# Monitoring of moraine-dammed lakes: a remote sensing-based study in the Western Himalaya

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**Monitoring of lakes in glaciated terrain in the Himalayan region has been recognized as one of the priority areas especially after the Kedarnath disaster. Among all types of glacial lakes, moraine dammed lakes (MDLs) are the most important from disaster point of view. Remote sensing plays a significant role in view of availability of unbiased repeated data on the expansion or contraction of MDLs located in rugged terrains of the Himalaya. Monitoring of two MDLs, associated with Katkar and Gepang-gath glaciers in Zanskar and Chandra sub-basins respectively was done using satellite images of 1965, 1976, 1989, 2001, 2006–07, 2012 and 2014. Survey of India (SOI) topographical maps of 1962 were also referred to monitor the respective glaciers lakes. SOI maps show the presence of only one lake associated with Gepang-gath glacier. Areal extent of the MDLs had increased from 21 to 57 ha between 1965 and 2014, and from 27 to 80 ha between 1962 and 2014 for the Katkar and Gepang-gath glaciers respectively. Increase in peak discharge of the two lakes was also estimated using different empirical models in case of outbursts of these lakes. The lake outburst probability for both these lakes was found to be very low (less than 1%), however, possibility of outburst of lakes due to natural calamity like cloud burst, landslide or earthquake cannot be ignored. The rate of retreat of these two glaciers was observed to be high due to the presence of MDLs in comparison to surrounding glaciers in the valley.**

**Keywords:** Glacier, moraine dammed lake, peak discharge, retreat.

AFTER the Little Ice Age, glaciers have been reported to be retreating[1–4]. The pace of retreat is attributed to global warming in the last century. The retreat of glaciers has at times given rise to the formation of glacial lakes based on their local glacio-geomorphological conditions. Glacial lakes can be classified according to their topographic position and nature of dam[5–7], i.e. sub-glacial lakes, supra glacial lakes, englacial lakes or proglacial lakes. Among various types of glacial lakes, some are formed at the terminus of the glacier due to damming by moraine, brought down by glacier movement across the channel of glacier melt water, if there is a steady rise in the ablation rates of glaciers[6,8,9]. Large proglacial moraine dammed lakes (MDLs) can only form where debris supply at the glacier margin is greater than the capacity of melt stream to transport sediments away and affects glacier mass balance and hydrology[10,11]. Satellite data-based glacier inventory of the Himalayan region has reported that 24.16% area of glaciers is covered with debris[12], therefore, the probability of formation of MDLs is high in the Himalaya. Adjoining water bodies in the form of MDLs considerably accelerate the rate of ablation near the glacier terminus in comparison to ice beneath debris cover[10,13]. Expansion of glacier lakes has been reported[8,14–19] at the terminus of glaciers using remote sensing data in the Himalayan region since 1950s. Bahuguna[20] has shown good correlation of glacier retreat with change in pro-glacier lakes for the east-central Himalayan region.

MDLs formed in this way could be disastrous if breaching of dams occurs due to heavy rainfall, avalanche or excessive melting of glacier ice, resulting into glacial lake outburst flood (GLOF). These floods can cause extensive damage to the natural environment and human lives as a relatively small lake can cause extremely rapid dramatic floods[21,22]. Many events of flood outburst are reported in North America, Europe and the Himalaya[21,23,24]; these can be cyclic in nature. The first GLOF event was reported in 1926; flood released by Shyok valley, Jammu & Kashmir, India destroyed Abuden village and the surrounding areas which were at a distance of 400 km from the outburst source[25]. Few more GLOF events have been reported in the past, such as Friendship Bridge of the China–Nepal Highway and Koshi power station in Nepal[26], Mingbo valley, Dudh Koshi region, East Nepal[27], Shaune Garang glacier in Himachal Pradesh, India[28], and Tsho Rolpa glacier lake in Nepal[29]. Recently, a calamity occurred in Chorabari glacier at Kedarnath, Uttarakhand, India due to simultaneous cloud bursting and MDL[30]; however, no systematic record of floods is available due to outburst of MDLs in the Indian Himalaya.

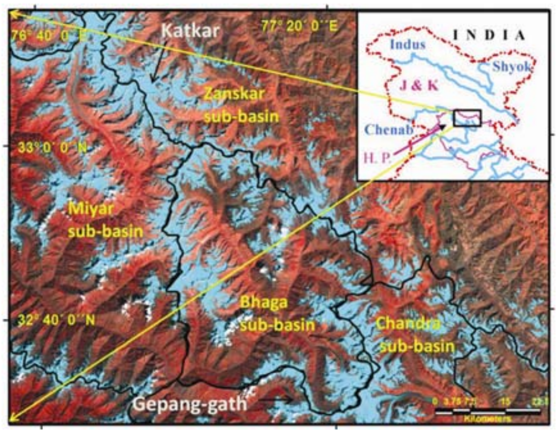


**Figure 1.** Location map of the study area.

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**Table1.** Models used for the estimation of lake volume

| Reference | Empirical relation for volume | Katkar lake Volume ($10^6$ m$^3$) | Katkar lake Comparison with area–depth relationship ($10^6$ m$^3$) | Katkar lake % Error | Gepang-gath lake Volume ($10^6$ m$^3$) | Gepang-gath lake Comparison with area–depth relationship ($10^6$ m$^3$) | Gepang-gath lake % Error |
|---|---|---|---|---|---|---|---|
| 31 | $43.24*(A)^{1.5307}$ | 18.29 | 1.83 | 9 | 30.73 | 1.27 | 4 |
| 46 | Areal extent * average depth | 20.12 | 0 | 0 | 32 | 0 | 0 |
| 39 | $3.114*A + .0001685(A)^2$ | 56.52 | –36.40 | 181 | 110.33 | –78.33 | –245 |
| 38 | $0.104*(A)^{1.42}$ | 15.50 | 4.62 | 23 | 25.09 | 6.91 | 22 |
| 40 | $0.493*(A)^{0.9304}$ | 29.22 | –9.10 | 45 | 40.06 | –8.06 | –25 |

The present study reports the occurrence, expansion and outburst probability of two MDLs in Western Himalaya using CORONA, Landsat and IRS images. Empirical relationship has been used to estimate volume[31] and peak discharge[32]. The objective of this study is to present evidences of expansion of the lakes which could be considered for establishing ground-based early warning system.

The lakes are located at the terminus of Katkar glacier in Zanskar and Gepang-gath glacier in Chandra sub-basin respectively (Figure 1). Both these glaciers are situated at the opposite side of a ridge line of the Indus and Chenab basins. Katkar glacier is a debris-free glacier with an area of 24.4 sq. km, having a slope less than 3° near the snout with reference to Survey of India (SOI) topographical map of 1962. Gepang-gath is a debris-covered glacier with an area of 13.1 sq. km, having a slope less than 2° near the snout with reference to SOI map of 1962. The oldest information about glacial extent is available on SOI topographic maps, surveyed in 1962, using vertical air photograph and limited field checks. Toposheets no. 52 C/16 for Katkar glacier and 52 H/2, H/3, H/6 and H/7 for Gepang-gath glacier have been used in this study. Multi-temporal mapping of glacier extent and lakes was carried out using satellite data such as CORONA of 1965, Landsat MSS of 1976, Landsat TM of 1989, IRS LISS III of 2001, 2006, 2007 and IRS LISS IV of 2008. Landsat data for 2012 and 2014 were used for the latest monitoring of glaciers and MDLs. Altitude information was obtained from the Global Digital Elevation Model (GDEM) version 2 of the Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER). The spatial resolution of ASTER GDEM v2 is between 71 and 82 m with accuracy of 17 m at 95% confidence level[33].

The study was carried out in three stages:

(i) Mapping of glaciers and moraine dammed lakes: First, the IRS LISS III and LISS IV data were georeferenced with the SOI topographical maps. Sufficient numbers of distributed ground control points (GCPs) were selected on the satellite data and maps for georeferencing. Drainage intersections were given priority as GCPs. Second-order polynomial model was used for registration with nearest neighbor approach. Georeferencing was performed at pixel level in conjunction with SOI maps at 1 : 50,000 scale with a positional accuracy of 12.5 m. Erdas imagine software has been used in the present analysis. Landsat images were reprojected with reference to georeferenced IRS LISS III and LISS IV. The extents of glaciers and MDLs were adopted from SOI topographical maps. These were digitized and first baseline information corresponding to the year 1962 was prepared. Glacier boundaries delineated using SOI (1962) and CORONA (1965) data were also compared and change in areal extent was observed to be less than 1%.

Extents of glaciers and MDLs were extracted from false colour composite (FCC) satellite images using key elements of visual interpretation as the procedures discussed in various publications[3]. FCC includes shortwave infrared (SWIR) band to improve the discrimination of snow and clouds. Image enhancement techniques are sometimes required to enhance the tone and texture of the glaciers. MDLs could be observed due to their typical black/blue tone on the image. Position of snout of the two glaciers was identified and mapped along the central line of the glaciers based on data of 1962/65, 1976, 1989, 2001, 2006, 2012 and 2014. Uncertainty in the change of snout position was estimated using standard procedures.

(ii) Lake volume and peak discharge estimation: Empirical relationship developed by Akiko[31] between area and volume of glacier lakes in Nepal and the Bhutan Himalayan region has been used in the present study

$$V = 43.24 * A^{1.5307}, \tag{1}$$

where $V$ is the volume of lake ($10^6$ m$^3$) and $A$ is its surface area (km$^2$).

Depth of lake was estimated using empirical relationship developed by Akiko[31]. Cross-section profile across the valley was carried out using ASTER DEM data, which were extrapolated over the lake to estimate the approximate depth of MDL. Depth determined using both methods was found to be approximately the same. Volume of lake was also estimated using various empirical relationships (Table 1). Error was also estimated with respect to area * average depth relationship. It was observed to be close to volume estimation using the Akiko[31] relationship.

Peak discharge was estimated using empirical relationship developed by Clague and Mathews[32], where volume is used as an input for peak discharge estimation

$$Q_{\max} = 75 * (V/1000000)^{0.67}, \quad (2)$$

where $Q_{\max}$ is the peak discharge ($m^3$/s) and $V$ is the lake volume (million $m^3$).

Many physical models were developed to estimate the peak discharge similar to eq. (2). However, no such relationship exists in the Himalayan region due to lack of the required parameters. Therefore, the relationship developed by Clague and Mathew[32] is used to estimate peak discharge. Table 2 shows the peak discharge of the lake in case of outburst estimated using various empirical relations.

(iii) Probability of outburst lake: The extent of a flood caused by the breach of a moraine dam is relevant for further hazard analyses. The present study uses the outburst probability model developed by McKillop and Clague[34] for assessing the dangerous nature of the MDLs and the equation proposed by Clague and Mathews[32] for estimating peak discharge of the lake in case of an outburst. McKillop and Clague[34] have developed the MDL outburst probability model by considering the utility of remote sensing in gathering information and also based on the inventory of 189 MDLs in British Columbia

$$P = \{1 + \exp - [\alpha + \beta_1(\mathrm{M\_hw}) + \textstyle\sum \beta_j(\mathrm{Ice\_core}_j) + \beta_2(\mathrm{Lk\_area}) + \textstyle\sum \beta_k(\mathrm{Geology}_k)]\}^{-1}, \quad (3)$$

where $\alpha$ is the intercept, and $\beta_1$, $\beta_j$, $\beta_2$ and $\beta_k$ are the regression coefficients for M_hw (moraine height-to-width ratio), Ice_core (moraine – ice free or ice core), Lk_area (lake area) and Geology (moraine constituents – sedimentary, metamorphic) respectively. Parameters such as moraine height-to-width ratio can be derived using digital elevation data by overlaying the satellite data over DEM. Presence/absence of an ice core in the moraine is established using the following method proposed by McKillop and Clague[34], The lake area is estimated using satellite data and main rock type forming the moraines is derived from lithological interpretation of the study area. The regression parameters have been taken from McKillop and Clague[34] and the four predictors taken from satellite data of 2014. The M_hw value was taken from satellite data to measure the moraine height and width. For further analysis, height of moraine such as ~35 and 40 m, width of moraine such as ~25 and 40 m and average width of lake such as 350 and 500 m respectively, were taken for Katkar and Gepang-gath MDLs.

**Table 2.** Models used for the estimation of peak discharge

| Reference | Empirical relation | Peak discharge ($m^3$/sec) | |
|---|---|---|---|
| | | Katkar lake | Gepang-gath lake |
| 41 | $0.0000055 * (PE)^{0.59}$ | 196 | 287 |
| 32 | $75\ (V)^{0.67}$ | 526 | 744 |
| 42 | $113(V)^{0.64}$ | 726 | 1012 |

In Figure 2, various features of the Katkar glacier have been depicted using IRS LISS IV data (5.8 m spatial resolution) of 26 August 2008. Areal extent of the glacier was estimated as 24.38 ± 0.017 sq. km in 1962 using SOI maps. Delineation of glacier boundary using SOI topographical maps of 1962 matched well with the CORONA image of 1965 and Landsat image of 1975, except near the glacier tongue where temporal changes are obvious. This is in contradiction with an earlier report of higher areal extent of the glacier using SOI topographical maps[35]. Areal extent of the glacier continuously decreased from 24.38 ± 0.017 to 23.58 ± .003 sq. km during 1962–2014. Figure 3 shows the per cent retreat in areal extent of glaciers with respect to 1962. The length of the glacier along the central line decreased from 12.56 to 11.0 km during 1962–2014 (Figure 4), showing a linear retreat of 30 m/year. Studies have reported an average rate of retreat less than 20 m/year for the Zanskar sub-basin[36,37]. However, these glaciers did not have MDL associated with them and higher rate of retreat of the Katkar glacier can be attributed to the presence of MDL. The altitude of the glacier snout was at 4520 m in 1962, which moved to 4572 m in 2014.

MDL of Katkar glacier was not present in the SOI topographical map of 1962, whereas the lake was observed on the CORONA image of 1965. However, supraglacial lakes smaller than this were present on the SOI map for other glaciers. This confirms that the lake had formed somewhere between 1962 and 1965. Glacial lakes are formed where the inclination of glacier surface is less than 2° (ref. 38). Slope near the snout of this glacier was found to be less than 3°, which provided suitable terrain condition for the formation of MDL. Area of MDL was observed to be 21 ha in 1965, which increased to 57 ha in 2014. MDL area increased significantly during 2001–2014, which also reflects more retreat over the same period (Figure 5). Expansion of MDL of Katkar glacier from 1965 to 1989 is higher than 1989 onwards (Figure 6). Beyond this altitude slope of glacier becomes 9°, which probably indicates reduction in rate of change of lake area in the future. Figure 7 shows the variation in MDL and areal extent of Katkar glacier.

Maximum depth of MDL was estimated using the method of Sakai[31], which was found to be 50 m in 1976 and 73 m in 2014, resulting $5.72 \times 10^6$ and $18.29 \times 10^6\ m^3$ volume respectively. Figure 8 shows the three-dimensional perspective view of Katkar glacier and lake, which was used to calculate depth of lake. Depth of lake was found to be 25 and 36 m in 1976 and 2014 respectively, using ASTER DEM extrapolation approach over

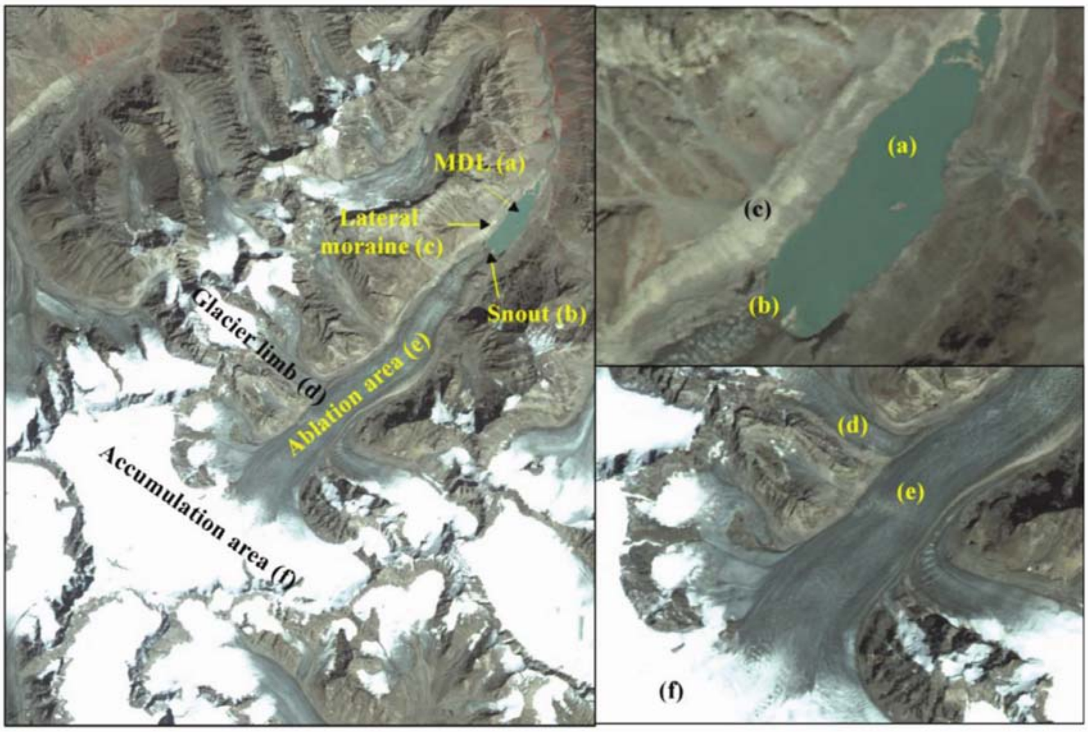


**Figure 2.** Glacier features. (a) Moraine dammed lake (MDL); (b) glacier snout; (c) terminal moraine; (d) glacier limb; (e) ablation area; (f) accumulation area.

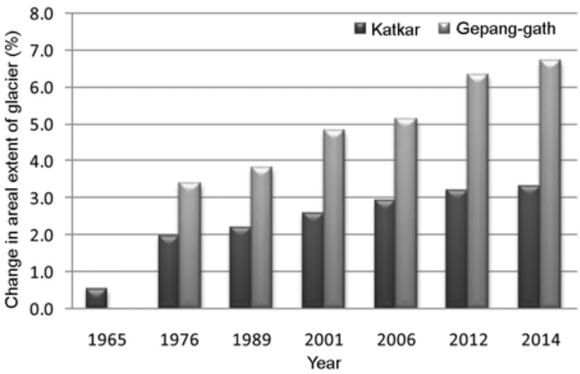


**Figure 3.** Retreat in areal extent of glacier with respect to 1962.

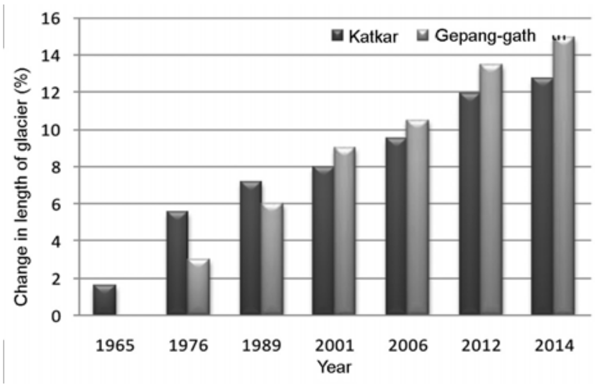


**Figure 4.** Retreat in length of glacier with respect to 1962.

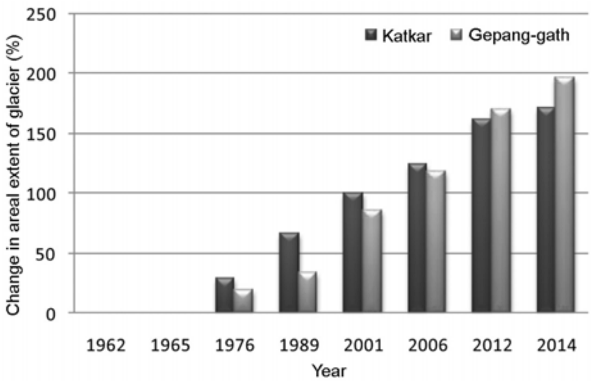


**Figure 5.** Increase in areal extent of lake with respect to 1962 and 1965 for Gepang-gath and Katkar respectively.

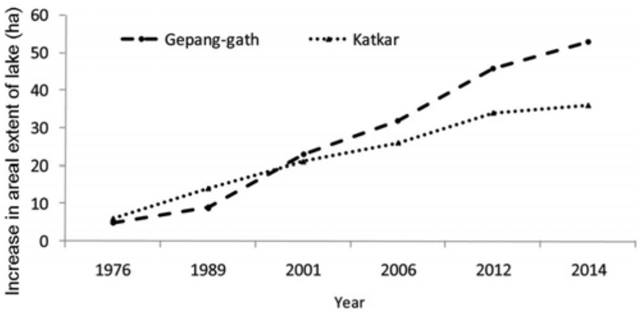


**Figure 6.** Change in areal extent of lake with respect to consecutive years.

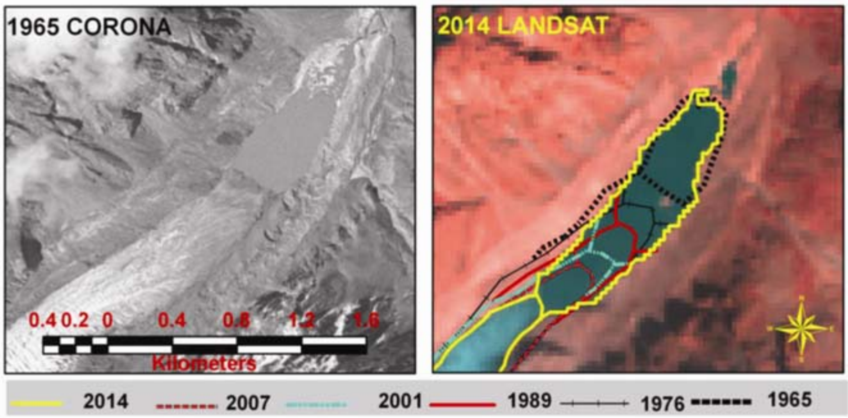


**Figure 7.** Variation in MDL and Katkar glacier.

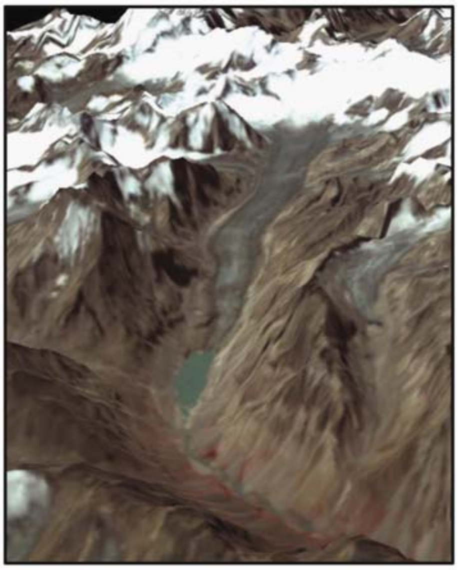

**Figure 8.** Three-dimensional perspective view of the Katkar glacier and the MDL.

the valley. The difference in volume using both approaches of depth estimation was found to be within 10%. Volume varied from 15.50 to $56.52 * 10^6$ $m^3$ (Table 1) using various empirical relations[31,38–40]. Peak discharge varied from 196 to 726 $m^3$/sec (Table 2) using various empirical relationships[32,41,42]. Average peak discharge lies near the peak discharge according to Clague and Mathews[32].

Gepang-gath glacier is debris-covered and located in the Chandra sub-basin. Approximately 29% area of the glacier is covered by debris. Areal extent of the glacier continuously decreased from $13.1 \pm 0.017$ to $12.22 \pm 0.003$ sq. km during 1962–2014 (Figure 9). Per cent retreat in areal extent of Gepang-gath glacier is higher than Katkar glacier (Figure 3). Length of glacier along the central line decreased from 6.7 to 5.7 km during 1962–2014 resulting into linear retreat of 20 m/year. Rate of linear retreat was observed to be gradually increasing from 1962 to 2014, reaching up to 31 meter per year during 2001–14 (Figure 4). Glaciers in Chenab sub-basin have shown an average retreat of 20 m/year (refs 37 and 43); however the accelerated rate of retreat in the last decade can be attributed to the presence of MDL at the snout of Gepang-gath glacier. Expansion of MDL of Gepang-gath glacier from 1965 to 1989 was lower than 1989 onwards (Figure 5). Width of the glacier was found to be around 500 m and altitude of glacier snout varied from 4079 to 4132 m from 1962 to 2014. Beyond this altitude, slope of the glacier was less than 5°, which supports the existing rate of change in MDL area. Expansion of MDL of Gepang-gath glacier from 1965 to 1989 was lower than 1989 onwards (Figure 6).

Lake area increased from 27 to 80 ha during 1962–2014. Figure 9 shows the variation in MDL and areal extent of Gepang-gath glacier. Maximum depth was estimated 50 m in 1962 and 86 m in 2014 using the method of Akiko[31]. Volume of lake was $5.70 \times 10^6$ $m^3$ in 1962, which gradually increased to $30.73 \times 10^6$ $m^3$ in 2014. Volume was also estimated by average depth of MDLs as 22 and 40 m during 1962 and 2014 respectively, using ASTER DEM. The difference in volume using depth from both approaches was found to be within 4%. Volume varied from 25 to $110 * 10^6$ $m^3$ (Table 1) using various empirical relations[31,38–40]. Peak discharge varied from 287 to 1012 $m^3$/sec (Table 2) using various empirical relationships[32,41,42]. Average peak discharge lies near to peak discharge by Clague and Mathews[32].

The present analysis shows that the presence of lake has accelerated the rate of retreat and the receded vacated area of the glacier has been occupied by the MDL. The rate of expansion of Gepang-gath lake is higher than the Katkar lake (Figure 6), which may be due to lower slope of Gepang-gath glacier in comparison to Katkar glacier. Uncertainty in terminus change and accuracy in areal extent of glacier and lake have been estimated using empirical relationships developed by Hall *et al.*[44] and Wang *et al.*[45]. Overall accuracy was estimated as ±107 m for SOI maps and Landsat MSS data (1962–1976), ±113 m

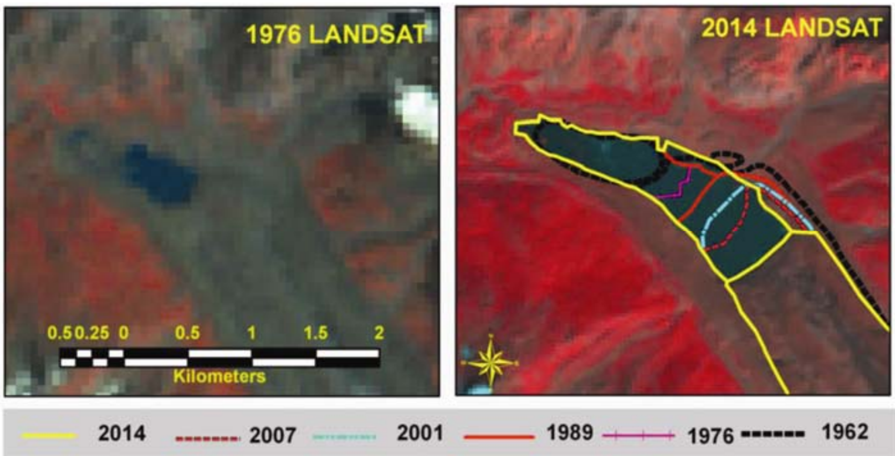


**Figure 9.** Variation in MDL and Gepang-gath glacier.

for Landsat MSS and TM data, ±49 m for Landsat TM and IRS LISS III data, ±45 m for LISS III data, and ±45 m for LISS III and Landsat ETM data. Changes in areal extent of glacier and MDL were measured with an accuracy of 0.017, 0.006, 0.002, 0.002 and 0.003 sq. km between each pair of datasets, i.e. 1962–1976, 1976–1989, 1989–2001, 2001–2006/07 and 2006/07–14 respectively.

The McKillop and Clague[34] probability model yields a very low outburst probability of less than 1% for both the lakes. A very low outburst probability indicates that if the lake increases its extent in due course of time, it may not cause an outburst flood. As all the MDLs of the Himalayan region are continuously dewatering by their outlet channels, lakes will not outburst on their own; however natural calamity like earthquake, cloud burst or avalanche may trigger the outburst of these lakes. Three glaciers located to the north of Gepang-gath glacier with steep slopes drain towards lake and may increase the chances of occurrence of landslides/avalanches in the area. The lake outburst may damage Sissu village, which is located to its SW at a distance of approximately 10 km. One glacier is located SE of Katkar glacier drains towards Katkar lake. But this glacier does not have a steep slope, so chances of avalanche or landslide are less. This is a preliminary assessment of the probability only and more field-based studies are needed to assess the hazardous potential of these lakes.

In present study, satellite images in conjunction with SOI topographical maps were analysed for identification and monitoring of crucial MDLs in parts of the Himalayan region over five decades. Katkar is a debris-free glacier which has shown higher linear retreat in comparison to Gepang-gath glacier which has debris cover. Both glaciers have shown increased rate of retreat in comparison to reported retreat in the regions which may be attributed to the presence of MDLs. Katkar glacier is expected to show less rate of increase in lake area from 2014 onwards in comparison to Gepang-gath glacier due to its steep slope (9° above snout) than the latter glacier (3° above snout). The empirical relationship provides reasonable estimates on MDL with the lack of detailed field survey for highly inaccessible and hazardous terrain like the Himalaya. Peak discharge was observed to vary from 196 to 726 $m^3$/sec for Katkar glacier and from 287 to 1012 $m^3$/sec for the Gepang-gath glacier. Both MDLs have shown a very low outburst probability of less than 1% in current scenarios, except due to occurrence of any natural calamity. This study suggests that Geopang-gath lake should be monitored regularly in view of its proximity to habitat areas downstream, possibility of avalanche from nearby glaciers having steep slopes high discharge capacity and high probability of its expansion in future.


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