JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol.83, April 2014, pp.385-392

Remote Sensing Based Assessment of Glacial Lake Growth on Milam Glacier, Goriganga Basin, Kumaon Himalaya

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Abstract: The climate change of the twentieth century had an evident effect on glacier environments of the Himalaya. Temporal images of Indian Remote Sensing satellites provide an opportunity to monitor the recession of glacier and development of glacial lakes in the Himalayan cryosphere with a cost to time benefit ratio. The recession of Milam glacier and subsequent growth of a proglacial lake near the snout was analysed using Resourcesat-1 and Resourcesat-2 data. The recession of 480 m during 2004 to 2011 and growth of 47 epiglacial ponds over Milam glacier shows the glacier is in a state of imbalance and losing the ice by downwasting.

Keywords: Proglacial lake, Epiglacial lakes, Milam glacier, Kumaon Himalaya.

INTRODUCTION

Global climate change during the twentieth century had a significant impact in modifying the cryospheric environment of the Himalaya. The changing climate had significant impact on the dynamics of glacier regime. These cryospheric fluctuations cause the formation and enlargement of glacial lakes in many mountain ranges (Reynolds, 2000; Yao et al., 2010; Govindha Raj, 2010). A glacial lake is defined as water mass existing in a sufficient amount and extending with a free surface in, under, besides, and/or in front of a glacier and originated by glacial dynamics. (Campbell, 2005).

A number of proglacial lakes formed and expanded in temperate valley glaciers during the 20th century caused by glacier thinning linked to climate change (Kirkbride and Warren, 1999; Boyce and others, 2007). Some of the studies show that proglacial lake formation increases the rate of glacier recession (Funk and Rothlisberger, 1989; Naruse and Skvarca, 2000). Recent expansion of glacial lakes in the Himalaya has mainly been studied in north Bhutan (Fujita et al., 2008; Komori, 2008) and in the Everest region (Yamada and Sharma, 1993; Sakai et al., 2000; Benn et al., 2001; Wessels et al., 2002; Bolch et al., 2008). The glacial lake inventory in SE Tibet with ALOS AVNIR-2 data shows an increase in number of glacial lakes from 96 to 123 between 1970 to 2009 (Wang et al. 2011). Fujita et al. (2009) and Bolch et al. (2008) studied the recent changes in the Imja glacial lake, Mt. Everest region of Nepal from multi temporal and multi sensor satellite data.

For the Himalayan cryosphere, observation from space is an excellent tool because many of the glaciers and glacial lakes are located at very high altitude, cold weather and rugged terrains, making it an arduous task to monitor by in situ methods. Satellite remote sensing facilitates the study of some of these features of the Himalaya systematically in a short span of time. This paper reports the growth of a proglacial lake in close proximity to the snout of Milam glacier and numerous epiglacial lakes in the ablation zone of Milam glacier, Goriganga basin, Kumaon Himalaya identified through temporal satellite data and field investigations.

STUDY AREA AND DATA USED

The Milam glacier (30° 26' N, 80°03'30" E) is one of the largest compound basins, valley glaciers of Kumaon Himalaya located in the Goriganga basin, Pithoragarh district. The glacier accumulates ice from two cirques on Trishul peak and its seven tributary glaciers. The ablation area of the glacier is covered with debris and many epiglacial ponds / lakes. The length of the glacier is 16.7 km and oriented towards SE from the Trishul peak. The glacier

Table 1. List of Satellite data used in the present study

Satellite	Sensor	Spatial Resolution (m)	Spectral Resolution (µm)	Acquisition Date/ Remarks
Resourcesat-1	LISS IV	5.8	0.52 – 0.59 0.62 – 0.68 0.77 – 0.86	04-03-2004
Resourcesat-1	LISS IV			26-09-2006
Resourcesat-2	LISS IV			30-10-2011
Cartosat-1	AFT, FORE	~30 (vertical)		Digital Elevation data (DEM)
Google Earth data				07-11-2004 21-10-2009

highest altitude is 5600m and the snout is at an altitude of 3580m. The Accumulation Area Ratio (AAR) of Milam glacier is 55 % (Sangewar and Shukla, 2009). Milam glacier lies north of the Trans Himadri fault (THF) and lithologically dominated by calc-phyllites and green siltstone of the Milam Formation of the Tethyan succession (Dumka, 2011).

The river Goriganga, a major tributary of Kali river initiates its flow from the melt waters of Milam glacier. The study area location and Milam with its tributary glaciers is shown in Fig.1.

Resourcesat - 1 and Resourcesat -2 satellite Linear Imaging Self Scanning (LISS- IV) sensor data were used in the present study. Apart from the satellite data, in-situ field expedition was carried out during July 2011 in Goriganga basin. Table 1 shows details of the data used for the present study.

METHODOLOGY

Orthorectified Resourcesat-2 LISS IV image acquired in 2011 was used as the master image and Resourcesat-1 LISS IV image acquired in 2004 and 2006 co-registered with the master image with an RMSE of 1 pixel. The satellite data are in UTM projection and WGS84 datum.

The glacier boundary was delineated from the LISS IV data considering the image characteristics of the glacier using ArcGIS software. The snout of the Milam

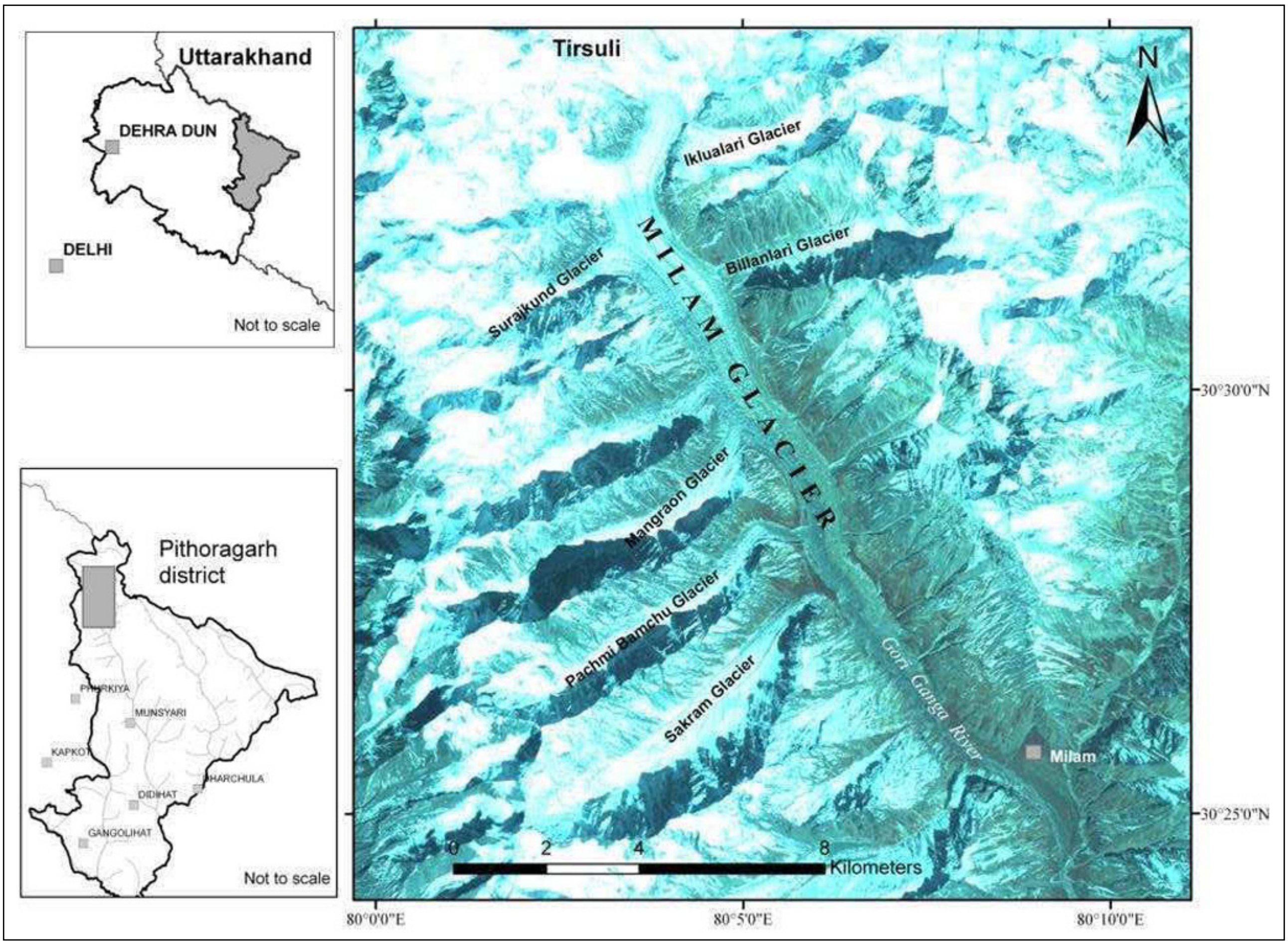

Fig.1. Location map of the study area shows the Milam glacier and tributary glaciers (source: Govindha Raj, 2011).

glacier is clearly visible as a large ice wall in the 2004 and 2011 imageries with the appearance of melt water coming from the snout (Fig. 2a and b). The glacier boundary was overlaid and assessment was carried out for the retreat along the maximum length of the glacier between 2004 and 2011.

The satellite data of 2011 (Fig. 2a) shows the existence of a proglacial lake bounded by moraines near the terminus of the glacier and the change detection study using 2004 data shows the lake is lacking in 2004 (Fig 2b) dataset. For checking the Resourcesat-1 LISS IV data acquired ion 2006 was analysed for the existence of a lake near the snout. The 2006 image shows only a small epiglacial lake at the terminus part (Fig 4b).

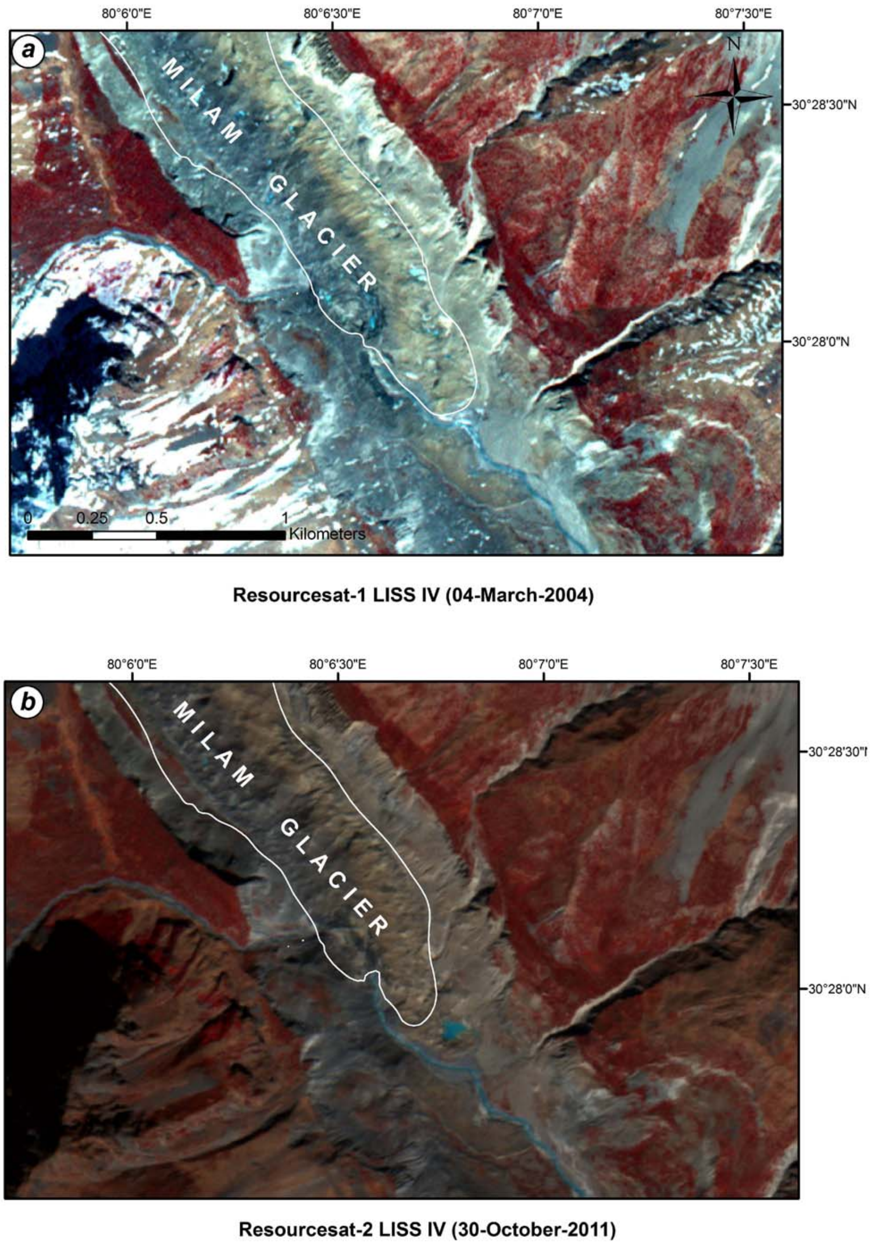

Fig.2. Temporal satellite images shows terminus of Milam glacier. (**a**) Resourcesat-1 LISS IV data of Milam glacier in 2004; (**b**) Resourcesat-2 LISS IV data of Milam glacier in 2011

RESULTS AND DISCUSSION

The Milam glacier boundary marked on 2004 and 2011 images shows the Milam glacier active snout receded 480m from its position in 2004 (Fig. 3a). The 2004 satellite data has no evidence of a lake at the snout portion and, hence, it is assumed that the lake must have formed after 2004. Subsequently data of 2006 shows a minor epiglacial lake at the terminus of the glacier (Fig 4b). The dimension of the epiglacial Lake in 2006 is insignificant to estimate the boundary. The 2011 LISS IV data shows the occurrence of a large proglacial lake at the snout portion (Fig. 3a). The complex textures surrounding the lake indicate that the earlier snout (2004, 2006) portion detached from the active glacier turn into the ice core debris damming the lake and the snout receded back. The in situ field survey carried out during July 2011 confirmed many of the observations.

In 2011 the lake is dammed by the end moraines and detached ice-core mantled debris (Fig. 3b & 3c) from the Milam glacier and positioned at old snout location. The field photo (3d) shows the person standing over the old snout converted ice-cored debris and the present active snout in the background. The active snout is located at the right side of the glacier terminus having an irregular tongue and melt water is coming out through the cave (R-channel) located at right side of the tongue (Fig. 3a, d). Figure 3e shows the downstream of the Milam glacier having the broad 'U' shaped valley and outwash plain with many recessional moraines.

Epiglacial or supraglacial is the process acting or features visible at the surface of the glacier (Singh et al. 2011). In the recession process of a glacier, glacier ice tends to melt near

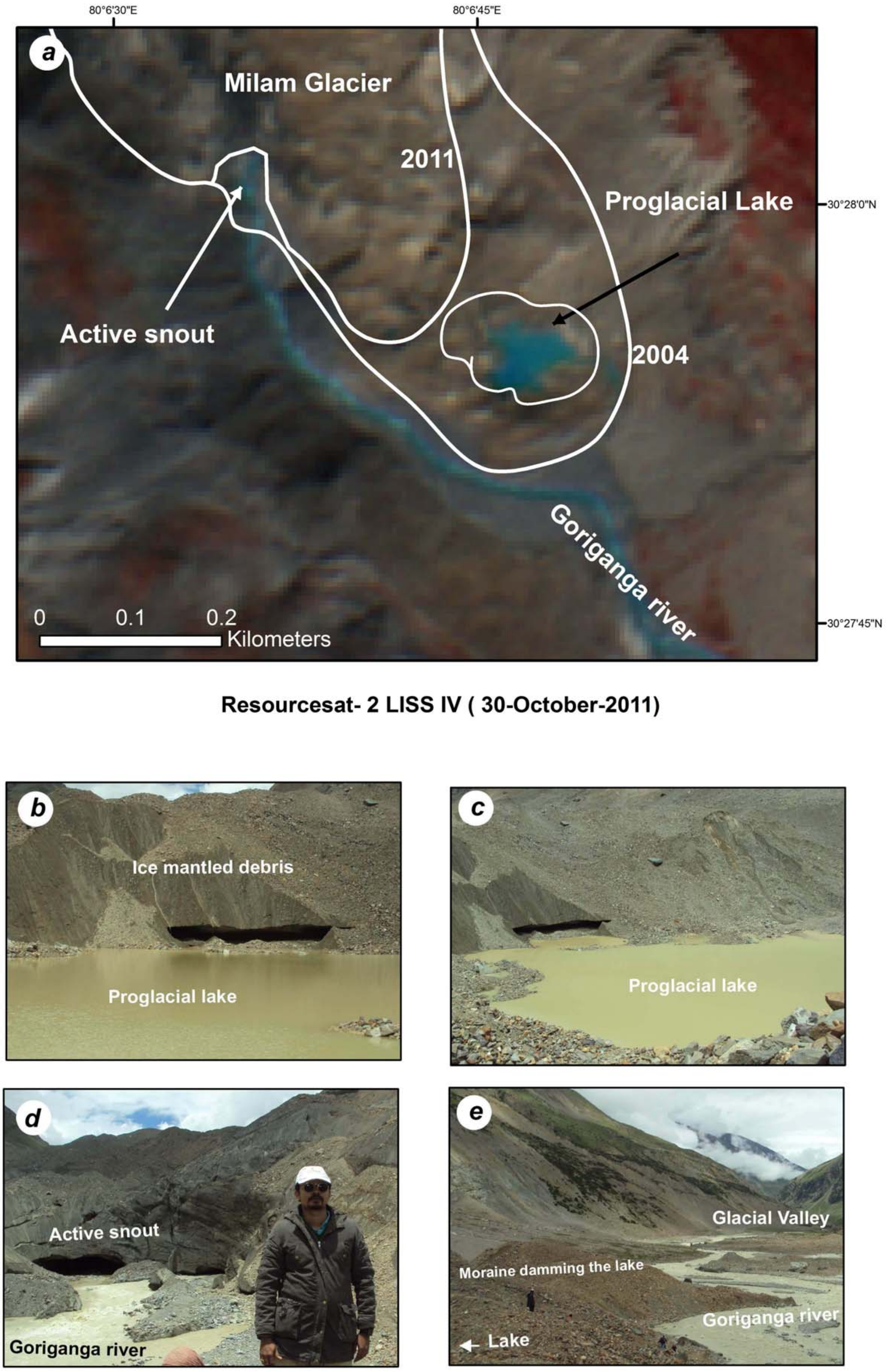

Fig.3. **(a)** Resourcesat-2 LISS IV data of 2011 showing the proglacial lake and the recession of Milam glacier from 2004; **(b) & (c)** Field photograph of the ice-mantled proglacial lake; **(d)** Present snout of Milam glacier with the melt water coming out from the cave at the bottom; **(e)** 'U' shaped valley of Milam glacier towards downstream.

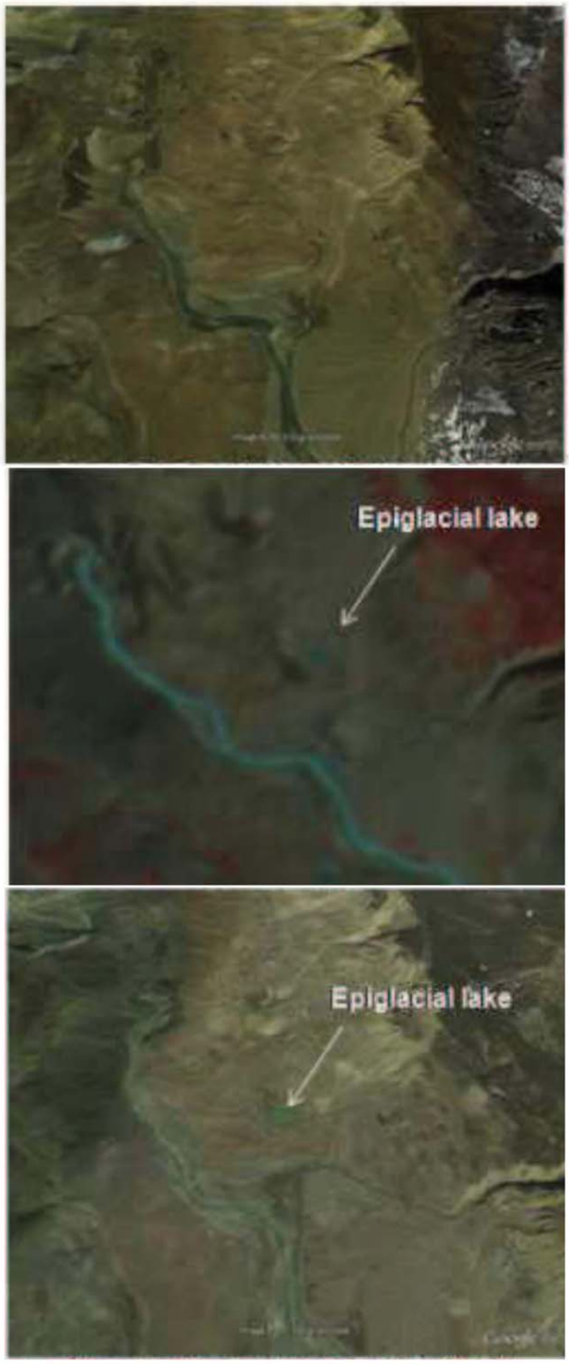

Fig.4. Temporal images of Milam glacier. (**a**) Google earth data of 2004; (**b**) Resourcesat-1 LISS IV data of 2006; (**c**) Google earth data of 2009.

terminus part of the glacier surrounded by moraines and debris. As a result, many epiglacial ponds/lakes are formed on the glacier tongue. These epiglacial ponds sometimes enlarge to become a large lake by interconnecting with each other and have a tendency to deepen further.

Due to the absence of any other data of the study area the Google earth data of 2004 and 2009 and Resourcesat-1

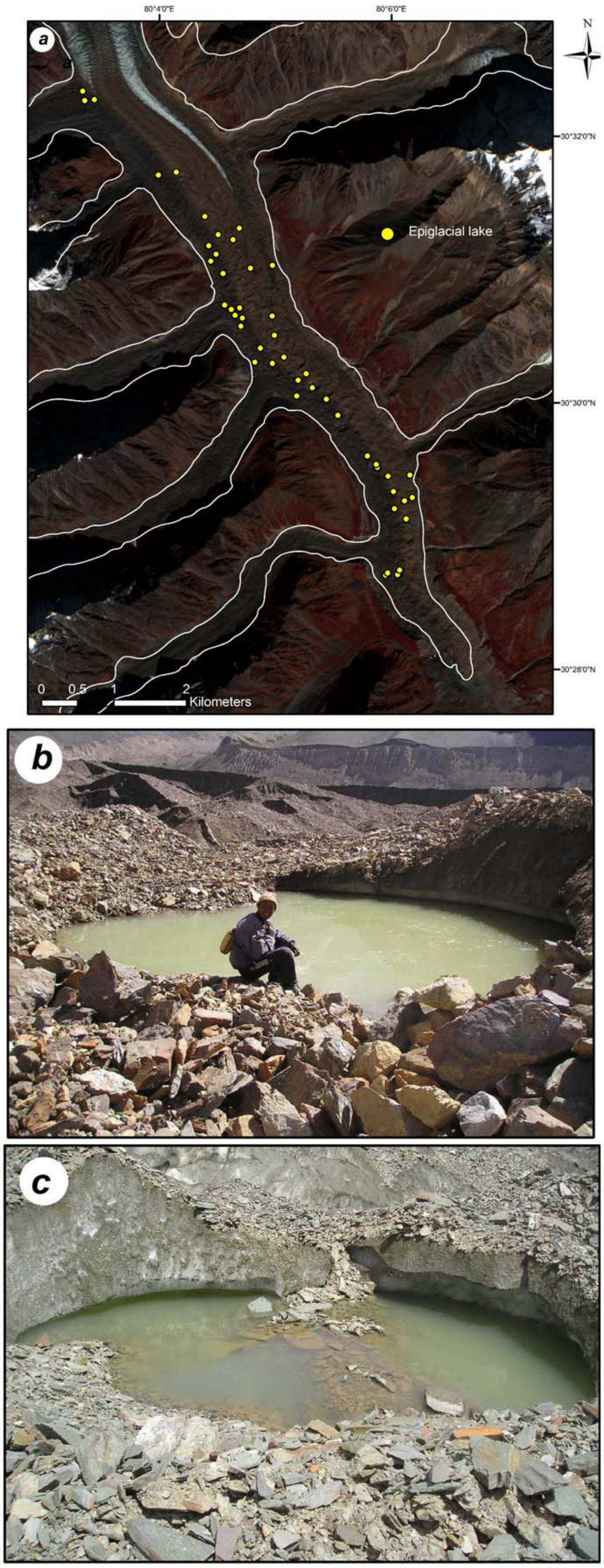

Fig.5. Milam glacier with the epiglacial lakes (**a**) LISS IV data of 2011 shows the Milam glacier with the locations of epiglacial lakes; (**b**) & (**c**) Field photograph of some of the epiglacial lake on Milam glacier.

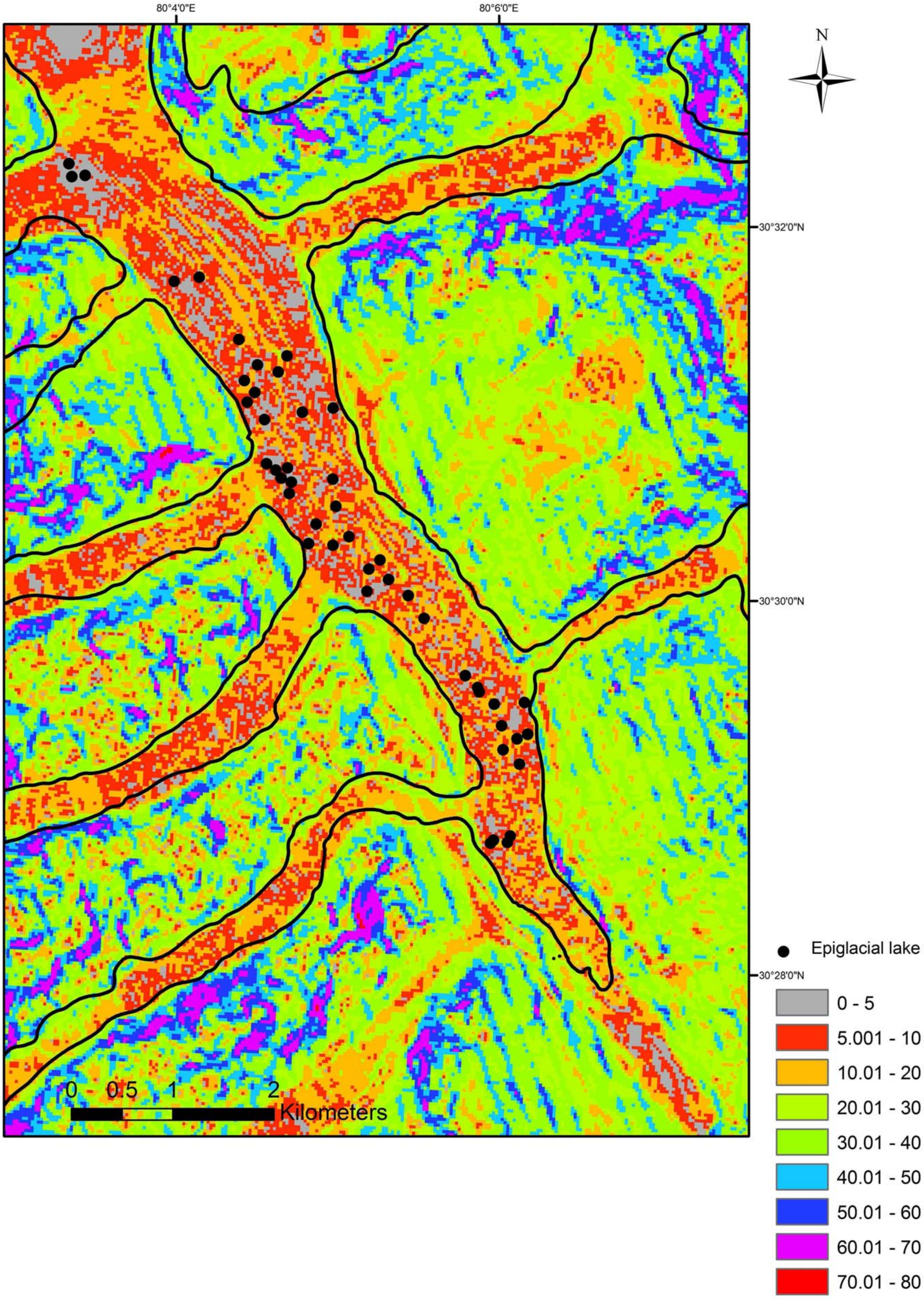

Fig.6. Slope map of Milam glacier overlaid with the epiglacial lakes locations.

LISS IV data of 2006 (Fig. 4a, 4b & 4c) used for cross checking the origin of the lake. The Google earth image of 2004 doesn't shows a lake at the snout but 2009 image shows the presence of an epiglacial pond/lake at the terminus portion of Milam glacier. The LISS IV data of 2006 shows an epiglacial pond at the terminus which is insignificant in dimension. But the 2009 image show increased dimensions of the epiglacial lake. In 2011 the formation of a separate proglacial lake bounded ice-mantled debris at the terminus of Milam glacier indicates that the epiglacial lake might have contributed for the fast disintegration of the terminus portion to form a separate moraine (ice-cored) dammed lake and subsequent retreat of the glacier. The field photo of the proglacial lake (Fig. 3b, 3c) shows a cave at the bottom of the ice-core mantle which may be the earlier melt water cave of the glacier (R channel ?). This clearly represents the activity of epiglacial lakes in disintegrating glacial ice and triggering its retreat.

An inventory carried out on 2011 LISS IV data shows the presence of 47 epiglacial lakes/ponds over the Milam glacier (Fig. 5a). The lakes overlaid on slope map of Milam glacier (Fig. 6) shows >90 % of the epiglacial lakes on Milam glacier are falling in the inclination of <5° which is matching with the predicted value for the formation of epiglacial lakes worldwide (Sakai and Fujita, 2010; Quincey et al., 2007). The melt water generated from the epiglacial lakes can drain through the conduits/cracks (hydro-fracture) in the glacier ice and increases the glacier melt and finally disintegrates the glacier. Many of the epiglacial ponds over Milam glacier is at the junction of the transverse tributary glacier with the main longitudinal Milam glacier. The dimensions of some of the epiglacial lakes indicate they are deeper and larger in size (Fig. 5b & 5c). The present disintegration of the snout of Milam glacier indicates that in future the tributary glaciers may detach from the main glacier due to the increase in melting of glacial ice by epiglacial lake activity. Some of the previous studies indicate that glacial lake formation within debris-covered glaciers reduces the glacial ice thickness by accelerated ablation and ice dynamics. (Sakai and Fujita, 2010; Krawczynski et al., 2009; Das et al., 2008). The formation of 47 epiglacial lakes/ ponds and the accelerated recession of Milam glacier during the last decade (Govindha Raj et al., 2012; Govindha Raj, 2011) indicate that the glacier is in a state of thinning and down-wasting.

In a study of Tasman glacier, Rohl (2008) has reported that epiglacial lakes contribute to disintegration of the glacier terminus by exposing ice faces at the surface. The formation of a terminal glacial lake (proglacial lake) results in reduced compression in the lower part of the glacier, as the glacier ice at the terminus receives no pressure from adjacent ice or the terminal moraine. This reduced compression in turn, reduces emergence velocity, leading to further lowering of the glacier surface. Various studies suggesting that glacial lakes accelerate the disintegration of glacier ice by draining water through the conduits/ cracks (hydro-fracture) in the ice and accelerate the melting at the glacier bottom and finally disintegrate the glacier. (Sundal et al.,2009; Das et al., 2008; Van der Veen, 2007;Benn et al., 2001)

CONCLUSION

In future, many of the epiglacial ponds over the Milam glacier are likely to grow further by collapse of ice walls and coalesce with adjacent ones and may lead to the disintegration of glacial ice and split the glacier. The formation of a standalone moraine dammed glacial lake depends on the (a) process affecting the growth of epiglacial lake and (b) occurrence of hydro-fracture/cracks/crevasses in the glacier.

Highly crevassed Milam glacier is an ideal location to monitor the glacial ice disintegration by proglacial and epiglacial lake activity. This paper presents the utility of remote sensing in detecting and monitoring the growth of glacial lakes in highly glaciated terrain of Indian Himalaya. In view of fast receding and increase in melting of glaciers in Himalaya a systematic inventory of glacial lakes using high resolution satellite data and in situ field survey is recommended.

Acknowledgements: The authors thank Dr. V. K. Dadhwal, Director, National Remote Sensing Centre (ISRO) and Dr. Arun Chaturvedi, Director, Glaciology Division, Geological Survey of India for providing necessary support to carryout joint research activities. The authors acknowledge the constructive comments of the reviewer for improving the quality of an earlier version of the manuscript.

References

Arshad, A., Rozina, N. and Rakhshan, R. (2012) Glacial lake outburst flood hazards in Hindukush, Karakoram and Himalayan Ranges of Pakistan: implications and risk analysis. Geomatics, Natural Hazards and Risk, v.3(2), pp.113-132.

Benn, D., Wiseman, S., and Hands, K. (2001) Growth and drainage of supraglacial lakes on debris-mantled Ngozumpa Glacier, Khumbu Himal, Nepal. Jour. Glaciology, v.47(159), pp.626-638.

Bolch, T., Buchroitner, M., Peters, J., Baessier, and Bajracharya, M. (2008) Identification of glacier motion and potentially dangerous glacial lakes in the Mt. Everest region/ Nepal using spaceborne imagery. Natural Hazards and Earth System Sciences, v.8, pp.1329-1340.

Boyce, E.S., Motyka, R.J. and Truffer, M. (2007) Flotation and retreat of a lake-calving terminus, Mendenhall Glacier, south-east Alaska, USA. Jour. Glaciology, v.53(181), pp.211-224.

Campbell, J. Gabriel (2005) Inventory of Glaciers and Glacial Lake and the identification of potential Glacial lake Outburst Floods (GLOFs) affected by Global Warming in the Mountains of India, Pakistan and China/Tibet Autonomous Region. Final Report submitted to APN, 2004- 03-CMY, p.39.

Das, S., Joughin, M., Behn, M., Howat, I., King, M., Lizarralde, D., et al. (2008) Fracture propagation to the base of the Greenland Ice Sheet during supra-glacial lake drainage. Science, v.5877, pp.778-781.

Dumka, R.K. (2011) Determination of Crustal Strain Field in Kumaun Himalaya using Global Positioning System (GPS) Geodesy. Lambert Academic Publishing, ISBN-13: 978-3-8465-0859-6.

Encyclopedia of snow, ice and glaciers. (2011) Eds. Vijay P. Singh; Pratap Singh; Umesh K. Haritashya. Springer, p.1253.

Fujita, K., Sakai, A., Nuimura, T., Yamaguchi, S. and Sharma, R. Rishi, 2009. Recent changes in Imja Glacial Lake and its damming moraine in the Nepal Himalaya revealed by *in situ* surveys and multi-temporal ASTER imagery. Environ. Res. Lett., v.4045205, 7pp.

Fujita, K., Suzuki, R., Nuimura, T. and Sakai, A. (2008) Performance of ASTER and SRTM DEMs, and their potential for assessing glacial lakes in the Lunana region, Bhutan Himalaya. Jour. Glaciology, v.54(185), pp.220–228.

Funk, M. and Rothlisberger, H. (1989) Forecasting the effects of a planned reservoir which will partially flood the tongue of Unteraargletscher in Switzerland. Ann. Glaciol., v.13, pp.76–81.

Govindha Raj, K.B. (2010) Remote Sensing based hazard assessment of glacial lakes: a case study from Zanskar basin, Jammu & Kashmir. Geomatics, Natural hazards and Risks, v.1(4), pp.339-347.

Govindha Raj, K.B. (2011) Recession and reconstruction of Milam glacier, Kumaon Himalaya, observed with satellite imagery. Curr. Sci., v.100(9), pp.1420-1425.

Govindha Raj, K.B., Vinod Kumar, K., Mishra, Rakesh and Mukhtar Ahmad, M. (2012) Recession of Milam glacier, Kumaon Himalaya. Curr. Sci., v.102(10), pp.1351-1352.

Komori, J. (2008) Recent expansions of glacial lakes in the Bhutan Himalayas. Quaternary Internat., v.184, pp.177-186.

Krawczynski, M.J., Behn, M.D., Das, S.B. and Joughin, I. (2009) Constraints on the lake volume required for hydro-fracture through ice sheets. Geophys. Res. Lett., v.36, L10501.

Kirkbride, M.P. and Warren, C.R. (1999) Tasman Glacier, New Zealand: 20th-century thinning and predicted calving retreat. Global Planet. Change, v.22(1–4), pp.11–28.

Naruse, R. and Skvarca, P. (2000) Dynamic features of thinning and retreating Glaciar Upsala, a lacustrine calving glacier in southern Patagonia. Arct. Antarct. Alp. Res., v.32(4), pp.485-491.

Quincey, D.J., Richardson, S.D., Luckman, A., Lucas, R.M., Reynolds, J.M., Hambrey, M.J. and Glasser, N.F. (2007) Early recognition of glacial lake hazards in the Himalaya using remote sensing datasets. Global Planetary Change, v.56, pp.137-152.

Reynolds, J.M. (2000) On the formation of supraglacial lakes on debris-covered glaciers. IAHS Publ. 264 (Symposium at Seattle 2000 – Debris-Covered Glaciers), pp.153-161.

Rohl, K. (2008) Characteristics and evolution of supraglacial ponds on debris-covered Tasman Glacier, New Zealand. Jour. Glaciology, v.54(188), pp.867–880.

Sakai, A. and Fujita, K. (2010) Formation conditions of supraglacial lakes on debris-covered glaciers in the Himalaya. Jour. Glaciology, v.55(195), pp.177-181.

Sakai, A., Chikita, K. and Yamada, T. (2000) Expansion of a moraine-damned glacial lake, Tsho Rolpa, in Rolwaling Himal, Nepal Himalaya. Limnology and Oceanography, v.45(6), pp.1401-1408.

Sangewar, C.V. and Shukla, S.P. (2009) Inventory of the Himalayan Glaciers: A Contribution to the International Hydrological Programme. Geol. Surv. India, Spec. Publ. No. 34, 594p.

Sundal, A.V., Shepherd, A., Nienow, P., Hanna, E., Palmer, S., and Huybrechts, P. (2009) Evolution of supra-glacial lakes across the Greenland Ice Sheet. Remote Sensing of Environment, v.113, pp.2164-2171.

Van der Veen, C. J. (2007) Fracture propagation as means of rapidly transferring surface melt- water to the base of glaciers. Geophys. Res. Lett., v.34, L01501.

Wang Weicai, Yao, T. and Yang, X. (2011) Variations of glacial lakes and glaciers in the Boshula mountain range, southeast Tibet, from the 1970s to 2009. Annals of Glaciology., 52(58), 09-17

Wessels, R., Kargel, J. and Kieffer, H. (2002) ASTER measurements of supraglacial lakes in the Mount Everest region of the Himalaya. Annals of Glaciology, v.34, pp.399–407.

Yamada, T. and Sharma, C. (1993) Glacier lakes and outburst floods in the Nepal Himalaya. Proceedings of the Kathmandu Symposium, 218. IAHS Publication, pp.319–330.

Yao, T., Li, Z., Yang, W., Guo, X.J., Zhu, L.P., Kang, S.C., Wu, Y.H. and Yu, W. (2010) Glacial distribution and mass balance in the Yarlung Zangbo River and its influence on lakes. Chinese Sci. Bull., v.55(20), pp.2072–2078.

(Received: 30 October 2012; Revised form accepted: 4 April 2013)