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ASSESSMENT OF GLACIAL LAKE OUTBURST FLOOD IN CHANDRA BASIN, WESTERN HIMALAYAS

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ABSTRACT

Glaciers in many parts of the Himalayas are thinning and retreating as a result of global warming and climate change. These melted glaciers result in formation of lakes between the frontal moraine and the retreated glacier. These lakes are often dammed by unstable moraine and have a propensity to breach and cause destruction in the downstream valleys. Since year 1990 to 2015 there has been an increase of approximately 14% area in lakes of the Trans Himalayan region. In this study a hazard assessment of two prominent glacial lakes in Chandra Basin, Western Himalayas, Himachal Pradesh is performed using 1D and 2D hydrodynamic modelling. A potential glacial lake outburst flood (GLOF) scenario is simulated for the Samudra Tapu lake at ~4200 m and Geepang Gath lake at ~4100 m which have been observed to expand in volume significantly since 1980. The GLOF modelling is performed using the dam breach model. The peak flow is used for mapping the flood in the HEC-RAS 2D version 6.1 software for the simulation of peak discharge and the flood height at the downstream of the lake outlet. The impact of GLOF on the downstream landuse and landcover is assessed by a flood inundation map and the areas to be likely affected is determined. Furthermore, this study also discusses about the need for robust monitoring of these lakes in the high-altitude region and establishment of mitigation protocols to avert loss and damage of life and property due to GLOF hazards.

Keywords: *GLOF, Chandra Basin, Hydrodynamic modelling, glaciers, high-altitude*

INTRODUCTION

The Himalayas, also referred to as the third pole as they hold the world's third-largest amount of glacier ice, following Antarctica and Arctic. Headwaters from Himalayan glaciers serve as an important source of freshwater to major rivers in India (Kumar et al., 2005). However, with the warming of the globe these regions are highly sensitive to change and glaciers are receding at an exceedingly high rate in most parts of the world (IPCC 2022; ICIMOD 2010; Maskey et al., 2020). A study by Shugar et al. (2020) estimate that global glacier lake volume has increased by around 48%, between 1990 and 2018. Several studies on the Himalayan region, have made an effort to detect and monitor the change in existing glacial lakes and addition of new ones using remote sensing techniques (Worni et al., 2013; Zhang et al., 2015; Nie et al., 2017) and field investigations (Richardson and Reynolds, 2000).

The melted glacier often results in the formation of lakes between the frontal moraine and the retreated glacier (Carrivick and Tweed 2013). The lakes located at the snout of the glacier are mostly dammed by the lateral or end moraine, where there is high propensity of breaching. Such lakes could induce hazard as they may hold a large quantity of water. Breaching and the instantaneous discharge of water from such large moraine dammed lakes can cause flash floods enough to create enormous damage in the downstream areas (Jain et al., 2012). GLOF risk assessments have been performed at different scales ranging from basin wide studies to site specific assessments. Nearly 9000 glacial lakes and about 200 glacial lakes with a potential hazard risk have been identified in the Himalayan region which has resulted around 40 GLOF events in over the past four decades (Yamada and Sharma 1993; Ives et al. 2010). Based on the analysis carried out 2018 in the basins in Himachal Pradesh using LISS III satellite data, 1154 lakes were identified of which 59 lakes had an area greater than 10 ha, 73 lakes area ranged between 5-10 ha and 1022 lakes had an area less than 5 ha (Randhawa et al., 2020). The national level lake inventory and GLOF risk assessment were done by Worni et al. (2013) identifying 251 lakes of which 104 were potentially dangerous. Current and future potential of GLOF across the state of Himachal Pradesh in India was studied by Allen et al. (2016) wherein the flood impact on societal vulnerability on downstream areas was analyzed. Sattar et al. (2019) assessed the evolution and potential GLOF hazard risk of Safed Lake in the downstream settlement in Uttarakhand using HEC-RAS 1D and 2D modeling. Das et al., (2014) analysed the devastating Kedarnath floods of Uttarakhand digital elevation models and satellite images by quantifying of debris flow following dam breach (Frey et al., 2010; Allen et al., 2016; Linsbauer et al., 2016; Zhang et al., 2019) are some of the only available studies on Himalayan glaciers that not only inventory and assess current GLOF risk but also detect sites for potential future lake formation and their risks based on methods and models using geospatial techniques.

The present research aims at assessing the evolution and potential GLOF hazard from large moraine dammed lakes like Samudra Tapu and Geepang Gath in the Chandra Basin. The evolution of these lakes is measured using satellite imageries from 1980 to 2022. The GLOF risk is simulated for a breach at peak discharge using HEC-RAS 2D version 6.1. The impact of exposed landuse and landcover features to the flooding extent in the basin are also assessed.

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STUDY AREA

The Chandra Basin is located in the Lahul-Spiti valley of Himachal Pradesh India. The basin is drained by the Chandra River originating from the glacier of the Bara-lacha la pass (Randhawa et al., 2020) and nearly 44% of the basin is covered with snow and glaciers. The basin is located in monsoon-arid transition zone and receives precipitation between July and September due to Indian summer monsoon and experiences precipitation due to westerly disturbance which meets the Bhaga River in Tandi, to form Chenab River. The basin includes nearly 52 moraine dammed lakes between January and April in winter season. (Bookhagen and Burbank 2010). Samudra Tapu lake at (32.11°N and 77.74° E) and Geepang Gath lake at (32.52°N and 77.21°E) are the two largest proglacial lakes in this basin at ~4200m and ~4100 m above mean sea level respectively. Samudra Tapu lake with an area of 154 ha is fed mainly by the Samudra Tapu glacier which is covered by unconsolidated sediments. Geepang Gath lake with an area of 101.5 ha fed by the Geepang Gath glacier which is prone to avalanches. Samudra Tapu lake is dammed by a relatively flat moraine

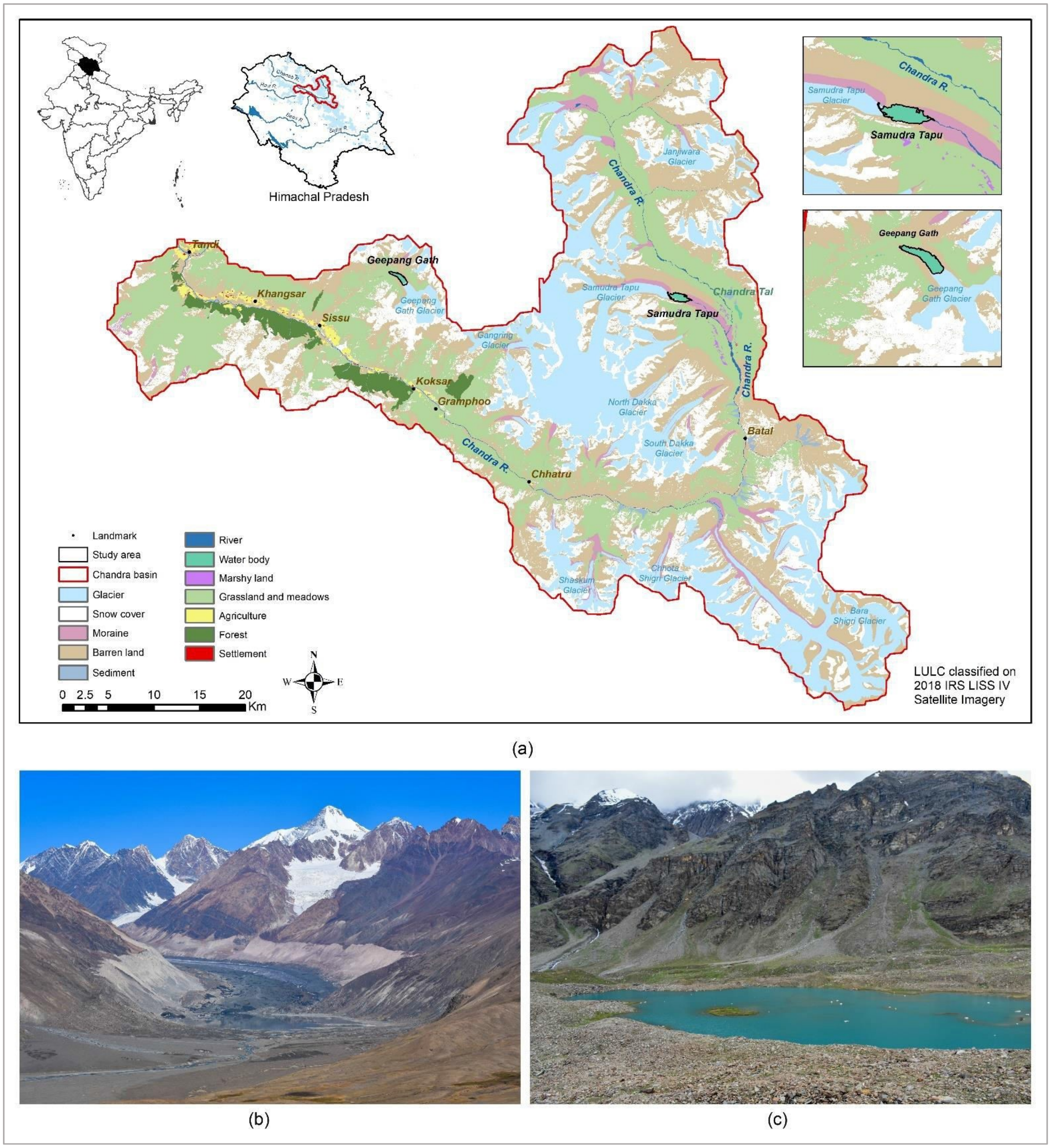

Fig. 1: Location and extent of (b) Samudra Tapu lake and (c) Geepang Gath lake in the (a) Chandra Basin, Himachal Pradesh

debris complex with a "hummocky" surface suggesting possible presence of buried ice cores. Whereas Geepang Gath has undergone a significant glacier retreat is dammed by end-moraine dam. Also, being a proglacial lake, they are located at the snout of the parent glacier, which is marked by a tall ice-wall and a zone of glacier-calving (Figure 1(b) and 1(c)). Streams discharging from both the lakes drain into the Chandra River travelling across major settlements present in Batal, Chhatru, Khoksar, Sissu, Khangsar and Tandi. These settlements cover an area of 36 ha with nearly 300 individual buildings and several farmlands.

MATERIALS AND METHODS

Lake area estimation

To estimate the change in area of the extent of Samudra Tapu and Geepang Gath lakes since 1980 remote sensed images of Landsat and Sentinel from 1980, 1992, 2000, 2010, and 2022 were used as shown in table 1. A combination of index-based and manual delineation was used to arrive at the lake extent for different years. All of the images were resampled to 30m. Normalized Difference Water Index (equation 1) was calculated to identify the extent of water pixels in the study region. Different thresholds were utilized to exclude snow cover and non-water pixels. The identified pixels of water cover were then cross-verified with visual interpretation of different false color composite.

(1)

Table 1: Details of satellite data used for deriving the extent of open water in Samudra Tapu lake and Geepang Gath lake.

Year	Satellite/ sensor	Date of acquisition	Resolution	Bands used
1980	Landsat 3 MSS	1980-09-16	60/ 30m	B4, B7
1992	Landsat 5 TM	1992-08-14	30m	B2, B4
2000	Landsat 7 ETM+	2000-09-29	30m	B2, B4
2010	Landsat 5 TM	2010-09-17	30m	B2, B4
2022	Sentinel 2A MSI	2022-09-26	10m	B3, B8

Estimation of lake volume and peak discharge

To demonstrate the two lake's propensity to outburst two steps were adopted i.e., 1) simple empirical method and 2) GLOF hydrodynamic modelling. The first step is based on the empirical relationship of the lake characteristics and the second step followed, is a mathematical model for predicting the breach parameters and determining the incremental velocity and depth of the inundation that occurred during the outburst event of the lake.

The areal extent of the lakes was delineated with the sentinel 2 images of the year 2022. As no ground estimation of the total volume of the lakes was done an empirical formula shown in equation 2 of (Christian Huggel, 2002), was used to estimate the volume of the two lakes. The equation was used for the lake over the Swiss Alps during the time of its outburst and from then the equation is widely used for the Himalayan landscapes

$$V=0.104 \times A^{1.4} \qquad (2)$$

Where V is the volume of the lake in m^3 and A is the area of the lake in m^2.

The peak discharge of the lakes was calculated after estimating the volume, using equation 3 proposed by (Christian Huggel, 2002)

$$Q_{max} = 0.00077 \times V^{1.017} \qquad (3)$$

Where V is the volume of the lake in m^3 and Q_{max} is the peak discharge from the lake during the event of GLOF.

2D unsteady flow modeling of GLOF using HEC RAS

For performing the flood simulation in the downstream areas of the lakes the two-dimensional unsteady flow of the Hydrologic Engineering Center's River Analysis System (HEC-RAS v 6.1) developed by the US Corps of Engineers were used. The model can simulate the multichannel flow and multi-directional flow which are the dynamic characteristic of GLOF (M.J. Westoby, 2014). The modelling and mapping of the 2D unsteady flow were performed with SRTM DEM data for the month of July,2022 of the Chandra basin by creating the terrain model. The terrain was divided into mesh with equal dimensions of grids of 50x50. The cell created has a set of terrain properties like the elevation and manning's roughness coefficient (Ashim Sattar, 2019).

At first, the projection system of the study area was defined i.e., UTM 43N. A 2D flow area and the storage area within the terrain were established for each lake. The 2D storage area connection was defined and the breaching were performed. The Froehlich (2008) regression equations were used to estimate the breach parameters of the moraine dam, to calculate the dimensions the breach parameter calculator within the HEC RAS v 6.1 were used for. The material properties of a dam have a great role to control the GLOF event, as it affects the erodibility factor of the dam and these properties are also taken into consideration and are shown the table 2. Field observations were tallied with the software generated inputs for the moraine parameters. The Breach simulation time of 24 hrs were defined for both the lake, with a date time interval of 1 hour. From the unsteady flow simulation, the flood inundation, the depth of the flood, the time of the peak velocity and the incremental elevation of the water surface in the downstream areas are obtained as shown in the results.

Table 2: Moraine dam input properties

Dam data	Samudra Tapu lake	Geepang Gath lake
Top of dam elevation (m)	4173	4090
Toe of dam elevation (m)	4158	4075
Dam crest width (m)	55	60
Breach height (m)	15	15
Breach Formation time	2.97	1.83
Breach bottom width (m)	88	80
Failure mode	Over topping	Over topping
Time of breach from start of simulation (hours)	2.9	1.8

Impact of GLOF on LULC

The landuse and landcover (LULC) of the Chandra basin was produced through supervised image classification of IRS LISS IV image of 2018 having a 5.8m resolution. To derive the impact of the GLOF event on LULC, the LULC was intersected with the water depth for both Samudra Tapu and Geepang Gath lakes. Both the LULC and depth raster were converted to vectors. The intersect tool of ArcGis was then used on these vectors to obtain the LULC and depth overlap. Agriculture and settlements were the main land use considered for assessing the damage at Batal, Chhatru, Khoksar, Sissu, Khangsar and Tandi which serve as major commercial and tourist hotspots. The approximate distance of the settlements from the two lakes are as shown in table 3.

Table 3: Approximate distance of major settlements from the lakes

Settlement	Distance from Samudra Tapu lake (in kms)	Distance from Geepang Gath lake (in kms)
Batal	24	
Chhatru	55	
Khoksar	78	
Sissu	92	12
Khangsar	101	9
Tandi	117	25

RESULTS AND DISCUSSION

Evolution of Samudra Tapu and Geepang Gath lakes during 1980-2022

Based on the satellite imagery-based delineation, the spatial extent of Samudra Tapu and Geepang lakes were explored. It was observed that Samudra Tapu lake has expanded from 23.9 ha in 1980 to 151.1 ha in 2022. The expansion is approximately 6.5 times its coverage at ~0.15 ha per year in the last 4 decades. Similarly, Geepang Gath lake has expanded nearly 5.5 times from an area of 18.4 ha in 1980 to 1.015 ha in 2022 with an average rate of 0.13 ha per year. The aerial change and statistics for the two lakes during the years 1980,1992,2000,2010 and 2022 are shown in figure 2 and table 4. The expansion of these lakes is largely attributed to sub-aerial melting, thermo-erosional notching and glacial conduits (Benn et al. 2000). The largest lakes in the glacial regions of Nepal, Bhutan and Tibet might also have formed in this manner (Richardson and Reynolds 2000). Apart from the normal ablation, calving is a dominating factor to increase the ice loss and lake volume (Thakuri et al. 2016). The ice–water interface can accelerate the loss of ice through calving process as seen in Geepang Lake (Patel et al., 2017). One of the causes of accelerated melting could be a thin layer of debris on the ice surface (Patel et al. 2017).

Table 4: Expansion of Samudra Tapu and Geepang Gath lakes during 1980-2022

Year	Samudra Tapu lake area (ha)	Geepang Gath lake area (ha)
1980	23.9	18.4
1992	69.4	40.4
2000	68.7	44.7
2010	119.3	64.7
2022	154.1	101.5

GLOF modeling

The breach for modelling the GLOF event for the two lakes were simulated for the maximum flow recorded for the maximum volume of the lake as of 2022. Using the empirical formula for estimation of volume (equation 2), Samudra Tapu lake and Geepang Gath lake holds ~65.34 $x10^6$ m^3 and $33.46x10^6$ m^3 of water respectively. The peak discharge for calculated using equation 3 which shows Samudra Tapu lake has the potential of 68321.93 m^3s^{-1} of peak flow and Geepang Gath lake has 34592.57 m^3s^{-1}. The maximum depth of inundation can reach upto 14.59 m and 31.62 m whereas the maximum velocity of the water would reach upto 11.59m/s and 43.51m/s during the GLOF caused by Samudra Tapu lake and Geepang Gath lake respectively (figure 3,4,5 and 6). The maximum breach flow achieved for Samudra Tapu lake and Geepang Gath lake were 1555.8 CMS and 803.21CMS at the time of the breach respectively. The topography plays a critical role for the depth and velocities of the outburst flow achieved in the simulation. Geepang Gath lake located at an elevation gain of nearly 1200m from the main channel of the Chandra River with a distance of just 12 km highly impacts the velocity of the water flowing downstream. The steeper slope in the case of

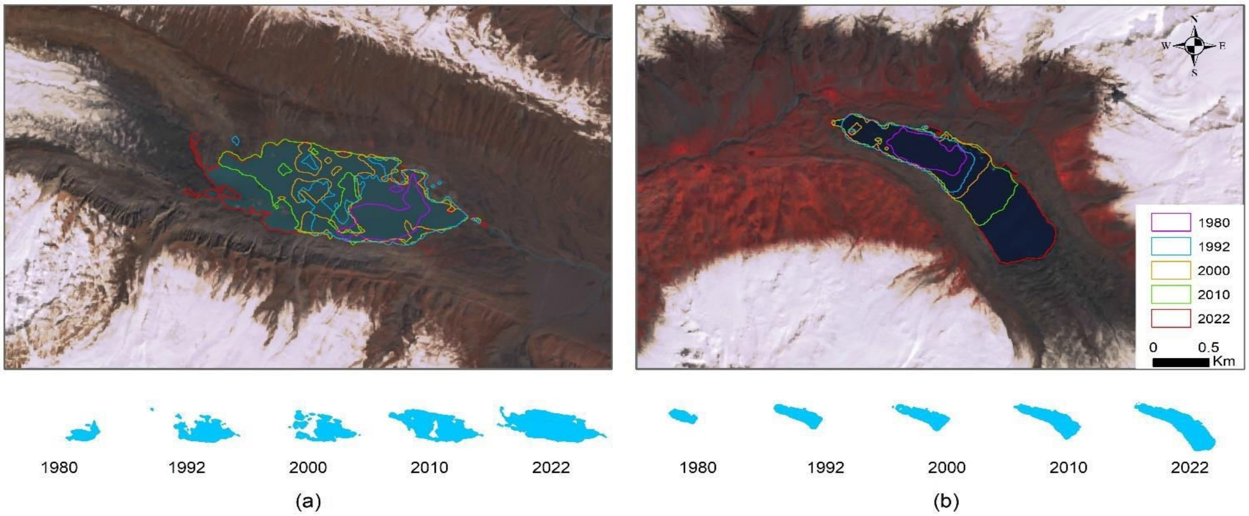

Fig. 2: Evolution of (a) Samudra Tapu lake and (b) Geepang Gath lake during 1980-2022

Geepang Gath lake's GLOF puts the vicinity landscape and the settlements to a greater risk of damage due to the hazard as compared to the case of Samudra Tapu lake's outburst.

Impact of GLOF on downstream settlements.

The GLOF model simulated for breaching of Samudra Tapu lake and Geepang Gath lake is observed to pose significant impact on the landuse and landcover of the downstream. The GLOF simulation results from Samudra Tapu lake indicate that certain parts of the settlements of Batal, Chhatru, Teling (near Atul tunnel), and Koksar will be inundated. Batal faces an inundation of 390.4 sq m while Chhatru, Koksar, and Teling experience inundation of 286 sq m, 3003.5 sq m, and 3904.2 sq m respectively. The maximum depth of inundation of settlements at Batal is in the range of 0.1m to 5.6 m while Chhatru experiences an inundation depth of 0.2m to 1m and Koksar a depth of 0.1m to 6.7m. Teling experiences inundation up to a depth of 4.1m. A total of 7584.2 sq m of settlement area was simulated to be inundated. Agricultural areas are also affected due to the flood inundation with a total of 35152.3 sq m going under water with depths ranging between 1m to 6m. The depth of water in agriculture fields near Koksar reaches up to 2.7m while certain fields near Koksar and Teling can be inundated up to 4.8m depth. Fields that lie near the river below Kangsar can experience inundation depths up to 3.6m as shown in the figure 3.

In this simulation for Samudra Tapu lake the maximum velocity of the flood water is 9.3m/s and the mean velocity is 2.1m/s. The velocity of the flood water is upto 4.7m/s while exiting the lake. It reaches to 5.7m/s near Batal. A little downstream of Batal, near a bend in the river, the velocity increases from 1.6 to 4.75m/s. A little upstream of Chhatru, the velocity reaches 7 m/s. At Chhatru, it reaches 5.1 m/s. At Sissu, and Khangsar the velocity ranges from 2.5 m/s to 5.6 m/s and 2.2m/s to 5.3m/s respectively while ranging between 1.7-3.6 m/s and at Tandi before joining Bhaga River. considering the breach time at 2.9 hours from the start of the simulation the peak flood takes nearly 3.1, 6.6, 8.1, 9.6, 10.6 and 12.1 hours to reach Batal, Chhatru, Khoksar, Sissu, Khangsar and Tandi respectively. The wide river bed and flatter topography near Chandratal and Samudra Tapu lake serve as a buffer to increase the duration of the flood.

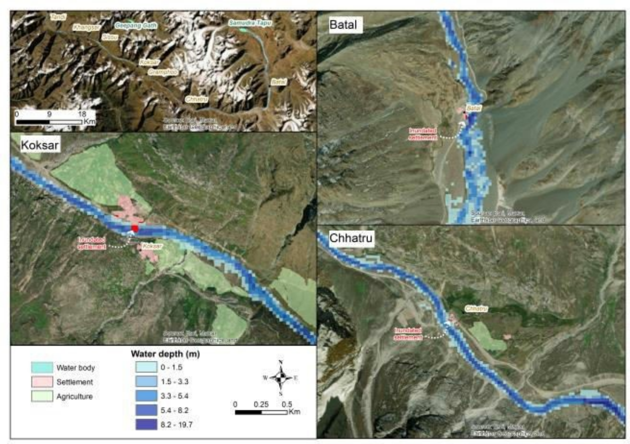

Fig. 3: GLOF inundation due to Samudra Tapu lake at the downstream areas.

However, the gradual slope from Samudra Tapu lake to Khoksar allows the floodwater to stay for a longer duration at these locations. The flood waters will largely impact the roads connecting Manali to Kaza and Chandratal. The Batal bridge and the buildings in the region serve as the major stopover areas to the large number of tourists visiting the landscape and therefore is highly vulnerable to the GLOF hazard from Samudra Tapu lake.

For the Geepang Gath lake's GLOF event simulation, the downstream Sissu is the only village that is experiencing inundation of the settlement area. An area of 3552.3 sq m is inundated up to a depth of 13.8m. Agriculture inundation is a total of 38318.5 sq m and can experience inundation up to 6 to 7m depth. The inundation of fields is mainly faced in

Sissu (up to 10m) and fields near the river at Kangsar (up to 2.3m).

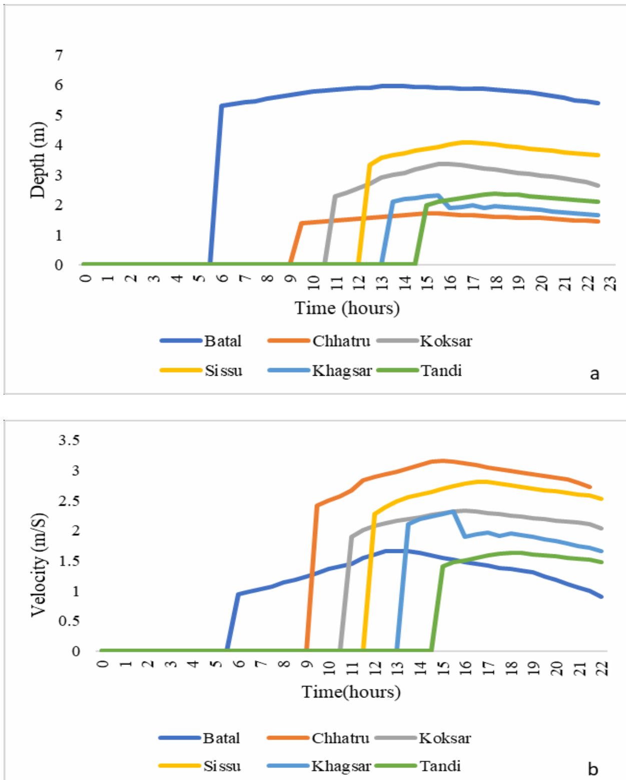

Fig. 4:(a) Depth of inundation and (b)velocity achieved at major settlements due to GLOF at Samudra Tapu lake

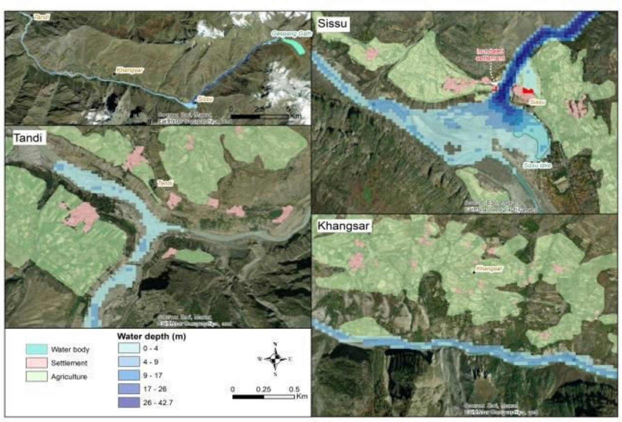

Fig. 5: GLOF inundation due to Geepang Gath lake at the downstream areas.

In this simulation the maximum velocity is of floodwater 110.4 m/s and the mean velocity is 8.1 m/s. The exit velocity at the lake is up to 6.2 m/s. A little downstream of Geepang Gath lake, the velocity reaches higher than 40 m/ s, and up to 110 m/s. While reaching near Sissu, the velocity of floodwater ranges from 30 – 40 m/s. The high velocity is buffered at the Sissu lake as it reduces to less than 5m/s. The velocity of the water then gradually reduces at Khangsar, ranging from 2 to 5 m/s. And at Tandi, it ranges from 1 m/s to 3m/s. Considering the breach occurring at 1.8 hours from the time of simulation, the maximum floodwater reaches Sissu, Khangsar and Tandi within 0.2, 1.2 and 2.7 hours respectively. Such high velocity waters will not only devastate the village of Sissu but also pose greater risk to the overall flow of the river and may extend beyond Tandi. A study by Mukhtar el al., (2021) has also indicated that the GLOF event of Gepang Gath Lake would destroy the road and highway connecting Leh and Manali as well as the bridge near Sissu connecting Sissu town to Sissu waterfall area.

Considering a possible increase in the discharges from Samudra Tapu lake and Gepang Gath lake in the future, GLOF hazard damage is likely to occur unless proper mitigation and adaptation strategies are in place.The slope of the valleys, and moraine dam heights are some of the major factors influencing the damage potential of glacial lakes (Huggel et al. 2002). The study also indicates that while Samudra Tapu lake has a high flood discharge potential, Gepang Gath lake has a high damage potential due to their location. With a rapid increase in the glacial ice melting, lake expansion, critical peak discharge and catchment topography (steep valleys and high moraine dams), the situation in the Samudra Tapu and Gepang Gath region is highly critical, which could lead to increased GLOF incidents affecting life and property (patel et al., 2017).

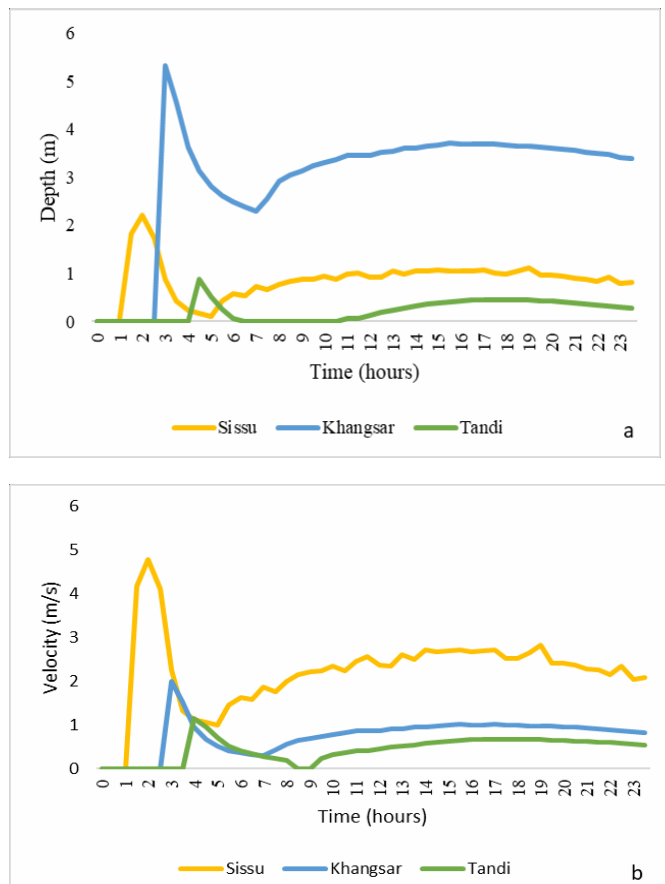

Figure 6:(a) Depth of inundation and (b)velocity achieved at major settlements due to GLOF at Geepang Gath lake

In this study the hydrodynamic modelling for GLOF has been simulated for Samudra Tapu lake and Geepang Gath lake considering the peak discharge from the lake and the maximum possible width of the moraine dam breach obtained by the empirical equations provided by the software. This means the output achieved are for the worst-case scenario of GLOF events at both the lakes. However certain limitations may also impede the model results.

Software like HEC-RAS do not have landuse and landcover feature as inputs wherein certain landscape features like wetlands, floodplains, peatlands and boulders have an enormous potential to buffer floods.

With changing climate and warming of the globe the formation of new lakes and expansion of the existing high-altitude Himalayan lakes are evident. This poses a serious risk to the ecosystem and people in those regions. The GLOF will likely become a more serious issue in the coming years due to the gradual glacier retreat and increased melt rates. Landslides due to heavy runoff and the steep terrain are and will continue to be major problems. GLOF can also be caused due to avalanches and landslides that can occur when the shearing stress of the snow is exceeded due to excessive snow load. Increased intensity of snowfall and temperature variability contribute to increased risk of these events.

Increased rainfall intensity and runoffs resulting from climate change are likely to increase the risk of floods. Uncertainty and variations in weather patterns possibly could cause major asset and crop losses. It is imperative to create an inventory, conduct assessments and monitor current changes in glacial lakes as well as the potential formation of future ones that pose a risk of GLOF hazard. The Himachal Pradesh government has taken some serious initiatives to tackle climate change. A state-level Governing Council and Executive Council on Climate Change have been set up for planning climate change mitigation and adaptation strategies and enhancing the state's preparedness for natural disasters such as lake outbursts, earthquakes, landslides, glaciers, flash floods etc.

CONCLUSION

The Himalayan region hosts a number glacial lakes likely to induce GLOF hazard and has also experienced disastrous GLOFs in the past. Climate change-driven glacial retreat is one the major reason behind the formation and expansion of such lakes. In this work, we analyzed the dynamics and evolution of two large moraine dammed lakes in the Chandra Basin, Western Himalayas, Samudra Tapu lake and Geepang Gath lake. The study employed the USE of HEC-RAS to model a GLOF scenario for the peak discharge using DEM and other input parameters. Samudra Tapu lake and Geepang Gath lake has expanded nearly 6.5 and 5.5 times respectively posing a potential risk of GLOF hazard. The simulation revealed that while Samudra Tapu has a high discharge potential and causes damage to roads and settlements to some extent, the damage due to Geepang Gath lake is very high especially to Sissu and adjoining areas. Due to the fact that this study has only been executed for the worst-case scenario, it is recommended to run simulations for multiple scenarios and also to include the potential of the landscape to aid in buffering the flood. A detailed site-specific investigation and continuous monitoring of these moraine dammed lakes and its structures are necessary to take informed actions to avoid a catastrophe. Further steps for damage reduction, flood protection and water management can be implemented.

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