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ORIGINAL ARTICLE

# Assessment of Proglacial Lakes in Sikkim Himalaya, India for Glacial Lake Outburst Flood (GLOF) Risk Analysis using HEC-RAS and Geospatial Techniques

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## ABSTRACT

**Existence and expansion of glacial lakes from Sikkim Himalaya enhances the susceptibility of the region to glacial lake outburst floods (GLOF) causing destruction of infrastructures and loss of life in the downstream region. Apart from the expanding glacial lake, various topographic factors play important role in its susceptibility to GLOF. This study aims to find out the GLOF susceptibility of a relatively stable lake, Shako Cho in terms of areal expansion using different topographic parameters. The lake volume has been estimated using area-based scaling method. Using Sentinel-2A satellite imagery and ALOS- PALSAR digital elevation model, probable avalanche pathway, steep lakefront area (SLA) have been mapped. Estimating the potential lake lowering height from the digital elevation model, potential flood volume (PFV) has been quantified. A band-ratio method has been employed to extract the debris-cover around the glacial lake. This lake has a PFV of 45.478*$10^6$ $m^3$ water. Sikkim being a hilly terrain, some of its glacial lakes are located in highly avalanche prone zone. Excessive snowfall often causes snow avalanche in those region. Thus a snow-avalanche triggered GLOF simulation in HEC-RAS 5.0.6, using 2D dam breach scenario has been performed to evaluate its impact on the downstream region.**

## INTRODUCTION

During recent decades, different parts of the Himalayan region, have been witnessing continuous retreating and thinning of glaciers at a high rate (Bolch et al. 2012) which might influence the development of future unstable glacial lakes at the different part of a glacier body (Quincey et al. 2007; Frey et al. 2010). The retreat of the glacier termini and transport of the glacier mass helps in the formation of new lakes and also in the expansion of pre-existing lakes, within the glaciers, developing as proglacial or supraglacial lakes (Gardelle et al. 2012; Carrivick and Tweed 2013; Debnath et al. 2019). The existing inventory and reports suggest that the glacial lakes of the Indian Himalayan Region (IHR) are generally less critical when compared to glacial lakes of other Hindukush Himalayan countries, such as Nepal or Bhutan (ICIMOD 2010). A clear exception to this trend has been observed in Sikkim, where many large and potentially critical glacial lakes exist (Worni et al. 2013). Continuous expansion of proglacial lakes over the observed years in Sikkim has indicated that the areas of the lakes have been increasing at critically faster rates, though the rate varies among different lakes. When glacial lakes exist in the front portion of a glacier (proglacial lakes), it enhances melting of ice since comparatively warmer lake water makes contact with the ice producing the calving effect, which is the detachment of large chunks of ice from the front portion of a glacier (King 2020).

Glacial lake outburst floods are generally short-lived flood and supply water with high-velocity to the downstream channel. As a result of the loss of dam material integrity due to the impact of ice, snow or rock avalanches entering the lake, glaciers calving the lake or seismic activity, glacial lakes may burst over time. (Richardson and Reynolds 2000a; Westoby et al. 2014). Snow avalanche around any moraine-dammed glacial lakes would cause mass inflow into the lake, following a probable ice avalanche trajectory (Dubey and Goyal 2020) can generate glacial lake outburst floods in the downstream area and any deglaciating regions worldwide (Vilímek et al. 2014; Carrivick and Tweed 2016; Emmer et al. 2016). Glacial lakes, mostly those which are proglacial in nature, have been assessed using topographical criteria from (Worni et al. 2013) and identified whether critical or not in terms of glacial lake outburst probability. In this study, an avalanche triggered glacial lake outburst flood simulation has been performed to quantify the intensity of destruction in terms of water discharge and flood volume to its downstream region.

## STUDY AREA

A glacial lake, named Shako-Cho (in Sikkimese, Cho = lake), which is located in the highly avalanche-prone zone of North Sikkim falling under the critical glacial lake category has been assessed. Shako Cho (88°36'58"E / 27°58'29"N) lake is located below the south face of Mount Kangchengyao (6889 m a.s.l) of Tista basin in North Sikkim district (Fig. 1). It contains a volume of 28.528*$10^6$ $m^3$ water as a storage. In the absence of in-situ data, the lake volume has been estimated using empirical method (Sharma et al. 2018). During the observation period of 2000 – 2018, the lake area has not been observed as expanding, thus making it comparatively ‘stable’ in terms of areal expansion. It is located in the highly avalanche-prone zone of Sikkim and surrounded by steep, glaciated hilly terrain (Sikkim State Disaster Management Authority, 2012). The lake is dammed by end moraines consisting of loose and granular material. The geographical location and topographical attributes make it prone to glacial lake outburst flood (GLOF) problem. A small tributary channel originating from the lake drains into the Tista river. A village named Thangu (3900 m a.s.l) located 12 km downstream of the lake may get affected if any glacial lake outburst flood takes place in future.

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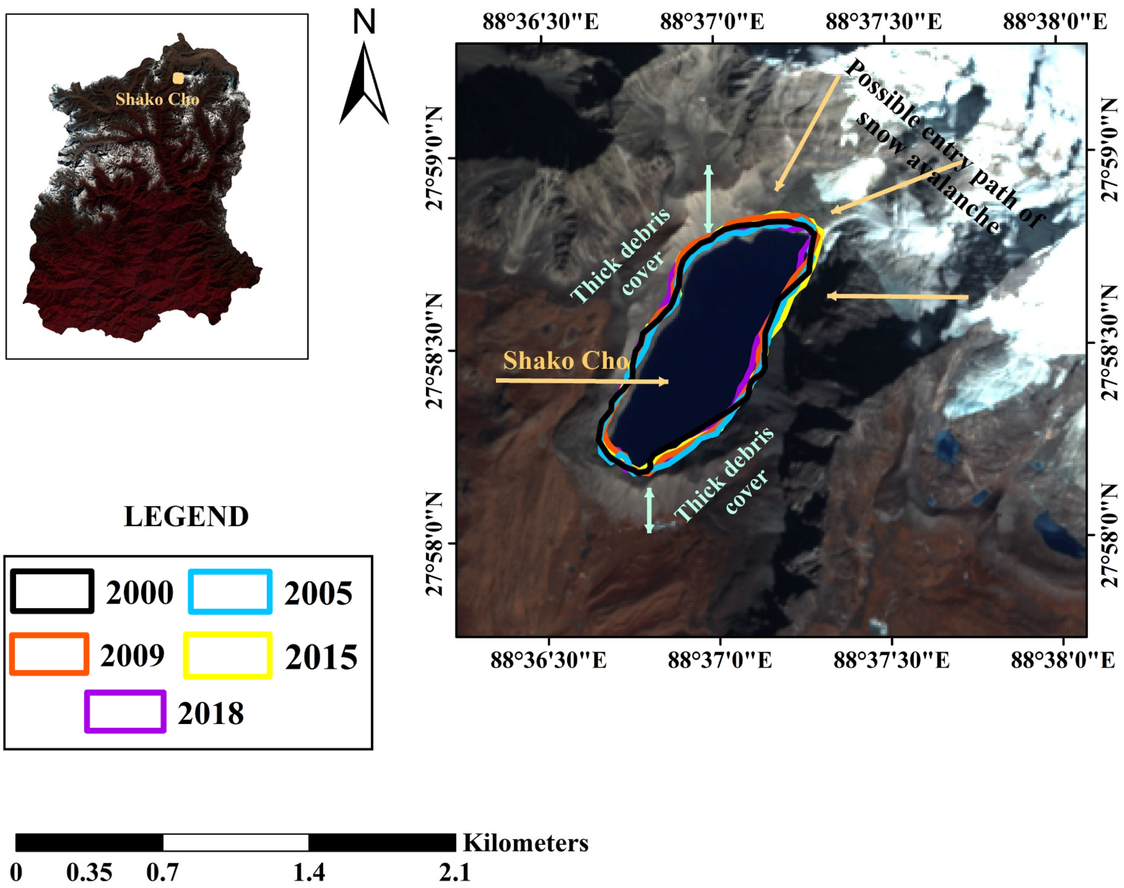


**Fig. 1.** Study area (Shako Cho, with its spatial extension from 2000-2018)

Snow avalanche or any impact of mass movement to the lake may lead to overtopping flow from the dammed periphery of the lake towards the downstream side (GAPHAZ 2017). This may erode the dam due to its sharp geometry and loose damming materials. During the study, it has been observed that some flow of water from the lake was noticeable. In the event of any avalanche or mass movement, an enormous impact can be expected on the lake leading to possible dam failure and release of large volume of water downstream through the above mentioned narrow channel towards the Tista river, with a high hazard potential to the nearby Thangu village area.

## DATA SETS USED

Sentinel-2A multispectral satellite datasets were mainly utilised for this study. This covered ablation period of November 2018 and for the accumulation period data of February 2019 has been used to delineate the probable snow avalanche pathway from the surrounding hills towards the lake. Elevation and slope information has been extracted for the study region using ALOS PALSAR digital elevation model (DEM) of 12.5 m (2006-2011) spatial resolution (Table 1) from the Alaska Satellite Facility (ASF) Distributed Active Archive Center (DAAC). The fine resolution of 10 m from Sentinel-2A imageries has been proved useful for the GLOF study.

**Table 1** Details of satellite data used

| Date | Sensor | Spatial resolution (m) |
|---|---|---|
| 2018/11/26<br>2019/02/04 | Sentinel 2A 1C MSI | 10, 20, 60 |
| 2006 - 2011 | ALOS-PALSAR digital elevation model | 12.5 |

## METHODOLOGY

Dams fail when the material strength is exceeded by driving forces that comprise, among others, the weight of the impounded water mass, seepage forces, earthquakes and shear stresses from overtopping flow or displacement waves (Korup and Tweed 2007; Massey et al. 2010). Overtopping flow of water can be caused due to heavy rainfall or a sudden influx of water from upstream areas. On the contrary, displacement waves are generally triggered by mass movements entering the lake, such as snow and ice avalanche, rockfalls, landslides or debris flow (Costa and Schuster 1987; Clauge and Evans 2000; Huggel et al. 2004; Carey et al. 2012). Lake dams that are prone to failure, magnitudes of potential GLOFs can be approximated with empirical relationships (Evans 1986; Huggel et al. 2004; Kershaw et al. 2005) or calculated using empirical and physical models. Different types of dam breach and flood models have been applied to model glacial lake outburst scenarios and to assess potential downstream impacts (Huggel et al. 2003; Bajracharya et al. 2007; Wang et al. 2008; Mergili and Schneider 2011; Osti et al. 2013).

Glacial lakes, those which are at high risk are situated at the high altitude and remote areas. Remote sensing based approaches for monitoring and risk assessment methods provide them a feasible way (Washakh et al. 2019). All existing glacial lakes are not unstable and most of the lakes will not burst out catastrophically (Huggel et al. 2004). Lake outburst probability is a function of the susceptibility of a dam to fail and the potential of external trigger processes (Richardson and Reynolds 2000a). Dam stability depends mainly on its geometry, internal structure, and material properties (Costa and Schuster 1987; Korup and Tweed 2007; Fujita et al. 2009). Dam stability can change over time, as for instance melting of stagnant ice within moraine dams can contribute to weakening of overall dam structure (Clauge and Evans 2000; Richardson and Reynolds 2000b; Worni et al. 2012). Different

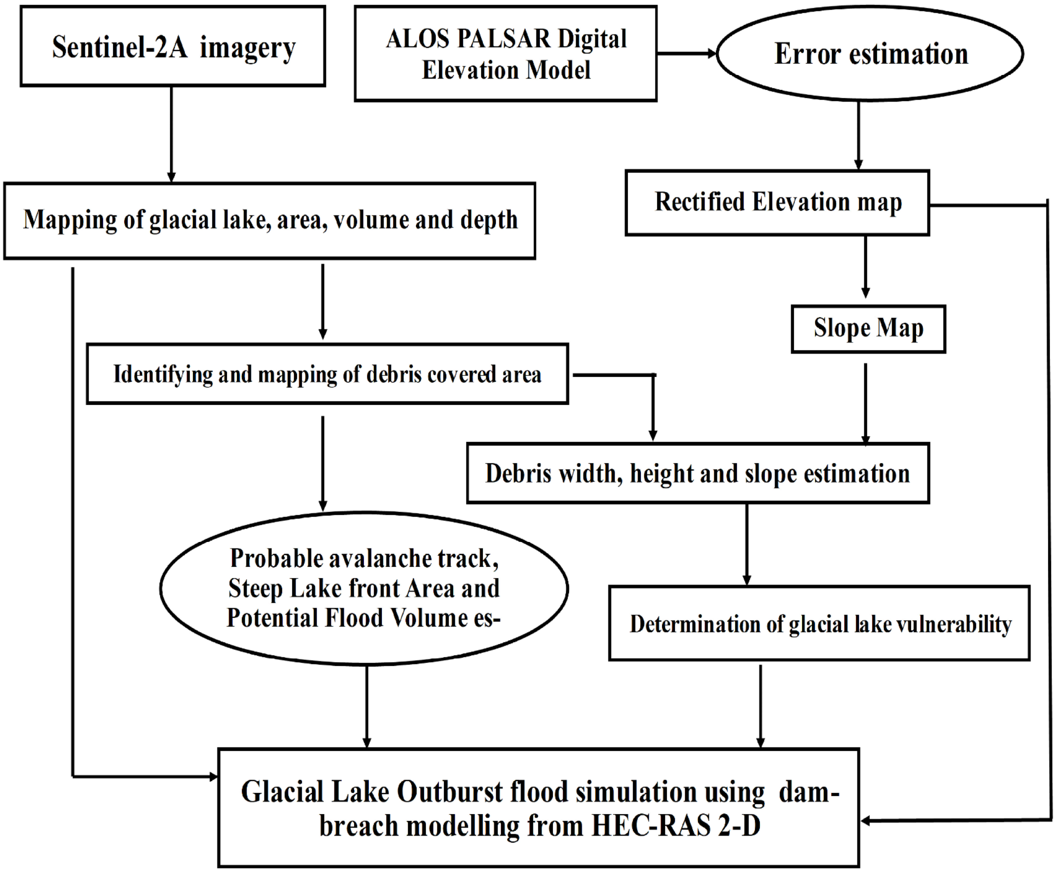


**Fig. 2.** Flowchart of methodology followed.

authors (Huggel et al. 2004; Wang et al. 2008) proposed key parameters such as the dam width-to-height ratio, top width of dam, distal dam flank steepness or freeboard for a qualitative lake stability assessment. Parameters of most likely dam breaching help to assess the outburst probability of a particular lake. However, even unstable glacial lakes normally need a trigger to induce dam failure: In this study, due to absence of in-situ based observation, this study entirely follows a remote-sensing based approach consisting various steps. The methods and steps are as depicted in the flow diagram (Fig. 2). The major steps are a) all proglacial lakes were categorised according to their respective vulnerabilities towards glacial lake outburst flood based on topographic characteristics, b) among such critical lakes, one of the relatively stable lakes, namely, Shako-Cho was chosen for assessing its potential flood volume and finally, c) two-dimensional dam-breach analysis of Shako-Cho was performed for simulating a snow-avalanche prone GLOF. Prior to carrying out the above steps an error estimation of the ALOS-PALSAR digital elevation model (2014) (DEM) was performed (Hazra and Krishna 2019) and the observed error (Table 2) was rectified for the DEM.

### Category of Glacial Lakes

Proglacial lakes of Sikkim, have been categorised using topographical parameters given by Worni et al. (2013) and classified as (i) critical glacial lakes, (ii) potentially critical glacial lakes and iii) uncritical glacial lakes. A band ratio method has been used to map debris cover around the glacial lake, using blue and short-wave infra-red band (band 1 and 5 from Sentinel-2A mage). Clean glacier ice has a high reflectivity in the visible to near-infrared wavelengths (0.4–1.2 μm) and a very low reflectivity in the SWIR wavelength region (1.4–2.5 μm) (Alifu et al. 2015). Threshold for selecting the debris cover has been taken between -0.38 and 0.00. Glacial debris around the glacial lakes have been mapped (Fig. 3) and extracted from Sentinel-2A imagery (using eq.1) and have been digitised accordingly. The height and slope of the moraine dams have been extracted from the digital elevation model. The top width has been estimated using the height of the moraine dam. The following criteria (Fig.4) have been taken for determining the potentiality of lake outburst flood. The glacial lakes of Sikkim Himalayas have been categorised in the following categories (Fig. 6).

$$\frac{(Blue - SWIR\ 1\ band)}{(Blue + SWIR\ 1\ band)} \tag{1}$$

where, Blue = reflectance in blue band, SWIR 1 = reflectance in short-wave infra-red band.

**Table 2** Error estimation from digital elevation model

| Error | ALOS-PALSAR Digital Elevation Model |
|---|---|
| Average Error | 31.183 m |
| Mean Absolute Error | 17.006 m |
| RMSE | 35.519 m |
| Standard Error | 4.2516 m |

### Probable Avalanche Pathway and Potential Flood Volume Estimation

Alean (1985) analyzed ice avalanches in the Swiss Alps with volumes between $0.2*10^6$ m$^3$ and $5*10^6$ m$^3$, and found angles of reach between 17° and 32°. Such dimensions are useful to delimit a reasonable range of potential ice avalanches which might trigger a GLOF (Worni et al. 2013). Areas adjacent to the Shako Cho falls under highly avalanche-prone zone of North Sikkim district (Sikkim State Disaster Management Authority, 2011). In this analysis, the

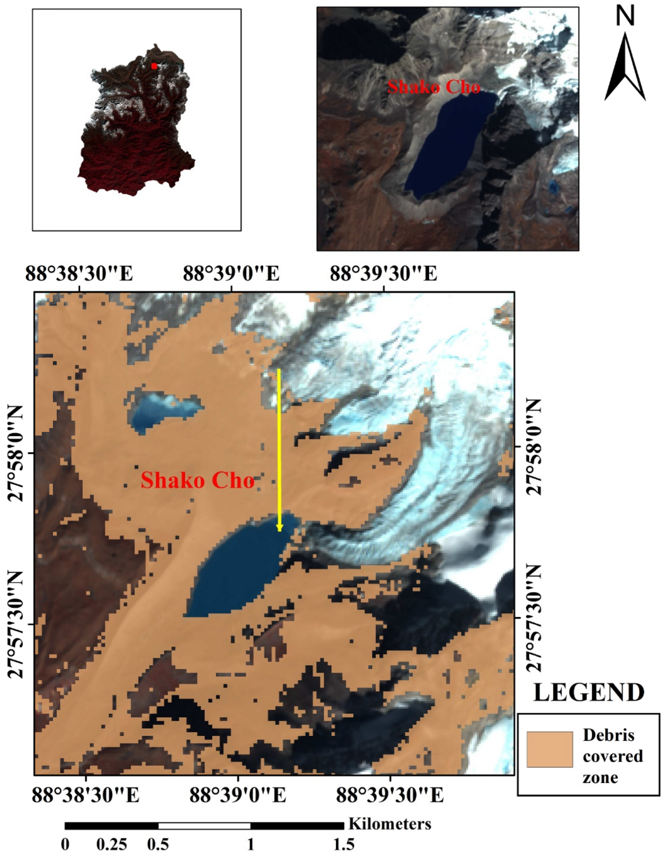


**Fig. 3.** Extraction and mapping of debris cover around the Shako-Cho lake.

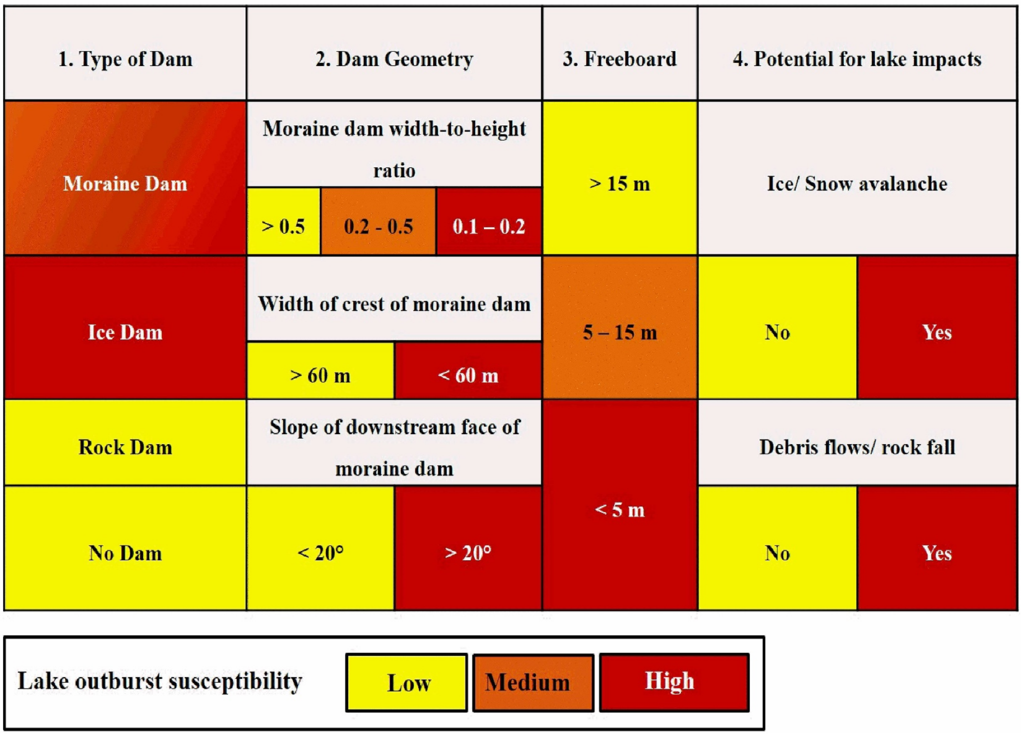
thickness of an avalanche has not been considered. But to propagate a glacial lake outburst flood (GLOF) from an avalanche, knowledge of avalanche volume is necessary. A minimum threshold of $0.1*10^6$ $m^3$ has been applied by Richardson and Reynolds (2000a), which is large enough to destroy a village. Although, GLOF models triggered through ice avalanche, at least the volume of $0.5*10^6$ $m^3$ is required (Worni et al. 2014; Somos-Valenzuela et al. 2015). Knowledge of avalanche volume helps to find out the average angle between the initial point of the avalanche to the last point, based on an equation given by Huggel et al. (2004). The equation follows,

$$\tan(\alpha) = 1.11 - 0.118 \log(V) \qquad (2)$$

where, V = the avalanche volume in $m^3$, $\alpha$ = the average slope trajectory or 'look-up' angle in degree (°)

Minimum threshold of average angle has been kept as 17°, as the avalanche rarely exceeds beyond that (Huggel et al. 2004). A flow direction map has been generated from the sink filled ALOS-DEM to map the projected path up to which the look-up angle has been attained. For the sake of the analysis, the projected path has been considered as ± 3° of the look-up angle threshold. Thus, zones which fall between the slope region of topographic angle of 14°- 20° (look up angle) or also known as alpha ($\alpha$) angle have been marked as probable avalanche pathway around the lake. Shako Cho with its corresponding probable path of mass inflow to the lake areas respectively in both ablation and accumulation period has been portrayed in Fig. 5a and 5b. The avalanche originates from the highly elevated snow accumulation zone and follows the steep slopes. The yellow patches (Fig.5a and 5b) represents the topographical slope (30°- 45°) which is favourable for slab avalanche. Slopes greater than 50° cannot hold large amount of snow and hence more prone towards sluffs or powder snow avalanche. The red patches, adjacent to the lake area represents the direction or the probable path (from avalanche starting point to run-out zone) through which mass inflow might take place in case of a snow avalanche to the lake.

After a GLOF initiates, the down cutting into the moraine dam will be going on until the angle between the glacier lake and downstream area is lowered to 10°, which is termed as depression angle. Following Fujita et al. (2013), the steep lakefront area (SLA), where the angle would be greater (steeper) than the threshold 10° angle and the depression angle area has been mapped up to 1 km downstream area from the glacial lake. Although after a GLOF event



<table>
<tr><th>1. Type of Dam</th><th colspan="6">2. Dam Geometry</th><th>3. Freeboard</th><th colspan="2">4. Potential for lake impacts</th></tr>
<tr><td rowspan="2">Moraine Dam</td><td colspan="6">Moraine dam width-to-height ratio</td><td rowspan="2">> 15 m</td><td colspan="2" rowspan="2">Ice/ Snow avalanche</td></tr>
<tr><td colspan="2">> 0.5</td><td colspan="2">0.2 - 0.5</td><td colspan="2">0.1 – 0.2</td></tr>
<tr><td rowspan="2">Ice Dam</td><td colspan="6">Width of crest of moraine dam</td><td rowspan="2">5 – 15 m</td><td rowspan="2">No</td><td rowspan="2">Yes</td></tr>
<tr><td colspan="3">> 60 m</td><td colspan="3">< 60 m</td></tr>
<tr><td>Rock Dam</td><td colspan="6">Slope of downstream face of moraine dam</td><td rowspan="2">< 5 m</td><td colspan="2">Debris flows/ rock fall</td></tr>
<tr><td>No Dam</td><td colspan="3">< 20°</td><td colspan="3">> 20°</td><td>No</td><td>Yes</td></tr>
</table>

| Lake outburst susceptibility | Low | Medium | High |
|---|---|---|---|

**Fig. 4.** Glacial lake susceptibility to GLOF (after Worni et al., 2013)

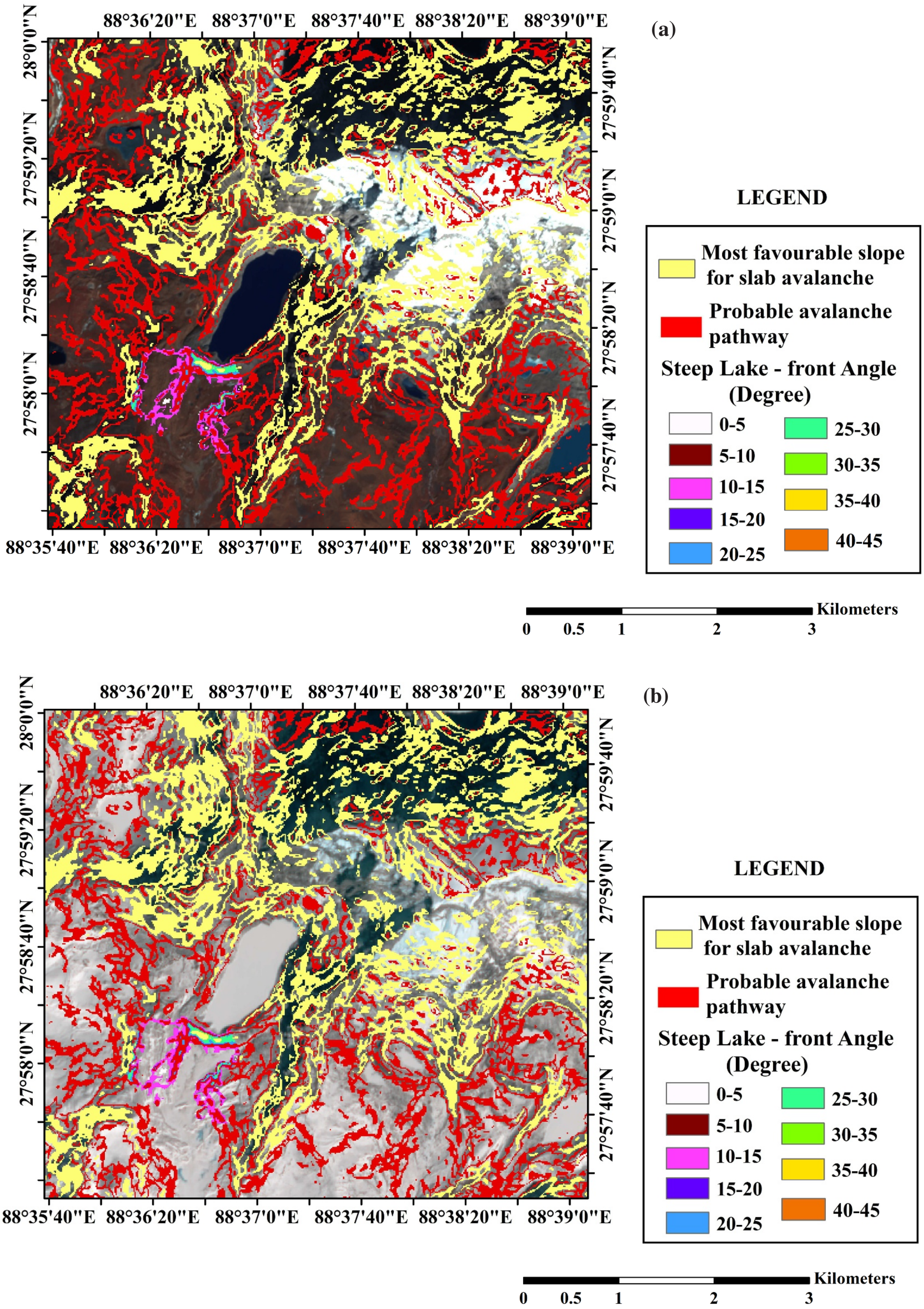


**Fig. 5.** Probable avalanche pathway and steep lake angle (SLA) around Shako Cho lake **(a)** during ablation **(b)** during the accumulation period

the SLA might not exist. Thus a potential flood volume (PFV) that can be generated after any triggering event like snow avalanche takes place; leading to a GLOF. The following formula has been used.

$$PFV = \min\,[\,D_{\mathrm{m}}\,;\,H_p\,] \times A \qquad (3)$$

where, $D_m$ = mean depth of the glacial lake, $H_p$ = potential lowering height

The method of calculating potential flood volume (PFV) given by Fujita et al. (2013) has been followed, where it is measured as the product of glacier lake area and either mean depth ($D_m$) or potential lowering height ($H_p$), whichever has the relatively lower value. $H_p$ is the measurement of glacial lake lowering that is expected to happen during a GLOF. The digital elevation model (DEM) having a 12.5 m resolution, has been used to map the depression angle and then with the help of Sentinel 2-A imagery and google earth image, the SLA has been determined. The bedrock dammed lakes may not produce GLOFs by a dam failure, but it might cause GLOF by overtopping (Dubey and Goyal 2020).

### Glacial Lake Outburst Flood (GLOF) Modelling

Based on the categorisation of the glacial lakes, most of the glacial lakes (irrespective of sizes) in Sikkim fall under the 2nd and 3rd category in terms of their potential towards GLOF Although many glacial lakes have been observed as expanding over the years, Shako Cho has been found uniform in size. The objective of the modelling is to measure the magnitude of the lake outburst flood event in terms of the maximum discharge and maximum volume (debris/avalanche), depth of the probable flood water and the probable maximum travel distance.

To measure the potential lake outburst from glacial lakes, two approaches, (i) Empirical method and (ii) 2-D flood routing model has been adopted. Different scientists have used different formulae to determine the peak discharge ($Q_{max}$) of glacial lakes based on field-based data as well as historical records based on empirical methods. The maximum discharge of a glacial lake strongly depends on the type of dam and the drainage (Huggel et al. 2004). There are mechanically and hydraulically different mechanisms associated with the lake drainage pattern, which differentiate between ice, moraine and bedrock dammed lakes.

Ice-dammed lakes that empty by progressive enlargement of subglacial channels have been found to produce smaller outburst floods for the same stored water volume than mechanical or sudden-break failures of ice dams and failures of moraine-dammed lakes (Haeberli 1983; Costa and Schuster 1987; Clague and Evans 1994). In the Indian Himalayan Region, ice-dammed lakes are generally non-existent (Worni et al. 2013). Therefore to evaluate the moraine-dammed lakes, the dam geometry, freeboard height influence hydraulic gradients within the moraine (Clauge and Evans 2000; Richardson and Reynolds 2000a). In this study, the following formula, given by Evans (1986), has been used to empirically derive the peak discharge of the two glacial lakes.

$$Q_{max} = 0.72 \times V^{0.53} \quad (4)$$

where, V = volume of the lake in million $m^3$

## 2D Flood Routing Using HEC-RAS

Knowledge of glacial lake water volume and bathymetry is necessary for the accurate modelling of GLOF hazard generated by any glacial lake. Due to absence of ground data, area-based volume scaling (Sharma et al. 2018) has been used as an input in this study

$$V = 0.052272 \times A^{1.1766} \quad (5)$$

where, V= volume of the glacial lake and A = surface area of the lake.

HEC-RAS is the most commonly used open-source model for studying glacial lake hazards all over the globe (Alho et al. 2005; Alho and Aaltonen 2008; Carling et al. 2010; Klimeš et al. 2014). Two dimensional HEC-RAS model solves shallow water equation (SWE) to produce depth-averaged and spatially distributed hydraulic characteristics of a given flow (Chanson 2004). Its ability to perform complex dynamic simulations makes it a reliable model to study the hydraulic behaviour of unsteady flows (Sattar et al. 2020).

In this study, the worst-case dam breach scenario has been computed based on breach width, failure time and breach mechanism (overtopping) for both lakes. The average breach width and failure time have been calculated using the formula given by (Froehlich 1995). The total breach width ($B_w$) as a function of the total volume ($V_w$) of water upstream (lake volume) and the height of the breach ($h_b$). The following formulas have been used.

$$B_w = 0.1803 \times K_0 (V_w)^{0.32} \times (h_b)^{0.19} \quad (6)$$

$$(Tf) \text{ in h} = 0.00254 \ (V_w)^{0.53} \times (h_b)^{-0.9} \quad (7)$$

where, $B_w$ Breach width, $V_w$ = Volume of lake water, $h_b$ = Height of the breach, $Tf$ = Time for breach formation, $K_0$ = 1.4 (overtopping) constant.

For routing the initial breach hydrograph, along the flow area from the Shako Cho lake to Thangu village, the HEC-RAS 2D (Version 5.0.6) has been used. The upstream lake area has been marked as 2D storage area and the downstream area up to the desired locations have

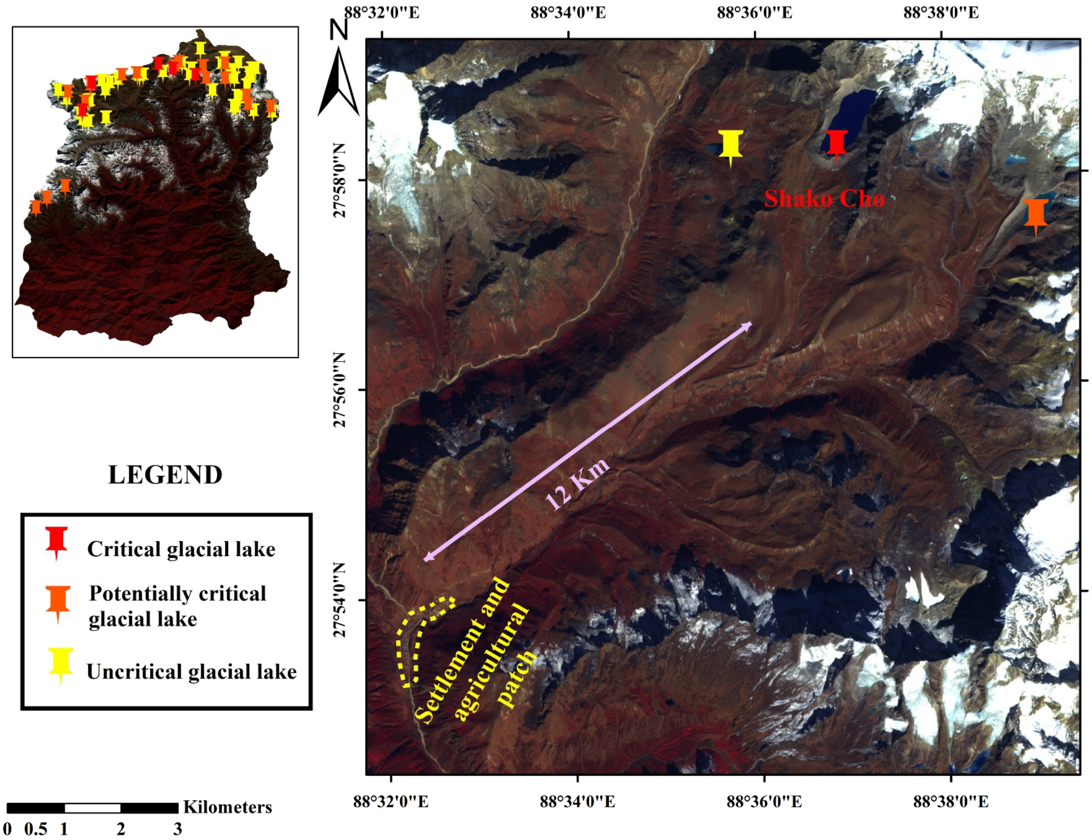


**Fig. 6.** Vulnerability assessment of glacial lakes in Sikkim

been marked as 2D flow area, through which the water, following the stream channel would pass through. ALOS PALSAR DEM has been used for the extraction of terrain information. A 2D mesh is constructed within the given flow area, with an individual cell dimension of 10m* 10m resolution. the cells have been defined with Manning's N value. To define the Manning's N value, a buffer of 1 km on each side of the river has been created and the LULC (Land-use/Land-cover) wise the N values have been assigned to each class. Thus for the entire flow area, an average N value has been computed, based on the LULC of the 2D flow area. The average N value for Shako Cho lake has been taken as 0.053. The HEC-RAS 2D dynamic modelling provides solutions based on depth-averaged shallow water equations (Hervouet 2007). The multi-dimensional computation of hydraulic properties of the flood wave yields spatially distributed outputs of water depth, velocity, and inundation. Glacial lake outburst floods are associated with the short-lived flood with high-velocity water supply to the downstream channel. Its temporal characterization needs assessment in a shorter time in the order of a few minutes to seconds (Sattar et al. 2019). Thus, 2D unsteady flow simulation has been performed using the potential flood volume (PFV) of water as an input parameter for both the lakes, considering snow avalanche generated GLOF.

## RESULTS AND DISCUSSION

The increasing temperature along with melting snow may have accelerated the development of small new glacier ponds as well as rapid expansion in the areas of existing glacial lakes. Glacial lakes of Sikkim are mostly moraine-dammed and some of them are highly prone to GLOF. Previous studies show that anomalous rise in temperature, the monsoon precipitation and displacement waves from rock and avalanche may increase GLOF susceptibility (Emmer and Cochachin 2013; Allen et al. 2016; Kaushik et al. 2020). Excessive snowfall can be a triggering reason for snow avalanche, which might induce a GLOF. Globally it has been observed that a glacial lake with a PFV greater than 10 million $m^3$ of water is highly prone to GLOF (Fujita et al. 2013). From the analysis of the Shako Cho lake, the potential flood volume is obtained as $45.4781*10^6 m^3$ of water. Although, this lake has not expanded like other proglacial lakes in Sikkim, but an event of snow avalanche, heavy cloudburst or an earthquake may prove extremely disastrous to the areas downstream. After running the HEC-RAS 2D simulation for Shako Cho, the following result has been obtained. In this analysis, the overtopping mode of failure has been discussed.

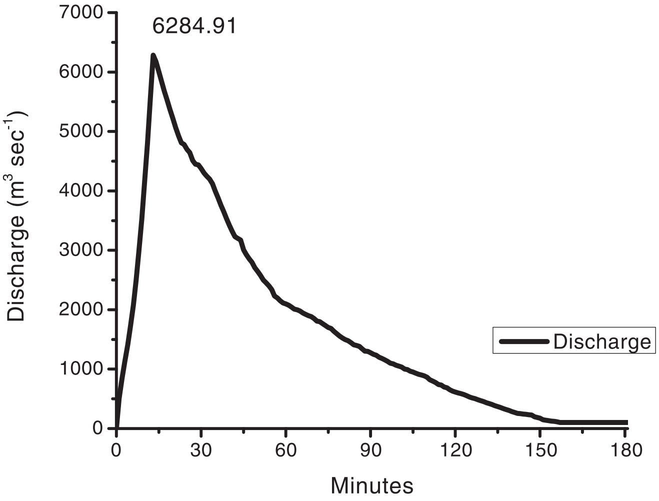


**Fig. 7.** Simulated lake outburst flood hydrograph (Shako Cho Lake)

In a scenario of a snow-avalanche, the simulation has been performed for 180 min.; i.e. 3 hours and total breach width as well as formation of breach timing has been observed as 162.17 m and 0.59 hours respectively. The lake level lowering has been found at

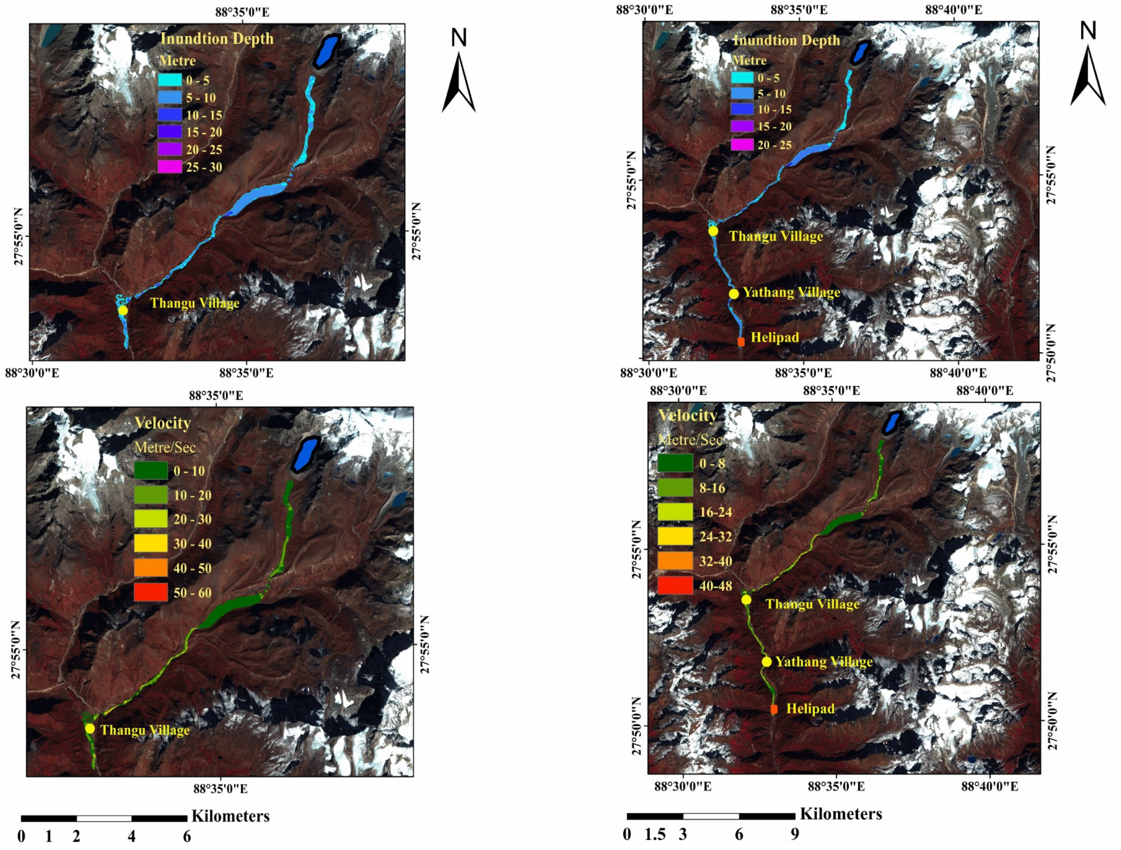


**Fig. 8.** Stages of inundation depth and velocity of water from Lake outburst flood near Thangu village, Yathang village and Helipad ground

39 m with a discharge value during that period has been inferred as 6284.9 $m^3$ $sec^{-1}$ (Fig. 7) with 35.703*$10^6$ $m^3$ of water volume. Highest flood discharge has been inferred 13 min. after the initial outburst flood takes place. The total breach depth has been observed as 76 m. based on the elevation obtained from the depression angle, up to which the breaching may take place. From the 2D unsteady flow analysis, it has been observed that after the breaching of the moraine dam takes place, the water may reach Thangu village, the nearest habitable place of the area which is 12 km downstream from the lake in about 17 min. The highest velocity that first strikes the vicinity of the village is measured as 11.45 m $sec^{-1}$ followed by increased velocity of 24.22 m $sec^{-1}$ in a small patch around the village. Whereas, the flow depth has been calculated as 5 m - 8 m spatially. Yathang village, which is around 3.5 km downstream from Thangu village, may receive the water within 2-3 min. after it crosses Thangu with a velocity of 8 m $sec^{-1}$ and depth of 6 m - 10 m (spatially) respectively. A helipad ground which is 2 km ahead of Yathang village (Fig. 8), would also get affected by the GLOF. Thus, this dam breach analysis signifies the intensity of an extreme GLOF scenario which can severely affect the population downstream.

Using remote sensing techniques, the evaluation and classification of glacial lake outburst probability are challenging and it has been discussed in different literatures (Clauge and Evans 2000; Huggel et al. 2004; Wang et al. 2012b). A study by Worni et al. (2013) for Indian Himalayan glacial lakes used , four topographic criteria and their critical values (Fig.4) to analyse their susceptibility towards lake outburst. In this study, similar values have been incorporated to analyse the GLOF susceptibility of the glacial lakes of Sikkim. Besides the geospatial analysis, expert knowledge is required for assessing the stability of the glacial lakes considering the dam, the glacial lake and its surroundings. The model results can be affected from the uncertainties associated with the different input parameters and the digital elevation model. By comparing the influence of the SRTM DEM and ASTER GDEM version 1 data on hydraulic GLOF modelling in Tibet, Wang et al. (2012a) concluded that there digital elevation model influence the flood inundation extent and water depths, but the deviation is of little significance, when predicting high discharge floods. Worni et al. (2013) also modelled the lake outburst probability of selective Indian Himalayan glacial lakes (including Shako Cho, Sikkim) due to snow and ice avalanche using BASEMENT to simulate a typical process chain of GLOFs. They ran the simulation for both small and large impact scenarios. According to their simulation the maximal breach widths were 140 m (small scenario) and 180 m (large scenario), respectively. The lake level was lowered in both scenarios by 32 m and about 16*$10^6$ $m^3$ water drained in 180 min. with a maximal discharge of 6100 $m^3$ $sec^{-1}$ and 6950 $m^3$ $sec^{-1}$ for small and large scenarios, respectively. In both scenarios the flood wave reached Thangu village about 50 min after lake impact with maximal flow velocities of 15 m $s^{"1}$ and maximal flow depths of 12 m. About 12 min. later the GLOF would have reached the village of Yathang 3.5 km below Thangu. The difference of output might be attributed due to the variation in various input parameters for both of the models. Although Shako Cho has not shown much variation in surface area, its location near the steep glaciated region, low width to height ratio of moraine dam as well as their unconsolidated, granular dam material make it easily erodible by overtopping flows, which clearly prove it as one of the most vulnerable lakes for GLOF within Indian Himalaya.

Apart from the topographical factors, the unprecedented growth of tourism and development of new constructions along the rivers in the downstream region of this mighty Himalayan terrain has amplified the risk associated with the GLOF disaster. Therefore, along with the topographical factors, hydrometeorological as well as social factors are needed to study in conjunction for any mitigation strategy for the risk of GLOF related disaster.

## CONCLUSION

Expanding glacial lakes, surrounded by avalanche-prone zones are susceptible to GLOF. The pro-glacial lakes of Sikkim are dammed by moraines with steep slopes and low width to height ratio can lead to GLOF. 2D unsteady flow modelling by HEC-RAS shows that Shako Cho can be a potential case of extreme snow avalanche generated GLOF by producing a huge volume of water spillage in the downstream areas within few hours of its occurrence. The validation of the results was through comparison and drawing upon the previous reports with similar approaches serving as case studies. Sikkim in recent past has not reported any GLOF related disaster. As it is evident that 'stable' lake like Shako Cho in a given topographical condition like this can be similar or sometimes even more disastrous like the expanding lakes of Sikkim leading to likely disruptions of social and economic activities downstream. Thus, local authorities and policymakers have to address the challenges of mitigating any impending GLOF disaster considering topographical, changing climatological, hydrological and social parameters of the study area. Assessment of GLOF risk through HEC-RAS and geospatial technique to simulate the scenario towards a better mitigation in any of the high altitude areas of Sikkim with potential risk could be of great value.

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