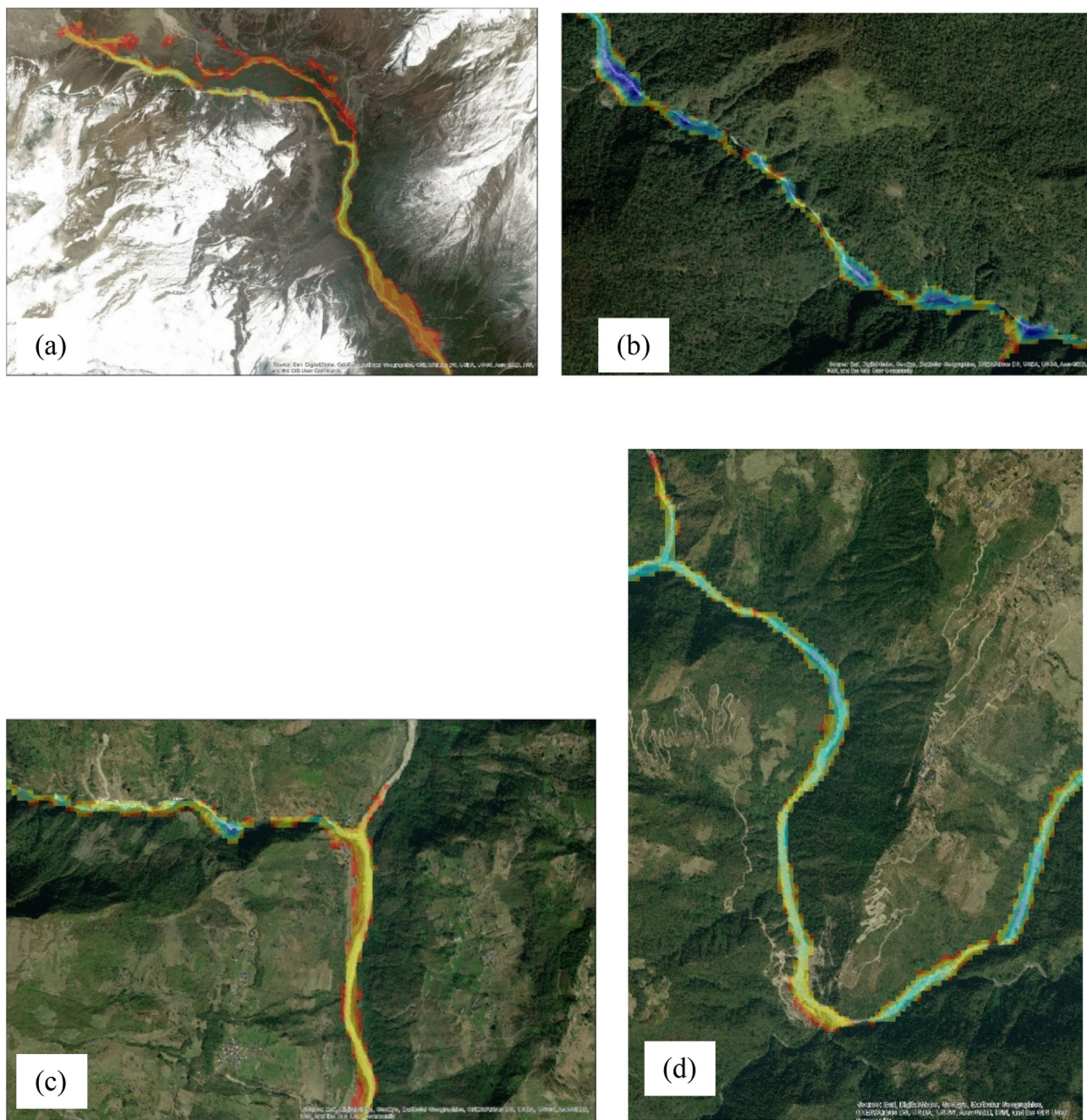


Fig. 13. Flood inundation map zoomed in view a) Merek, Langmale, Yak and Yangle Kharka, b) Barun river flowing within Makalu Barun National Park, c) Barun Bajar and d) Num and Gadhidanda.

Table 4
Land cover types exposed to potential GLOFs up to 100 km downstream by using Land Cover of Nepal 2010 data of ICIMOD.

S. no.	Land cover type	Thulagi Glacial Lake		Lower Barun Glacial Lake	
		Area (sq. km)	%	Area (sq. km)	%
1	Forest	1.1	8.5	3.3	18.6
2	Shrub Land	0.4	2.9	1.3	7.3
3	Grassland	1.2	9.2	1.4	7.6
4	Agriculture area	5.1	40.0	4.8	26.6
5	Barren area	0.4	2.9	4.4	24.7
6	Built-up area	0.3	2.4	0.0	0.0
7	River course	4.3	33.9	2.7	14.9
Total		12.8	100	17.9	100

discharge of 4750 m³/s which is almost similar to the results from this research. A previous GLOF in Barun River caused by Langmale Glacial Lake is taken as reference to compare the depths at Yangle Kharka. Langmale Lake caused GLOF with an estimated volume of 1.3 × 10⁶ m³ and had a maximum flood height of 4.8 m at Yangle Kharka [35]. The potential flood depth from Lower Barun GLOF is 11.2 m at Yangle Kharka which is almost three times that of Lower Barun.

National Strategic Action Plan of Nepal has set the target to reduce risk in 7 high-risk glacial lakes by 2030. To achieve this target Sendai Framework for Disaster Risk Reduction is considered as a main guidance. To fulfill this target understanding the disaster caused by GLOF and its risks is very important which falls under Priority Area 1 of the Sendai Framework for Disaster Risk Reduction as well as the Disaster Risk Reduction National Strategic Plan of Action of Nepal. Understanding risk caused by GLOF requires better information, impact modelling and risk assessment. Based on impact

modelling results appropriate decisions can be taken by decision makers before GLOFs occurrence. This research has carried out mapping of areas which might get affected by potential GLOFs which can be further reanalyzed and used in making risk sensitive land use plans. These can then be made public to establish effective disaster management information system and its dissemination. However, further analysis of this work needs to be carried out by gathering more data and information before incorporating the results in policy, decision making, capacity building and information sharing.

5. Conclusion

In Nepal, there are over 2070 glacial lakes out of which 21 are identified as potentially dangerous glacial lakes (PDGLs). The geometry, internal structures, material properties and particle-size distribution determines the stability of the moraine dam. Failure of these moraine dams results in rapid release of high volume of glacial lake water called GLOF. These GLOFs are triggered by events such as ice and rock avalanches, calving of terminal face of glacier rapid input of meltwater into lakes, atmospheric activities and earthquakes. Breach forms gradually with respect to time and width and manifests into progressive erosion and enlarging of channel in downstream face of dam. As a result, there is loss of life and properties in the downstream regions. Hydraulic flood models are used in quantitative assessment and hazards of these GLOF. NWS-BREACH model was used to assess the GLOF hydrograph which was then taken as input in HEC-RAS to simulate the nature of these GLOF propagation in downstream areas. The flood routing of GLOF was then used to produce inundation map to determine downstream affected areas.

The study has been carried out in Thulagi and Lower Barun Glacial Lakes which both lie and ranks I under PDGLs. These lakes are at an altitude of 4050 and 4534 m a.s.l respectively and are both fed by long debris-covered glaciers. The glacial lake area has found to be increased by three times in Lower Barun Glacial Lake within the past 30 years, however, the change is not so drastic in Thulagi. The lake area of Thulagi was 0.72 km² in 1988, 0.89 km² in 2000, 0.93 km² in 2010 and 0.94 km² in 2018. Similarly, that of Lower Barun was 0.64 km² in 1989, 1 km² in 2000, 1.59 km² in 2010 and 2 km² in 2018.

From NWS-BREACH model, variation of peak discharge at the time of breach was obtained by using different scenarios of 5, 10, 15 and 20 m. The peak flow ranged from 1399 to 5334 m³/s and 2619 to 7936 m³/s for Thulagi and Lower Barun in low and high breach scenarios respectively. For 20 m breaching of Thulagi and Lower Barun Glacial Lakes, the peak flow was achieved at 1 h 40 min and 3 h respectively. As the area and volume of water in Lower Barun is higher than that of Thulagi, the peak discharge is also higher in Lower Barun than in Thulagi. These peak flows from NWS-BREACH were then taken as input for upstream boundary condition in flood routing from HEC-RAS 2-D unsteady flow analysis model. The flood routing simulated peak discharge and flood height at different distances in the downstream from lakes outlet. The peak discharge was estimated at an interval of 5 km along 100 km downstream from the dam. Tal which has a big settlement along the Marsyangdi River lying 20 km downstream of Thulagi Glacial Lake can expect flood to arrive after 3 h with a peak discharge of 1796 m³/s. The flood height in Tal village was estimated to be around 14.9 m. In Lower Barun, Yangle Kharka lying 9 km downstream can expect flood to arrive after 3 h with a peak discharge of 6143 m³/s and a flood height of around 11.2 m. The maximum flood height reached around 16 m for Thulagi while it was around 69 m for Lower Barun.

The impact caused by the outburst of Thulagi and Lower Barun Glacial Lakes in the downstream regions were then evaluated through flood inundation map. Along the course of the river, 34% of the river would be flooded in Thulagi and 15% in Lower Barun. Among the different land covers, GLOF affects mostly agricultural areas in downstream regions of both lakes. However, in the path of Thulagi GLOF there are three major hydropower projects i.e., Upper, Middle and Lower Marsyangdi and so more area will be at risk if anyone of these hydropower projects are affected.

Nonetheless, on the basis of existing knowledge, it is not feasible to make a reliable prediction of a specific occurrence and so the difficulty involved in attempting to forecast GLOF hazard and danger was emphasized. Nepal consists of large number of glacial lakes but only a few have been studied. So, detail field survey of other lakes and downstream areas need to be incorporated for better prediction of GLOF events in future works.

CRedit authorship contribution statement

Sunwi Maskey: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Rijan Bhakta Kayastha:** Supervision, Writing - review & editing. **Rakesh Kayastha:** Resources, Supervision, Writing - review & editing.

Declaration of competing interest

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

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