

Chapter 6

Geospatial Analysis of Glacial Lake Outburst Flood (GLOF)



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Abstract The Himalayan region is a fragile ecosystem with a steep landscape where natural disasters such as the Glacial Lake Outburst Floods (GLOFs) event have been frequently observed that cause significant damage in valleys downstream areas. GLOF is one of the major unexpected serious hazards that can release a large volume of water with debris cover in a very short interval of time that caused loss of lives, properties, and severe damage to downstream infrastructures. In the present study, lake-terminating South Lhonak lake (Lat 27° 54' 41.88" N and Long 88° 11' 44.65" E) is located at an altitude of 5205 m above mean sea level (a.s.l.) in the Teesta basin, Sikkim has been identified as highest potentially dangerous glacial lake based on the criteria of area, elevation, slope, distance from the glacier and volume of water held, with maximum surface area 1.39 km² acquired on October 2020. Spatio-temporal analysis of the glacial lake using Landsat 5 and Landsat-8 satellite imagery shows that the glacial lake has been grown from 0.48 to 1.39 km² over the past 30 years. The depth of South Lhonak glacial lake is 39.54 m which has been calculated by using Huggle's formula. This study evaluates the one-dimensional hydrodynamic modeling for GLOF simulation at different downstream sites from the glacial lake. The HEC-GeoRAS has been used for the creation of river geodatabase. Consequently, simulation was carried out using HECRAS model at multiple sections along the river. The GLOF scenario was revealed due to overtopping failure of the frontal moraine, producing peak discharge, and releasing water volume of 54.96×10^6 m³. The result of this study reveals that the predicted peak discharges of the lake have been estimated for breach widths of 30, 40, and 60 m, and breach formation time has also been considered as 40, 30, and 20 min, respectively. The estimated flood peak was

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14,658.60 m³/s at the GLOF site, and the same got mitigated to 11,978.77 m³/s at the downstream end, respectively. The study's findings will aid in the formulation of risk management plans and risk reduction strategies in the event of a GLOF hazard.

Keywords South Lhonak lake · Glacial Lake outburst floods · HEC-RAS model · HEC-GeoRAS · River cross-section · Flood hydrograph

6.1 Introduction

The global climate variability during the first half of the twentieth century had a significant impact on the glacier lifecycle in the Himalayan region, resulting in several glaciers are melting rapidly and forming a large number of glacial lakes. The formation of different types of glacial lakes in the Himalayan region can be interpreted as a caution of glacier mass balance changes. The formation of glacial lakes occurs when the glaciers retreat (Sakai 2012; Zhang et al. 2015; Ahmed et al. 2021). The retreating and melting rate of glaciers are faster than ever, causing rapid accumulation of ice and snow on the glacier, this results in a prompt increase in the volume of the glacial lakes. Most of high altitude glacial lakes are surrounded by moraine dam which is formed by loose unconsolidated material deposited by the retreating glacier which can be burst suddenly, leading to discharge of huge volume of water with debris causing potentially devastating hazards that may destroy the livelihood and other infrastructure and this may also destroy the serene beauty of the Himalayan region. The water availability in Himalayan glaciers has the potential to serve India's vast population in the future decades (Bajracharya et al. 2007).

The Himalayas are not only the world's highest mountain range, but they also comprise the greatest freshwater reservoirs in the form of glacial snow and ice, but due to the effect of global warming, glaciers in the Himalayan region are melting rapidly, and the rate at which Himalayan glaciers are receding provides a compelling indication of climate change. In the last 200 years, the Gangotri glacier in the northern Himalayan region of India has retreated 2 km (Bhambri et al. 2012).

The Himalayan glaciers are known to be one of the most susceptible regions to the adverse effects of climate change. The Himalayan is a fragile ecosystem with a steep landscape prone to natural calamities such as landslides, avalanche, and glacial lake outbursts flood have been frequently observed (Singh et al. 2006). The resulting flood can devastate settlements and infrastructure in low-lying areas. The Himalayan glaciers employed a substantial effect on high terrain hydrology and provided water resources supporting the ecological life system in central Asia. Recent studies have shown that most of the Himalayan glaciers are under intensive shrinkage, offering the most negative glacier mass balance and indicating the most significant reduction in length of the glacier (Cogley 2006; Gardelle et al. 2013). The continuous retreating and thinning of glaciers, leaving the debris mass at the end of the glacier and that end moraine exposed may lead to the creation of new glacial lakes (Costa and Schuster 1998; Emmer 2017; Harrison et al. 2018; Mergili et al. 2021) thereby increasing

the risk of the downstream region to glacial lake outburst flood. The establishment of glacial lakes at higher altitudes grows the risk of catastrophic GLOF events in low-lying areas. This kind of flood event is frequently accompanied by dam breach formation and leads to moraine dam failure (Richardson and Reynolds 2000; Worni et al. 2014). GLOF represents a catastrophic event in the Himalayan glaciers and poses a potential risk to the downstream hydro-project power plant due to the extreme river flow. GLOF phenomenon is related to various flow characteristics in both spatial and temporal scales (Westby et al. 2014).

There are multiple inventories of glacial lakes, and state wide hazard evaluations are available for Sikkim Himalaya (Mool et al. 2003; Raj et al. 2013; Worni et al. 2013; Aggarwal et al. 2016, 2017; Sattar et al. 2019). Mool et al. (2003) described the first glacial lake inventory, where mapping 266 lakes with a total area having 20.2 km², out of 266 lakes, only 14 lakes have been identified as potentially dangerous. South Lhonak glacier has become one of the fastest receding glaciers in the Teesta basin; Sikkim and the accompanying proglacial lakes have grown to be the most rapid rate in the state (Aggarwal et al. 2017). In the last few years, the Hindu Kush Himalaya region has been witnessing multiple GLOF events that often result in catastrophic flooding downstream, with major geomorphic and socioeconomic impacts and livelihoods. Glaciers thinning and retreating phenomenon has been found in most provinces of the Hindu Kush Himalaya (HKH) (Bolch et al. 2012), which has resulted in the creation of numerous new glacial lakes. Most of the glacial lakes have been situated at the snout or ablation zone of the glacier, which is dammed by the end or lateral moraine, where there is the highest risk of breaching. These kind of lakes might be potentially dangerous and carry a huge volume of water. To analyze the potential threats from such lakes, it is essential to identification and mapping of such glacial lakes that have been categorized based on the number frequency of lakes of different areas and different elevations.

Regular monitoring of the glacial lakes is essential to prevent the GLOF hazard and assess the damage that may occur in the near future time. Remote sensing and GIS could play an important role in the identification of potentially dangerous lakes and proper monitoring of the GLOF events in real-time. The monitoring of glacial lakes has been carried out by using multi-temporal Landsat imagery and microwave remote sensing-based altimetry data (Thakur et al. 2021). One-dimensional hydrodynamic models were studied to analyze the GLOF event in the Himalayan region (Jain et al. 2012; Thakur et al. 2019).

In previous research, the inventory of glacial lakes was monitored and found to increase due to climate change and glaciers retreating (Reynolds 2000; Ageta et al. 2000; Benn et al. 2000). A semi-automatic water body extraction method based on the normalized difference water index (NDWI) was employed on Imja Glacial Lake by Bolch et al. (2008).

Remote sensing techniques combined with a flood simulation model can assist in identifying and preventing damage to downstream communities and infrastructure. The study's assessment analyzes the potential dangerous glacial lake using remote sensing technology coupled with HEC-RAS one-dimensional unsteady flow hydrodynamic modeling. This study incorporates (i) To estimate the volume of the glacial

lake using Huggel formulas, (ii) to evaluate different lateral moraine breach scenarios based on varying breach formation time and breach width, producing breach hydrographs, (iii) one-dimensional unsteady flow hydrodynamic mathematical modeling has been used to assess the potential threat of glacial lake, (iv) also study of flow hydraulic of potential GLOF and its downstream impact at different sites along the river and creation of flood inundation map using HEC-RAS model and GIS, including prediction of flow depth, flow velocity, flood travel time, and peak discharge due to GLOF hazard.

6.2 Study Area

The South Lhonak glacial lake, which is located in the North-western parts of Sikkim, is one of the Himalaya's fastest-growing glacial lakes. The South Lhonak glacial lake (Lat 27° 54' 41.88" N and Long 88° 11' 44.65" E) is situated at an altitude of 5205 m a.s.l. in the Teesta basin, Sikkim. The lake is entirely blocked by moraine-dammed, which is susceptible in the perspective of GLOF. In the present study, Glacial Lake's outburst flood risk assessment has been carried out in the South Lhonak glacial lake. A temporal examination of the glacial lake using Landsat 5 and Landsat-8 satellite imagery shows that the lake has been grown from 0.48 km² to 1.39 km² in the last 30 years. The maximum lake depth is 39.54 m, and it stores 54.96 × 10⁶ m³ of water. The GLOFs wave has been routed from the glacial lake up to 20 km stretch, as shown in Fig. 6.1.

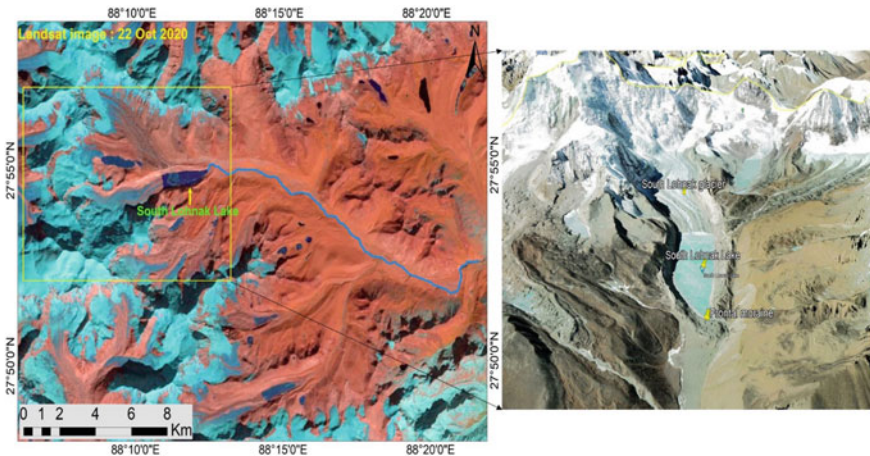


Fig. 6.1 The study area for GLOF

6.3 Dataset and Methodology

The data required to accomplish GLOF modeling are satellite imagery and SRTM 30 m DEM. To carry out GLOF modeling, glacial lake's analysis has been done by using HEC-RAS 1D hydrodynamic model and remote sensing techniques, and GIS. Time series of Landsat imagery has been used to identify potential lake sites and monitor the spatial and temporal variation in the lake area. Figure 6.3 gives the time series of Landsat images that show change detection in the glacial lake area from 1990 to 2020. Table 6.1 shows satellite data used in this study for identification of glacial lake area changes. After the analysis of temporal variation in satellite imagery, we have found that a glacial lake is formed at lower ablation zones of the mother glacier, which shows the breaching evidence, and the area of the lake keep growing as the continuous glacier retreat. Therefore, South Lhonak glacial lake has been found the most hazardous lake with its maximum area of 1.39 km², therefore, it has been selected for GLOF study. Figure 6.2 depicts the overall methodology adopted in this study.

The Manning coefficient for hilly terrain has a steep slope with no vegetation, gravel, cobbles, boulder, and bushes on the banks ranging from 0.03 to 0.07 (HEC-RAS Manual HEC 2010). In the present study, Manning coefficient has been taken from 0.04 to 0.10 as an input in the HEC-RAS model.

6.3.1 Hydraulic Analysis Using HEC-RAS

HEC-RAS is the most significant hydraulic model used for glacial hazard studies (Klimes et al. 2011). It is a user-friendly, reliable model that has the dynamic capability of performing complex flow simulations in the design, management, and operation of river systems.

In this study, HEC-RAS one-dimensional unsteady flow hydrodynamic mathematical modeling has been used to simulate the GLOF occurrence of the South Lhonak glacial lake in Teesta Basin to evaluate the downstream flood wave due to potential GLOF. The model is based on one-dimensional St. Venant equations performing flood scenarios caused by the Glacial lake outburst event. For unsteady flow simulation, the hydraulic model requires two basic inputs data for flow analyses: geometric and flow data. The pre-processing of the geometric data is done by HECGeoRAS. The geometric data includes all the layers related to river cross-sectional station, elevation data, river centerline, bank stations, and flow paths. This

Table 6.1 Satellite data used in this study for mapping of glacial lake area changes

Date of acquisition	Sensor	Spatial resolution (m)
21 September 1990	Landsat 4-5TM	30
22 October 2020	Landsat 8 OLI	30

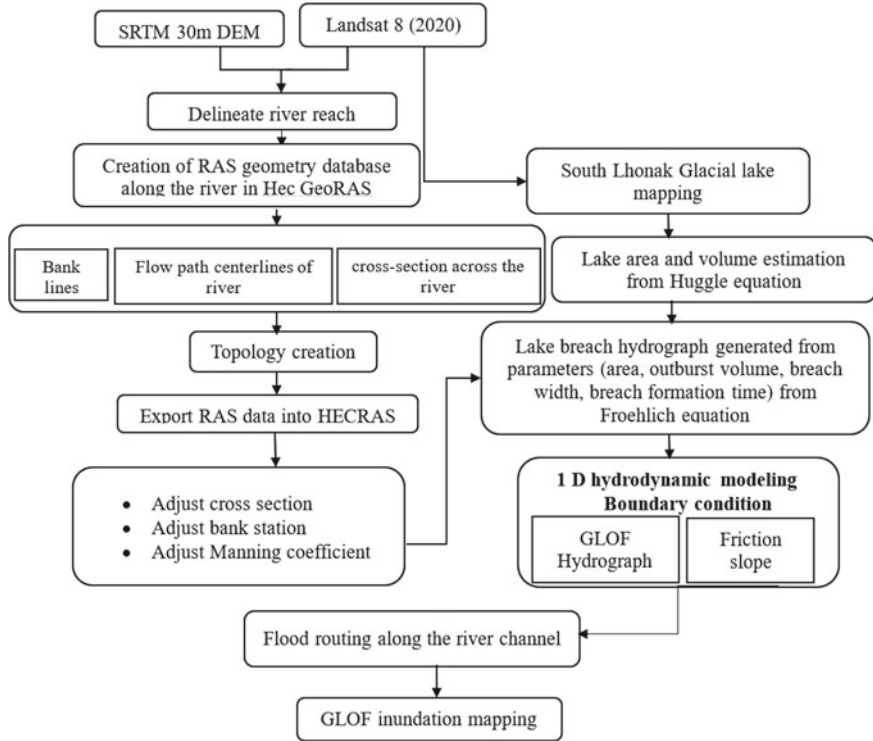


Fig. 6.2 Flowchart of methodology

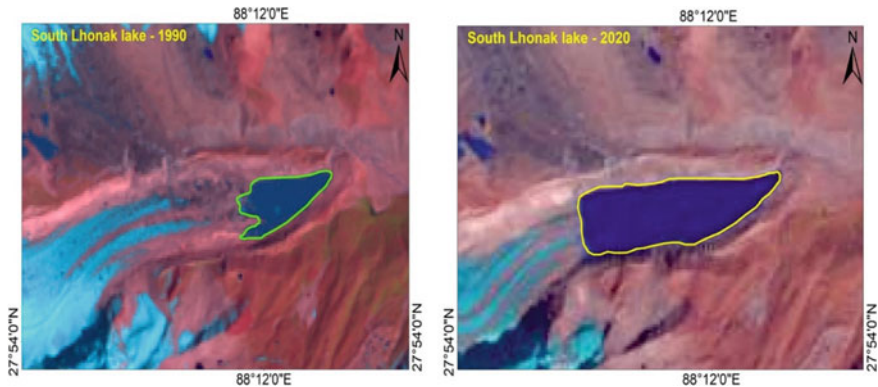


Fig. 6.3 Images showing growth of glacial lake area from 1990 to 2020

was accomplished by creating a vector layer of the streamline and flow paths along the stream at a distance of 1 km. The created geometric layers were imported into HEC-RAS for unsteady flow simulation. The other input data needed for GLOF modeling is flow data which requires upstream and downstream boundary conditions. The dam breach hydrograph is typically used for upstream boundary conditions and downstream boundary conditions considered as a channel bed slope. In this study, the glacial lake has been characterized as a dam failure structure with a certain crest length and elevation above the invert level. Its breach dimensions were specified as a simulation time series and considered the corresponding lake was taken into account. An inline structure known as the Latero-frontal moraine that is entered at the lower elevation of the lake. The failure catastrophe is modeled by breaching the inline structure before performing a dam break analysis. For the upper boundary, the glacial lake was considered a reservoir in the model by its elevation-storage relationship. The elevation-storage volume is generated based on the total volume and maximum depth obtained from the Huggel formulas. SRTM DEM has been used to generate a TIN terrain model for 1-D hydrodynamic modeling. From the terrain, the minimum elevation of the lake was obtained. The storage capacity at a minimum elevation of the lake is zero, and at maximum elevation, the total volume of the lake is obtained. Based on these two parameters, the elevation-storage capacity for the lake has been generated. These parameters are the inputs required by the empirical equations that estimate the peak outflow and failure time of the moraine dam breach event. The Froehlich model requires fewer input parameters for dam break analysis to estimate peak breach outflow hydrography.

In this study, unsteady flow data analysis was performed for calculating flood inundation water depths, flow velocity, and flood peak discharge at various sections downstream of the river flow.

6.3.2 Hazard Assessment of South Lhonak Lake

Glacial Lake volume releases a large amount of water and debris-covered involved in a GLOF. There is no assessment available to estimate glacial lakes volume in high altitude rugged terrain in the Himalayan region. However, Huggel et al. (2002, 2004) provided an empirical equation for calculating glacial lake volume in the Swiss Alps region. Due to unavailable bathymetric data of potentially vulnerable glacial lakes, they develop an empirical relationship based on the area to estimate the volume of glacial lakes. There are several empirical relationships, but the equation developed by Huggel is most extensively applied in earlier GLOF hazard studies where bathymetric surveying data were not available. The volume of the lake in this study was estimated by Huggel et al.'s (2002) equation:

$$V = 0.104 A^{1.42} \quad (6.1)$$

where V is the volume of the glacial lake (m^3) and A is the lake area (m^2). Using Eq. 6.1, the lake's volume was estimated to be $54.96 \times 10^6 \text{ m}^3$.

In any dam breach event, estimation of dam breach characteristics is essential to predict the breach outflow hydrograph. This study employs the 1 HD modeling to evaluate the lake outburst hydrograph for the GLOF simulation. GLOF occurs when glacial meltwater cannot freely flow downward, resulting in new glacial lakes. These water bodies are trapped by the natural dam made by loose glacial moraine called moraine dam. These moraine dams cannot hold a large volume of water due to the water's pressure on the upstream face of dam that exceeds the stabilizing forces like soil shear and cohesion, resulting in overtopping failure of the moraine dam. The main breach characteristics that are required as an input of dam breach parameters such as breach width and breach formation time have been estimated by employing the empirical equations proposed by Froehlich:

$$B_w = 0.180K_o(V_w)^{0.32}(h_b)^{0.19} \quad (6.2)$$

$$T_f = 0.002(V_w)^{0.53}(h_b)^{0.9} \quad (6.3)$$

where B_w and V_w in Eqs. 6.2 and 6.3 are the breach width (m) and lake volume (m^3), h_b and T_f is the height of breach (m) and breach formation time (h) respectively. Here, the lake volume calculated using Eq. (6.1) shows the breach width (B_w) as a function of the volume of the reservoir (V_w) and height of breach (h_b). Similarly, Eq. (6.3) determines the breach formation time (T_f) based on the same parameters.

The present study, developed various dam breach scenarios based on varying breach width and breach formation time for producing peak discharge from glacial lakes to evaluate a potential GLOF event. The failure mechanism as an overtopping is considered in breach scenarios.

6.4 Results and Discussion

6.4.1 Growth of Glacial Lake

Majority of the glacial lakes in the high mountainous himalayan region are in contact with mother glaciers but due to constantly increasing of hydraulic pressure on unconsolidated and loose moraine material forming the dam like structure surrounding the lakes, that is considered as an important factor leading to a GLOF event. According to the previous study carried out by ICIMOD (2011), a total of 1104 glacial lakes have been reported in the Sikkim Himalayas, compared to 266 glacial lakes in 2004 having an area $> 0.01 \text{ km}^2$. Based on the satellite imagery, it has been observed that South Lhonak lake in the Teesta Basin of Sikkim has shown discernible increase in the last 30 years (Sharma et al. 2018; Aggarwal et al. 2017). It has been identified as

Fig. 6.4 Glacial Lake areal expansion in three decadal period

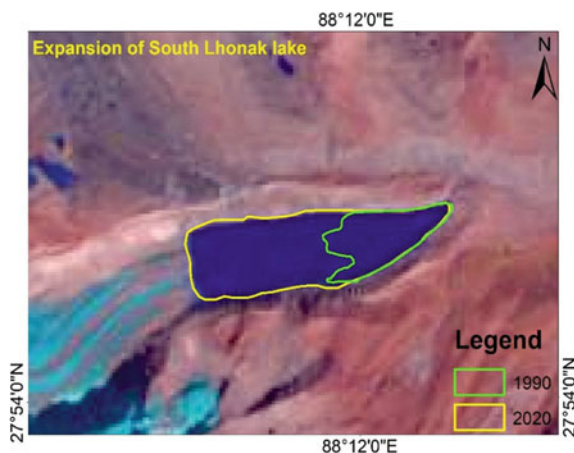


Table 6.2 Glacial lake area changes

Year	Area (km ²)
1990	0.48
2020	1.39

one of the most dangerous lakes with a high risk of outburst (Raj et al. 2013; Worni et al. 2014). The lake's area increased from 0.48 km² in 1990 to 1.39 km² in 2020. The expansion of the glacial lake area is shown in Fig. 6.4. The change in lake area from 1990 to 2020 is given in Table 6.2.

6.4.2 Assessment and Simulation of GLOF

GLOF simulation has been carried out for the South Lhonak lake in the Teesta basin, with a maximum lake area 1.39 km² in October 2020. The altitude of the lake is 5205 m. The volume and depth of the lake are calculated using Eq. 6.1, and it comes out to be 54.96×10^6 m³ and 39.54 m. A dam-break hydrodynamic simulation model was performed to assess a GLOF occurrence in the glacial lake.

As seen from Landsat imagery, it was found that this unstable moraine-dammed glacial lake is positioned at the snout of the mother glacier known as South Lhonak glacier, which has been retreating rapidly in the past few decades that reflect glacial lake has been expanding. Therefore, it has been chosen for the GLOF study. The flood routing from the glacial lake to the downstream end (length 20 km) has been characterized in the model by varying numbers of river cross-sections derived from SRTM DEM that has been given as an input in the HEC-RAS model shown in Fig. 6.5. Wang et al. (2012) examined impact of DEM data on GLOF modeling in Tibet and concluded that, whereas flood inundation extent and flow depths are affected

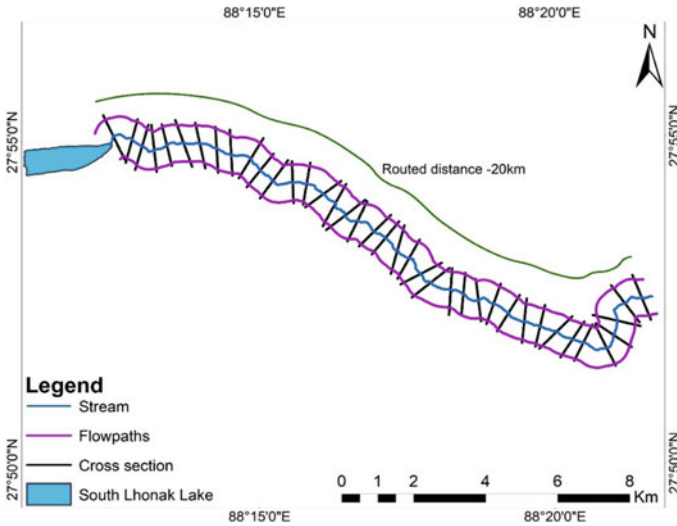


Fig. 6.5 River Network model setup for GLOF study of South Lhonak glacial Lake

by the adapted DEM, the level of deviation has little significance when predicting peak-discharge floods. Figure 6.6 depicts the cross-sectional profiles plotted over the streamflow across the downstream section.

The hydrodynamic model is intimately connected to flow discharge and water level. The South Lhonak moraine-breach was simulated to estimate the breach hydrograph, further routed along the downstream channel from the lake. The resulting GLOF wave due to breach of the frontal moraine dam has been propagated in the downstream area is simulated using the 1-D unsteady flow HEC-RAS model. The breach simulations have been executed to analyze the unsteady flow hydrodynamic model to input the dam-breach parameters (breach width and breach formation time). Therefore, to estimate the breach hydrograph, possible varying breach width (B_w) and breach failure time (T_f) of the lake was considered for different worst-case scenarios, in which breach widths of 30, 40, and 60 m and breach formation time has considered being as 40, 30 and 20 min, respectively.

Hydrodynamic modeling applied in the Himalayan region is generally associated with fraught and uncertainty because there is lack of information about the various properties of moraine and breach formation process. In GLOF event, numerous empirical relationship has been established to evaluate peak flows (Costa and Schuster 1988; Huggel et al. 2002). The initial flow hydrograph is a function of two important parameters i.e., breach width (B_w) and the breach formation period (T_f). B_w and T_f are dependent upon many factors, such as geometry, internal structure of the moraine dam, and the type and magnitude of the traumatic event (Koungkoulos et al. 2018).

Figure 6.7a–c show that nine scenarios of 1-D breach hydrograph were performed with varying breach width (B_w) and breach formation time (T_f). The results of these

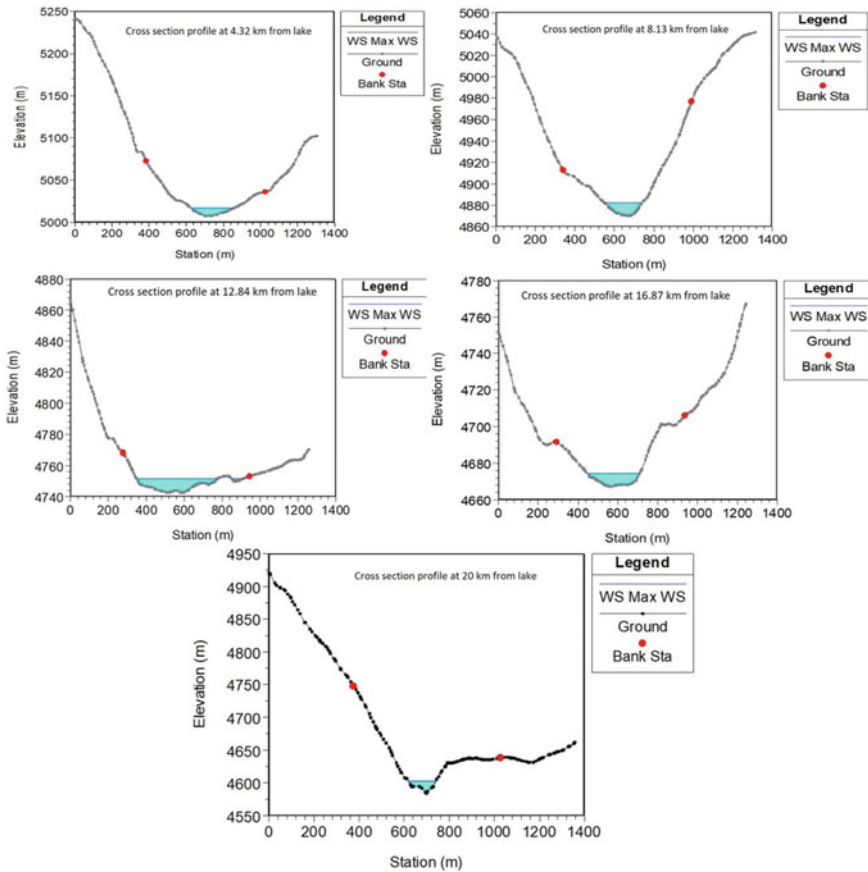


Fig. 6.6 Cross-sectional profiles with water surface levels at various sections across the river

scenarios are given in Table 6.3. We have considered nine scenarios with varied $B_w = 60$ m, $B_w = 40$ m, and $B_w = 30$ m with a constant T_f . These different scenarios were evaluated, and breach hydrograph was estimated.

It is inferred from this study, among the nine different breach scenarios, GLOF breach hydrograph for 40 m B_w and 30 min T_f , produced peak discharge of 14,658.6 m^3/s has been considered as an input for upstream boundary condition, generates flood routing at different sites along the river flow path, which gives different peak flood hydrographs and other significant flood wave parameters like flow depth, flow velocity, and flood peak arrival time.

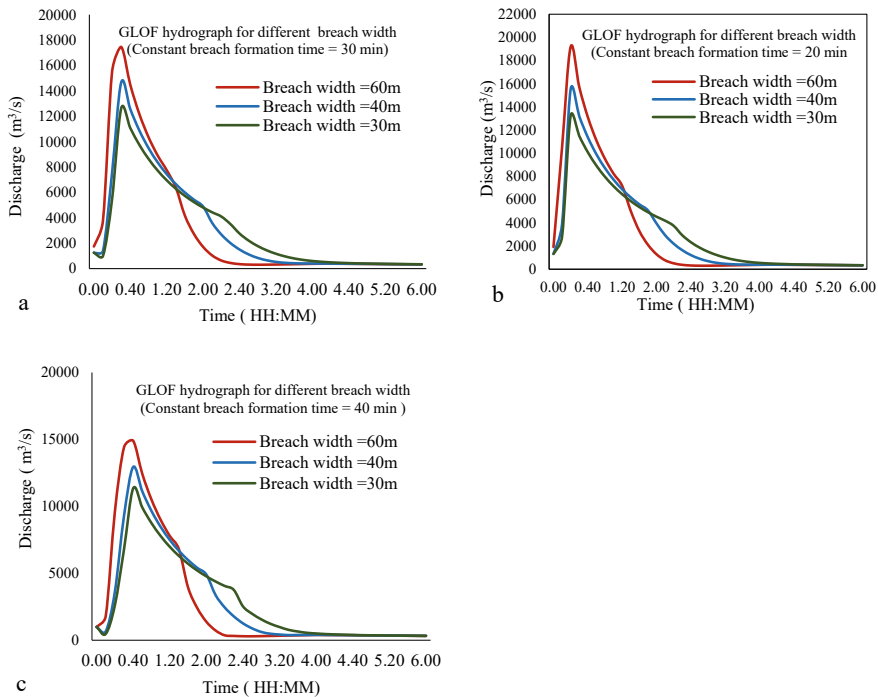


Fig. 6.7 a, b, c Showing peak discharge obtained for varied B_w keeping the T_f constant

6.4.3 Assessment of GLOF Hydrograph at Downstream Sites

The assessment of the different magnitude of flood peak hydrographs at various cross-sections across the river is shown in Figs. 6.8, 6.9, 6.10, 6.11 and 6.12. In this study, attenuated flood peak hydrographs have been evaluated at five different locations at a distance of 4.32, 8.13, 12.84, 16.87, and 20 km downstream from the lake. The estimated flood peak was 14,658.60 m³/s at the GLOF site, and the same got mitigated to 11,978.77 m³/s at the downstream outlet, respectively. The flood peak arrival time from lake to the outlet at a distance of 20 km is about 1 h 20 min. This reflects that the downstream river reach is relatively wide with a gentle slope compared to that narrow valley of upstream glacial area. As a result, flood water spreads across a floodplain resulting in a gradual decrease of peak discharge as it proceeds downstream from the lake, as shown in Table 6.4. In 2013, one of the largest GLOF events in the Chorabari lake in Kedarnath region of Uttarakhand, which is a part of the North-Western Himalayas was triggered by hydraulic pressure caused by massive precipitation and accelerated dam failure, resulting in devastation in a stretch of 18 km downstream along the river, with 6000 lives lost and a substantial quantity of property damage (NRSC 2016).

Table 6.3 Breach parameters like breach width (m) and breach formation time (minutes) for the different GLOF scenarios; Simulated peak flood (m^3/s) of the breach hydrographs

Failure mode- overtopping									
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9
Breach width (m)	60	40	30	60	40	30	60	40	30
Breach time (minutes)	20	20	20	30	30	30	40	40	40
Peak discharge (m^3/s)	19,178.73	15,512.6	13,235.73	17,464.62	14,658.6	12,619.42	14,403.21	12,938.85	11,333.93

Fig. 6.8 GLOF hydrograph at site 1

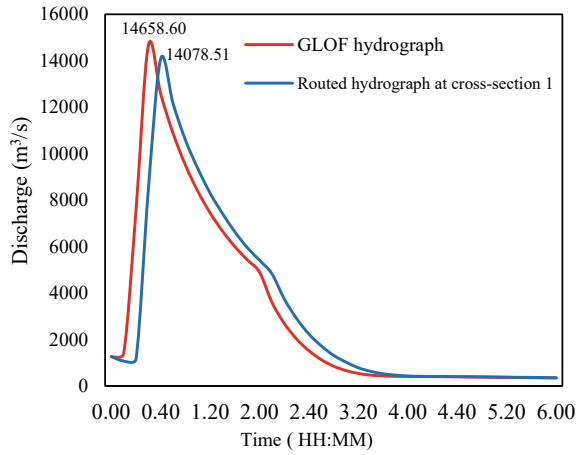


Fig. 6.9 GLOF hydrograph at site 2

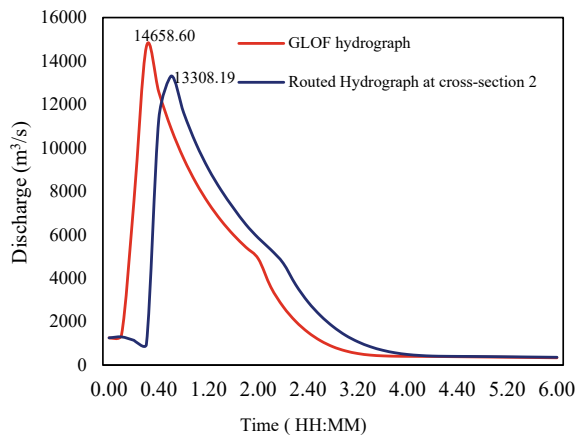
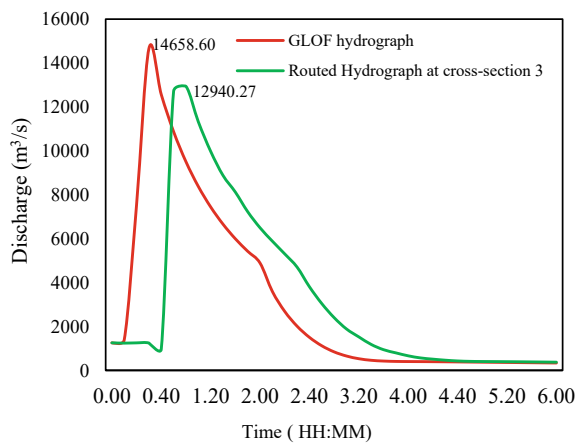


Fig. 6.10 GLOF hydrograph at site 3



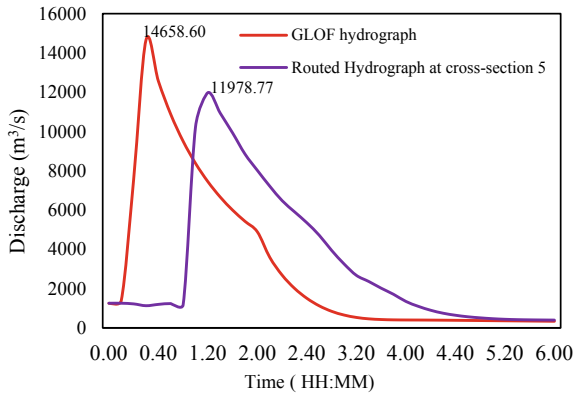


Fig. 6.11 GLOF hydrograph at site 4

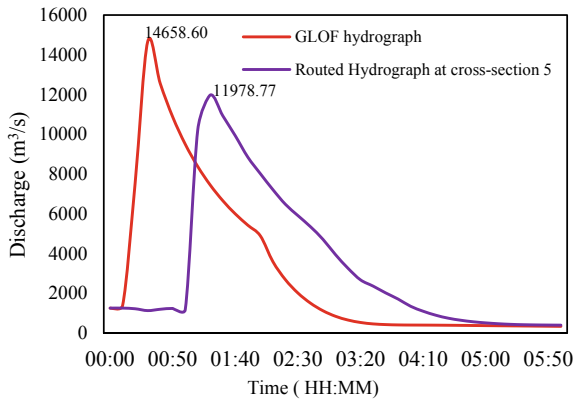


Fig. 6.12 GLOF hydrograph at site 5

High intensity of rainfall or snowmelt could cause a rise in the water level of glacial lakes, resulting in lake overflow or moraine collapse (Emmer and Cochachin 2013). However, temperature patterns and geological characteristics of lake type may provide useful information about external trigger causes of GLOF condition. In the Himalayan region, it has been found that, at least one GLOF event occurs every 3–10 years (Bajracharya et al. 2008), but with increasing temperatures and more climate variability, the frequency of GLOF events is predicted to rise in the coming decades. A hydrodynamic model has been performed to compute peak discharges and flood heights and simulate GLOF repercussions on the downstream section.

Table 6.4 Routed Peak flood and time of peak at different downstream locations along the flow path due to GLOF event

Sites	Distance from Lake (km)	Peak flood (m ³ /s)	Volume (1000 m ³)	Channel elevation (m)	Water surface elevation (m)	Depth (m)	Velocity (m/s)	Flood peak arrival time (HH:MM)
Cross section 1	4.32	14,078.51	77,748.76	5007.5	5017.28	9.78	9.91	00:40
Cross section 2	8.13	13,308.19	78,856.02	4870.09	4882.15	12.06	9.26	00:50
Cross section 3	12.84	12,940.27	81,020.58	4730.94	4738.74	7.8	7.09	01:00
Cross section 4	16.87	12,470.94	82,738.52	4644.54	4657.26	12.72	2.89	01:10
Cross section 5	20	11,978.77	82,960.86	4584.57	4603.43	18.86	9.62	01:20

6.4.4 Inundation Simulation

In the present study, one-dimensional unsteady flow routing has been performed from the lake up to the route of 20 km downstream. The flood hydrograph at just downstream of the lake and different sites across the river are shown from Figs. 6.8, 6.9, 6.10, 6.11 and 6.12. The total flood peak at the GLOF site from the lake is 14658.62 m³/s, and the flood peak at the outlet site is 11978.77 m³/s, and flood peak arrival time from the lake site to the outlet at a distance of 20 km is 01 h 20 min, respectively. The maximum flow depth and flow velocity along the flow path are 22.42 m and 11.29 m/s. Figures 6.13 and 6.14 show the spatial inundation map of flow depth and flow velocity along the river flow path from the South Lhonak lake to the routing stretch up to 20 km. The estimated flood depth and flow velocity in the downstream section varies depending upon the morphology of the river channel.

The figures and tabular data were generated using the finding of one-dimensional flow analysis. They include profiles of the expected peak flood levels and an estimation of the time from the commencement of the breach to the moment the location begins. They have profiles of the predicted peak flood levels and an estimation of the time from the commencement of the breach to the moment the location begins to be inundated. More hazard reference values such as flow depth, flow velocity, water surface elevation, and flood peak arrival time are shown in Table 6.4 for the downstream locations. The flood had created deep canyons, wiped the vegetation in riverbed, rocks, deposited debris and sediments along the river's course (Byers et al. 2019).

The analysis shows that the flood routing varies gradually decreases along with the downstream of lakes. Inundation maps shown in the figures illustrate the areas subject to flooding from a GLOF.

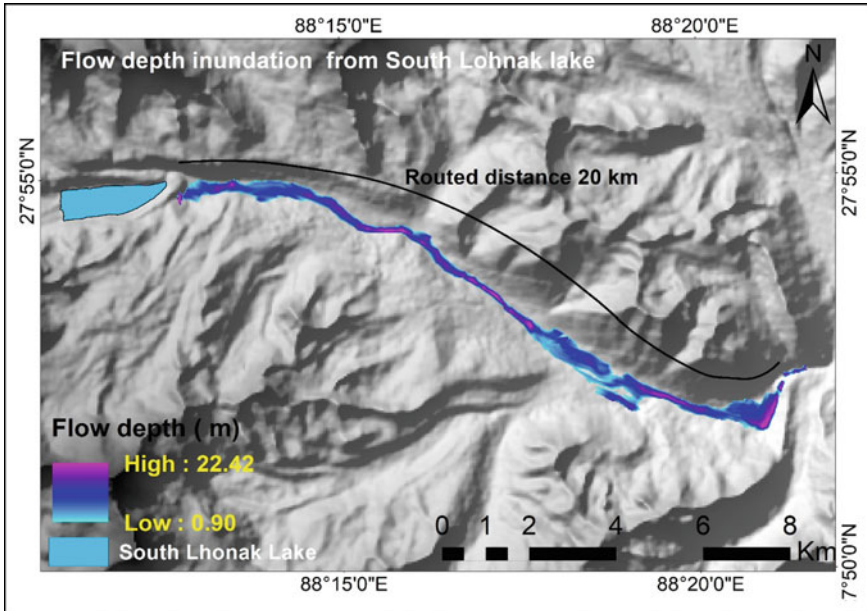


Fig. 6.13 Flow depth inundation map showing from glacial lake to the downstream valley

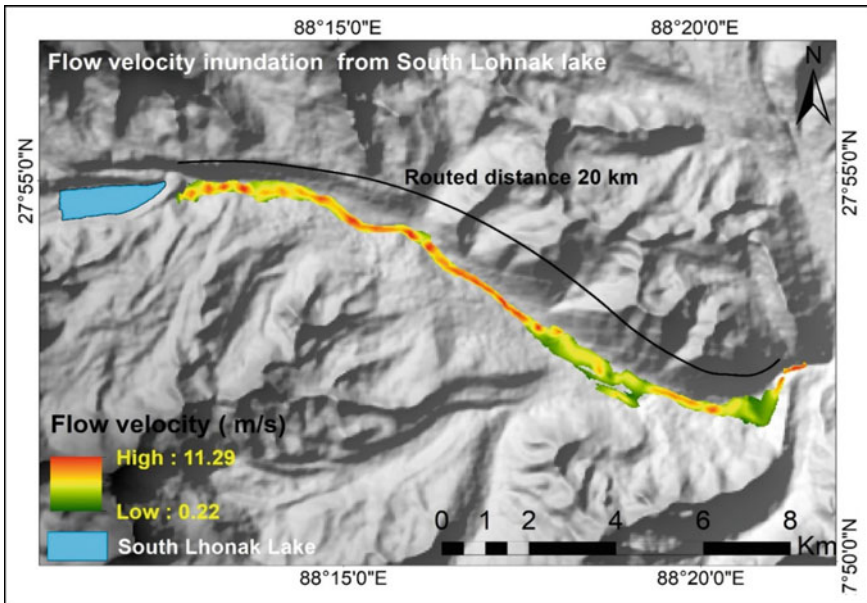


Fig. 6.14 Flow velocity inundation map showing from glacial lake to the downstream valley

6.5 Conclusions

The current study was conducted with the GLOF condition of the South Lhonak lake in the Teesta Basin, Sikkim. The glacial lake area expanded by approximately three times within the past 30 years. The lake was 0.48 km² in 1990 and 1.39 km² in 2020. In this study, cross-section details from the DGPS survey were not accessible due to rugged terrain with high altitudes. Hence, HEC-GeoRAS was used for automatic extraction of river cross-sections from an SRTM DEM, and these cross-sections were modified before being used in an HEC-RAS 1D unsteady flow hydraulic model. The breach of moraine dams leads to the sudden discharge of a huge volume of glacial lake water known as GLOF. For the simulation of GLOF outburst and flood propagation scenarios, the current methodology used dam-break and hydrodynamic models. The dam breach hydrograph was used as an input parameter in HEC-RAS to simulate the GLOF propagation in the downstream section. The estimated flood peak was 14,658.60 m³/s at the GLOF site, and the same got mitigated to 11,978.77 m³/s at the downstream end. The GLOF hazard findings are promising for prospective hydrodynamic modeling studies in India, particularly in the glacierized basins of Himalayas. HEC-RAS, a one-dimensional hydrodynamic model, would be very beneficial for GLOF modeling or flood control studies, as well as the design of hydraulic engineering structures. One of the key actions identified for the country is the monitoring of GLOF and disaster risk mitigation (Ministry of Environment 2010). Monitoring and assessment is further suggested for medium and low outburst-prone lakes. However, it remains a major challenge to enhance and intensify regional collaboration and coordination in order to manage, preserve, and protect the diverse and fragile ecosystems (SAARC 2014). The study's outcomes will aid in formulating risk management plans and risk reduction strategies in the event of a GLOF hazard (Clague and Evans 2000, Haritashya et al. 2018, Kaser et al. 2006).

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