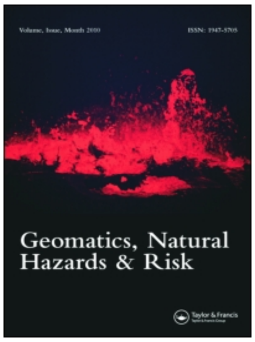

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Geomatics, Natural Hazards and Risk

ISSN: 1947-5705 (Print) 1947-5713 (Online) Journal homepage: https://www.tandfonline.com/loi/tgnh20

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Geomatics, Natural Hazards and Risk, 2013
Vol. 4, No. 3, 241–253, http://dx.doi.org/10.1080/19475705.2012.707153

Remote sensing-based inventory of glacial lakes in Sikkim Himalaya: semi-automated approach using satellite data

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(*Received 29 February 2012; in final form 25 June 2012*)

The climate change of the twentieth century had a pronounced effect on glacier environments of the Himalaya. The formation of supraglacial lakes and moraine dammed glacial lakes and glacial lake outburst flood is a major concern in countries such as Bhutan, China (Tibet), India, Nepal and Pakistan. This article depicts a semi-automated identification of glacial lakes in the Sikkim Himalaya, from the normalised difference water index-based methodology of Resourcesat-1 LISS III satellite data. The inventory shows the existence of 320 glacial lakes out of which 85 are new ones in the study area compared to 2003 inventory. Remote sensing proves to be the best tool in detecting and monitoring the hazardous nature of glacial lakes in the Indian Himalaya. To establish the hazard potential of glacial lakes, a systematic inventory of these lakes from high-resolution satellite data and in situ field survey is recommended.

1. Introduction

Global climate change of the twentieth century had a significant role in modifying the glaciated mountainous environment. The fluctuations in climate had significant effect on downwasting of many glaciers globally. These glacial fluctuations cause the formation and enlargement of glacial lakes in many mountain ranges (Richardson and Reynolds 2000, Govindha Raj 2010, Yao *et al*. 2010). The sudden catastrophic discharge of large volumes of water from these lakes is a characteristic of many glaciated regions of the globe. Such glacial lake outburst flood (GLOF) can cause extensive damage to the natural environment, human property and lives as they can drain extremely rapidly and cause dramatic floods. A glacial lake is defined as water mass exists in a sufficient amount and extends with a free surface in, under, besides and/or in front of a glacier and originated by glacier activities (Campbell 2005).

Recent expansion of glacial lakes in the Himalaya included studies 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 investigation of glacial lakes in Bhutan from ALOS PRISM and AVNIR-2 data shows the occurrence of 278 glacial lakes in the Bhutan Himalaya (Ukita *et al*.

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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 the multi-temporal and multi-sensor satellite data. The glacial lake inventory in SE Tibet with ALOS AVNIR-2 data shows an increase in the number of glacial lakes from 96 to 123 between 1970 and 2009 (Wang *et al.* 2011). Reynolds (2000) reported that in Bhutan Himalaya, large glacial lakes form only in the glaciers where the slope of the glacier surface is $<2^{\circ}$. The study carried out by Quincey *et al.* (2007) by means of microwave (SAR) and optical (SPOT-5) satellite data in Tibet shows that supra glacial lakes formed at the tongue of debris-covered glaciers have slope $<2^{\circ}$ and stagnant ice at the snout.

The International Centre for Integrated Mountain Development (ICIMOD) provided a first level assessment of glacial lakes in some parts of the Indian Himalayan region (Mool and Bajracharya 2003). The inventory carried out by ICIMOD in 2003 shows 266 glacial lakes in the Sikkim Himalaya with an area of 20.20 km^2 and 14 lakes are identified as potentially dangerous lakes.

In the snow and glaciated terrain of the Himalaya, satellite remote sensing was established as the best tool because many of the glacial lakes are located at very high altitude, cold weather and rugged terrain conditions, making it a tedious, hazardous and time-consuming task to monitor by conventional field methods. Satellite remote sensing technology facilitates to study the initial and qualitative hazard assessment of glacial lakes of the Himalaya systematically with a cost-to-time benefit ratio.

A systematic automatic glacial lake inventory from satellite data lacks in the Indian Himalaya. The purpose of this study is to establish a semi-automated methodology for the extraction of glacial lakes from the temporal data of IRS P6 (Resourcesat-1) Linear Imaging Self Scanning (LISS) - III sensor and make an inventory of glacial lakes over the Sikkim Himalaya.

2. Study area

The study area falls in Tista basin of the Sikkim Himalaya, India (Figure 1). The state of Sikkim is surrounded by Nepal in the west and Bhutan in the east, whereas China (Tibet) lies to its north and northeast and south joins with west Bengal. The major sub-basins are East Rathong, Talung, Changme Khangpu and Zemu, which are glacierized and Rangpo basin is non-glacierized.

3. Data used

The present study utilized temporal multispectral satellite data from Resourcesat-1 Linear Imaging Self Scanning (LISS) III sensor data from 2005, 2006, 2008, 2009 and 2010 and Cartosat-1 Digital Elevation Model (DEM) data. Table 1 shows the spectral and spatial characteristics of the data used.

4. Methodology

One of the important concepts in the determination of various objects through remote sensing is that the objects reflect energy differently in diverse parts of the electromagnetic spectrum. This variation depends on the properties of the objects under observation. By means of this inherent property of objects, various classifications methods such as Normalised Difference Vegetation Index (NDVI)

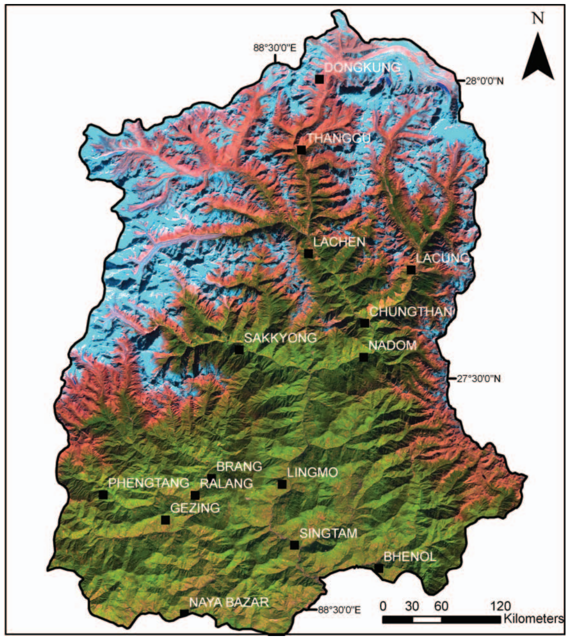

Figure 1. Location map of the study area.

Table 1. List of satellite data used in the present study and its spectral and spatial characteristics.

S. No.	Sensor	Date of acquisition	Resolution: Spectral (μm)	Resolution: Spatial (m)
1	Resourcesat-1	15-Nov-2005		23.5
2	LISS III	26-Jan-2006	Band 2: 0.52–0.59	
3		17-Dec-2008	Band 3: 0.62–0.68	
4		03-Feb-2009	Band 4: 0.77–0.86	
5		11-Apr-2010	Band 5: 1.55–1.7	
6	Cartosat-1		Digital elevation data	30.0 (vertical)

and Normalised Difference Snow Index (NDSI) are available for the delineation of objects. Based on ASTER imagery of the Mt. Everest region, Wessels *et al.* (2002) performed a spectral analysis of terrain features, which outlines the importance of turbidity when observing glacial lakes. The more turbid a glacial lake is, the higher its reflectance in the Visible and Near Infra-Red (VNIR) spectrum because of the high-suspended sediment load. When optical images are used, shadows are problematic, especially in the mountainous areas where the solar zenith angle is high. It is important to notice that the signature of these shadow areas is very similar to the one of glacial lakes with low turbidity.

Several methods are used to delineate open water features and enhance their presence in remotely sensed image data. The methodology adopted here is normalised difference water index (NDWI) proposed by McFeeters (1996) to differentiate water bodies such as glacial lakes in the present study area from the other features. Bolch *et al.* (2008) used the NDWI method to classify glacial lakes from ASTER in the Mt. Everest region and established the dangerous potential of the lakes. Huggel *et al.* (2002) used the NDWI method to establish glacial lakes hazard in the Swiss Alps, from Landsat data with the advantage of the low water reflectance in the NIR band. However, they noticed that with this method, glacial lakes could misclassify as shadow area because of the similar reflectance of these objects.

The present approach of using NDWI-based method for the automatic identification of glacial lakes from LISS III data is a unique approach in terms of methodology and data. Figure 2 shows the detailed methodology adopted in this article. The steps involved are conversion of digital numbers (DN) to spectral radiances and then to reflectance. The NDWI image was generated from the reflectance image. The NDWI output was processed with a decision tree approach for generation of lake layer.

4.1 *Conversion of DNs into spectral radiances*

Radiance reaching the sensor depends on the target reflectance and the solar irradiance on the target. Reflectance (ρ) can be defined as the ratio of the upward flux reflected from the surface to the incoming total flux impinging on to the surface.

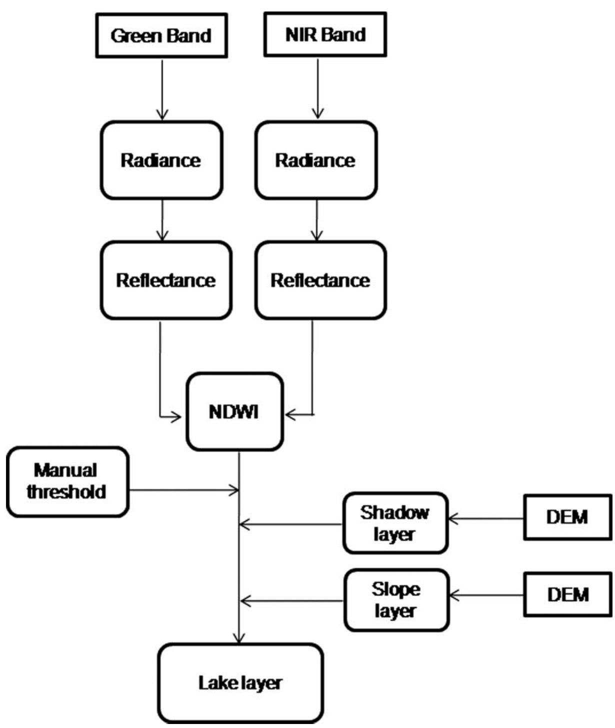

Figure 2. Methodology to automatically classify glacial lakes from LISS III data.

Spectral radiance from the pixel in each band, denoted as L_λ (mW cm^{-2} sr$^{-1}\mu$m^{-1}), is proportional to its digital number (DN) and can compute from the subsequent formula (Markham and Barker 1987):

$$L_\lambda = \text{Gain}_\lambda \times \text{DN}_\lambda \times \text{Bias}_\lambda \tag{1}$$

where L_λ is the spectral radiance (mW cm^{-2} sr^{-1} μm^{-1} counts^{-1}), Gain$_\lambda$ is the calibration gain coefficient of the sensor (mW cm^{-2} sr^{-1} μm^{-1} counts^{-1}), DN$_\lambda$ is the digital number of a pixel in a particular band (counts) and Bias$_\lambda$ is the Calibration offset of the sensor band (mW cm^{-2} sr^{-1} μm^{-1}). Table 2 shows the calibration gain coefficients of Resourcesat-1 LISS III sensor.

4.2 *Estimation of reflectance from spectral radiances*

Reflectance is the ratio of the upward flux reflected from the surface to the total inward flux impinging onto the surface. The reflectance property of materials is highly variable, angle-dependent and ideally given by bidirectional reflectance distribution function (BRDF), which conceptually describes reflectance from a surface for all possible angles and directions of the incidence combined with all possible angles and directions of existence (observation). The BRDF is usually unknown and hardly determinable and therefore directional reflectance is generally used.

For comparison with satellite measurements, it is appropriate to convert the solar irradiance to the radiance from the Sun at normal incidence on a perfectly reflecting diffuse surface. This quantity is called equivalent solar radiance (mW cm^2) and is equal to the solar irradiance (mW cm) divided by π. The reflectance is the ratio of the satellite radiance to its equivalent solar radiance. As there is neither any radiation transfer model available for the Himalayan terrain nor any field data on BRDF for the area, no specific topographic corrections are applied in this methodology for reflectance estimation.

The planetary spectral reflectance for any band of a satellite sensor calculated by the formula:

$$\rho_\lambda = \frac{\pi L_\lambda d^2}{E_{\mathrm{sun}\lambda} \cos \Theta_\mathrm{s}} \tag{2}$$

Table 2. Resourcesat-1 LISS III Bandpass solar exo-atmospheric spectral irradiance and saturation radiance values.

Band	Bandpass solar exo-atmospheric spectral irradiance (mW cm^{-2} sr^{-1} μm^{-1})*	Saturation radiance (mW cm^{-2} sr^{-1} μm^{-1})	
		G2	G3
2	1848.92	18.5	12.1
3	1576.79	18.2	15.1
4	1093.38	20.7	15.8
5	237.50	3.4	1.6

^Note: G, gain number used while acquiring the data. *Source: Pandya *et al.* (2007). With kind permission from Springer Science + Business Media: *Journal of the Indian Society of Remote Sensing*, Spectral characteristics of sensors onboard IRS-1D and P6 satellites: Estimation and their influence on surface reflectance and NDVI, 35(4), (2007), 333–350.

where ρ_λ is the reflectance of a pixel in a particular band, d is the Earth–Sun distance (AU), $E_{\mathrm{sun}\lambda}$ = mean solar exo-atmospheric spectral irradiance ($\mathrm{Wm}^{-2}\,\mu\mathrm{m}^{-1}$), Cos Θ_s = Cosine of solar zenith angle (degree).

Table 2 shows the bandpass solar exo-atmospheric spectral irradiance ($\mathrm{Wm}^{-2}\,\mu\mathrm{m}^{-1}$) for Resourcesat-1 LISS III sensor. The solar zenith angle picked from the header information of the LISS III data.

4.3 *Normalised difference water index*

The NDWI expressed as follows:

$$\mathrm{NDWI} = \frac{\mathrm{Green} - \mathrm{NIR}}{\mathrm{Green} + \mathrm{NIR}} \tag{3}$$

where Green is the reflectance of green band and NIR is reflectance in near-infrared (NIR) band.

This index is designed to (1) maximize the reflectance of water by green wavelengths; (2) minimize the low reflectance of NIR by water features; and (3) take advantage of the high reflectance of NIR by vegetation and soil features. As a result, water features have positive values, thus enhanced, while vegetation and soil usually have negative values and are therefore suppressed (McFeeters 1996).

For Resourcesat-1 LISS III sensor, NDWI is expressed as

$$\mathrm{NDWI} = \frac{B2 - B4}{B2 + B4} \tag{4}$$

where $B2$ and $B4$ are the reflectance in green band and NIR bands of Resourcesat-1 LISS III sensor, respectively.

A model developed on ENVI software incorporates the above set of equations to estimate the reflectance and finally the NDWI image from the digital satellite data.

5. Results and discussion

The final lake layer generated with the NDWI method is manually checked with the temporal LISS III satellite data and ICIMOD lake database for verification. The final lake layer generated from the 2010 data shows 320 glacial lakes compared to the 266 lakes shown by the ICIMOD database. The ICIMOD inventory includes glacial lakes, which are larger than 0.1 km^2, but the present inventory does not have any threshold for the spatial extent of the lakes. The temporal LISS III satellite data of 2005, 2006, 2008, 2009 and 2010 period show that out of the 266 lakes of ICIMOD, only 235 lakes are in existence. The lack of 31 glacial lakes is attributed to the dearth of melt water drainage due to the impact of environmental changes. The present inventory identified 85 new lakes with NDWI methodology. Figure 3 shows the 266 lakes identified by ICIMOD and 85 new lakes identified in the present study.

After classification, 14 potentially dangerous glacial lakes already identified in the ICIMOD database were verified in the classified lake layer (Figures 4(*a*)–(*c*)). The potentially dangerous glacial lakes are identified based on different criteria such as records of past events, field observations, geomorphological and geo-technical

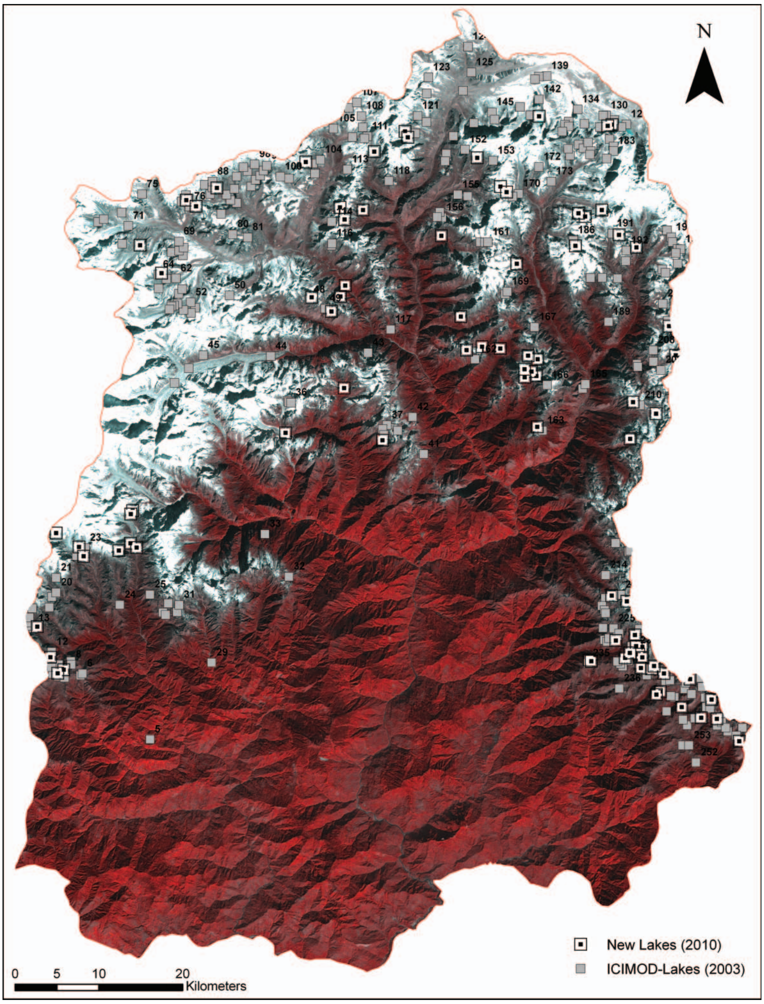

Figure 3. New glacial lakes identified (2010) and ICIMOD glacial lakes (2003) in the Sikkim Himalaya.

characteristics of the lake and environments and other conditions such as type, size and association with the mother glacier (Mool and Bajracharya 2003). Many new large lakes are also identified in the 2010 lake layer. However, detailed analysis of the lakes is restricted to 14 potentially dangerous lakes. Table 3 shows the area of 14 glacial lakes during 2003 and 2010.

Out of the 14 dangerous lakes, three lakes (lake no −54, 71 and 72) seem to have evidences of past GLOF and the reduction of area of lake −54 and 120 during 2010 may be attributed to the lake discharge or an outburst event. Out of the 14 lakes, 12 lakes show an increase in the area from 2003 to 2010. The drainage input to the lakes is closely linked to the snow precipitation and rate of ablation of the glacier. Kulkarni (2011) reported that the climate change is responsible for the glacial retreat, negative mass balance, early melting of seasonal snow cover and wintertime increase in stream runoff in the Indian Himalaya. The impression of climate change

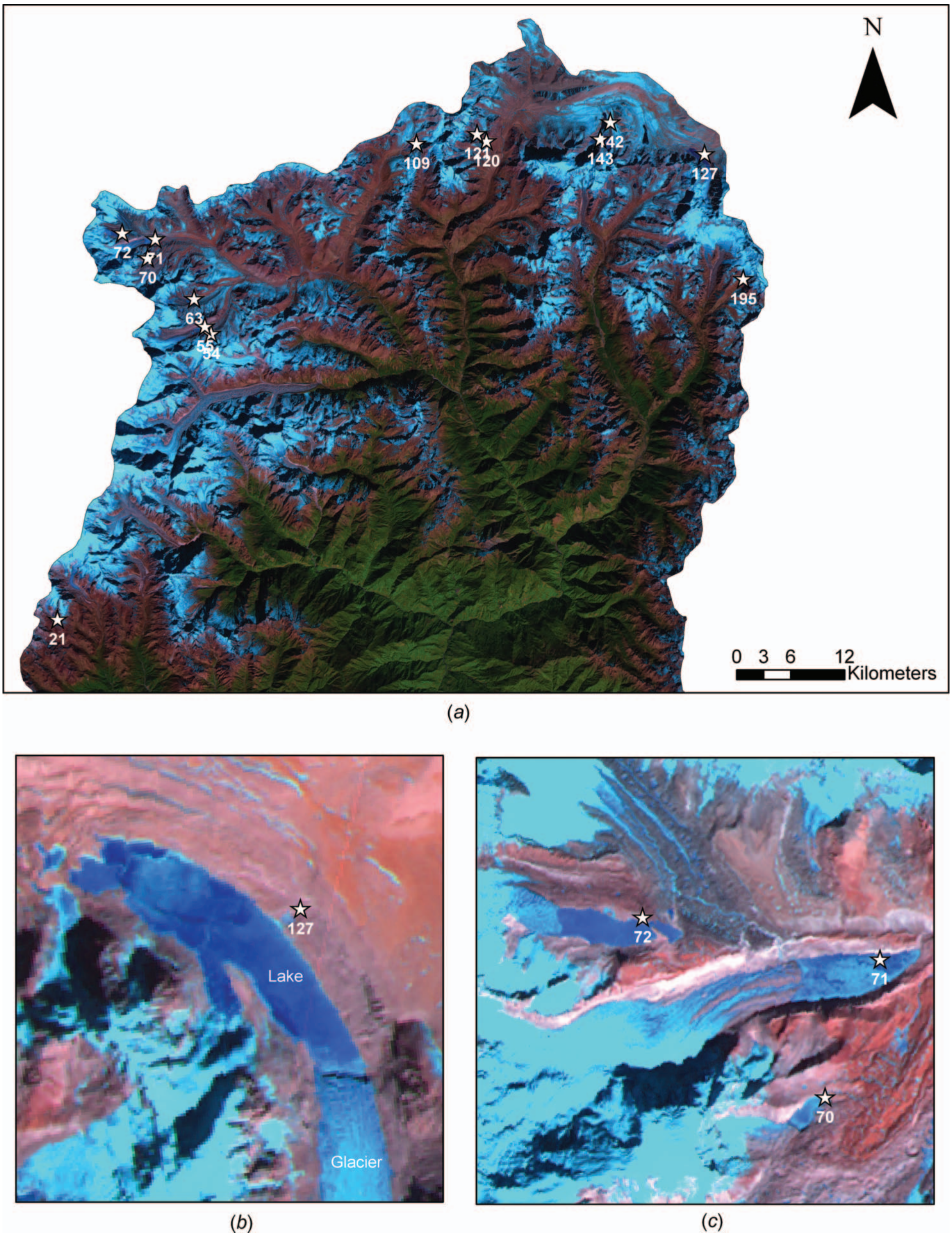

Figure 4. (*a*) Location of the potentially dangerous glacial lakes in the Sikkim Himalaya; (*b*) and (*c*) satellite data showing some of the potentially dangerous glacial lakes.

on glacial environments could be the reason for the accelerated growth of glacial lakes in the Sikkim Himalaya. Systematic observation of lake expansion is essential for the assessment of hazard potential.

The preliminary NDWI image shows bright pixels for glacial lakes and mountain shadows. Figure 5 shows the reflectance spectra of glacial lakes and other features. It

Table 3. Change in area of potentially dangerous glacial lakes in Sikkim Himalaya from 2003 to 2010.

Lake no.	Area in 2003 (m^2) ICIMOD database	Area in 2010 (m^2)	Change in area (m^2)	Lake type
21	290742.37	325593.42	34851.06	Moraine-dammed
54	130341.28	113561.67	16779.61	Blocked
55	95476.83	507284.46	411807.63	Moraine-dammed
63	147034.34	243923.42	96889.08	Moraine-dammed
70	115446.32	182929.50	67483.18	Moraine-dammed
71	592231.13	980137.87	387906.75	Moraine-dammed
72	395971.69	724131.55	328159.86	Moraine-dammed
109	351703.56	438102.76	86399.21	Moraine-dammed
120	269253.82	255101.07	14152.74	Valley
121	197485.44	215746.95	18261.51	Moraine-dammed
127	1588660.72	1719173.07	130512.35	Moraine-dammed
142	1067899.89	1115383.50	47483.61	Moraine-dammed
143	650773.78	864894.83	214121.05	Blocked
195	107951.65	127899.17	19948.52	Moraine-dammed

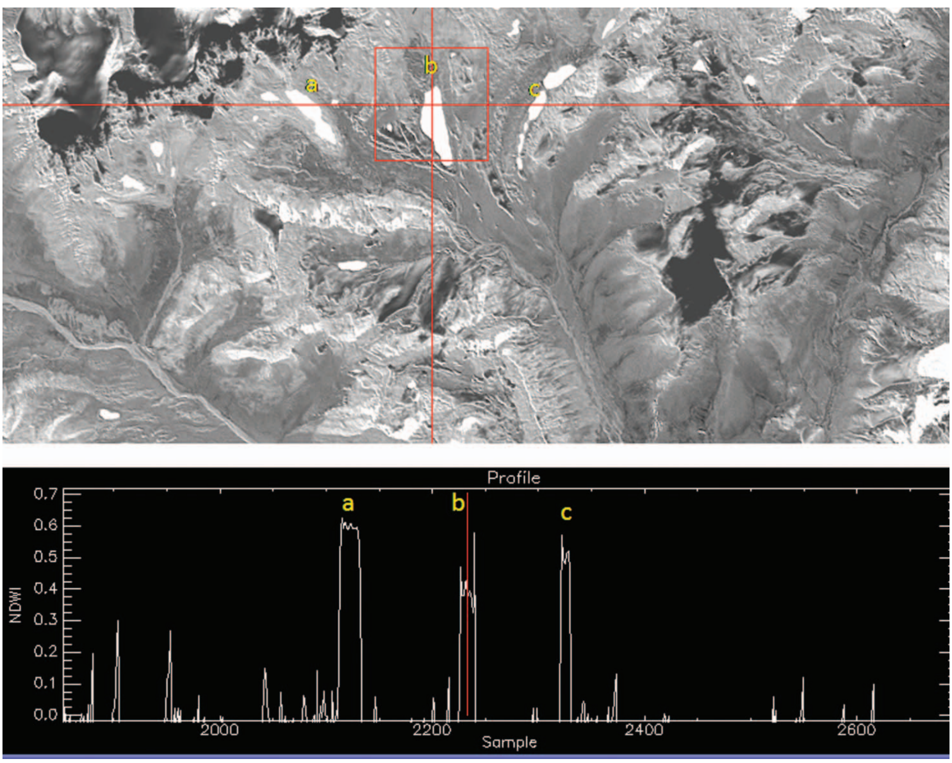

Figure 5. NDWI and corresponding reflectance spectra image shows glacial lakes and other features.

is very clear that those spectral values of glacial lakes are higher than that of shadows and other features. Based on this criterion, a manual threshold value applied to mask the mountain shadows from the NDWI image. The threshold value is determined empirically on each NDWI scene by the visual inspection of the spectral values and ranges from 0.2 to 0.3. This method generated the first lake layer. But still some shadow pixels are misclassified as lake pixels.

The first lake layer along with hill shade layer from Cartost-1 DEM is used to eliminate the misclassified pixels. The decision of pixels located in the hill shade areas eliminated many of the misclassified pixels and generated the second lake layer.

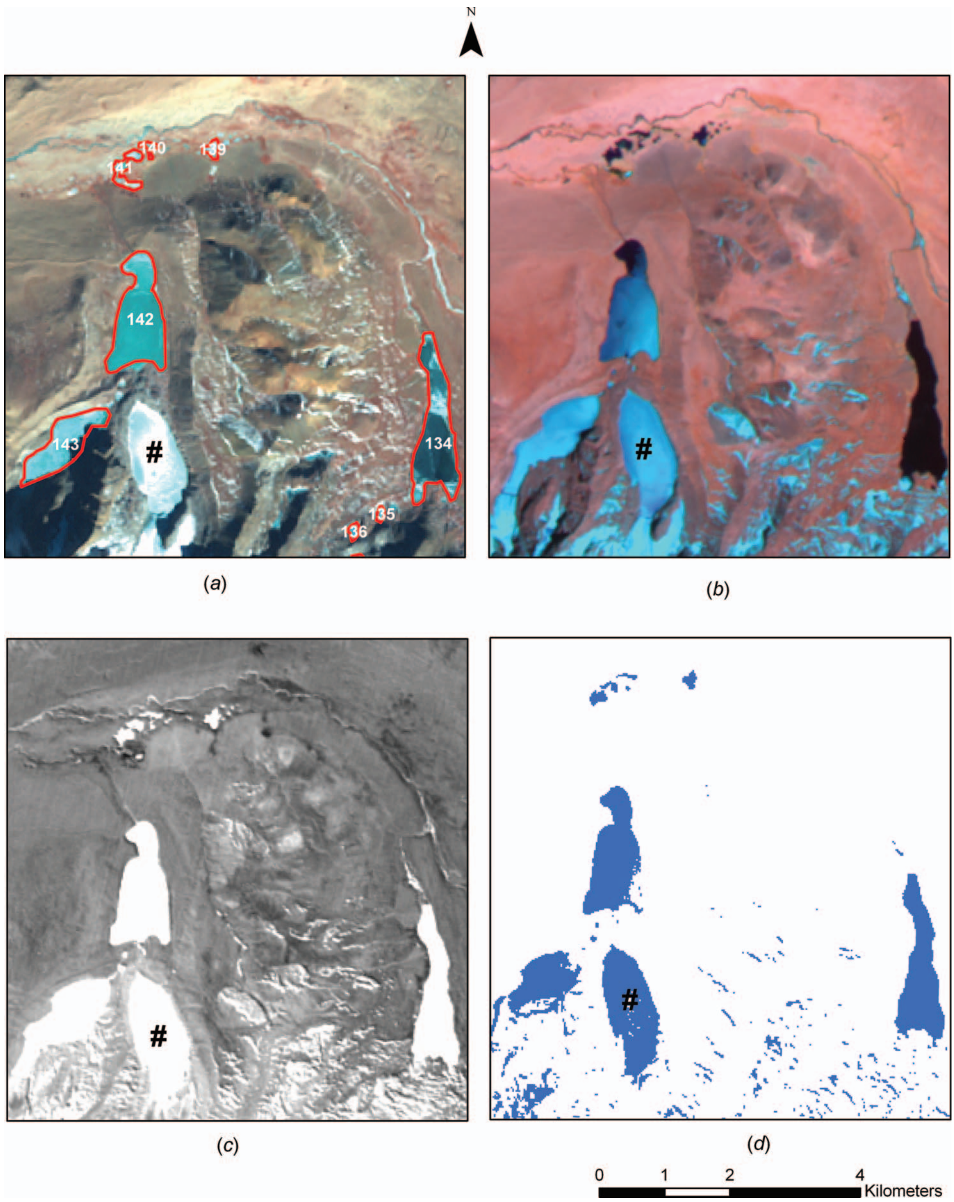

Figure 6. (*a*) ICIMOD glacial lake layer; (*b*) Resourcesat-1 LISS data (10 April 2010); (*c*) NDWI layer generated from LISS III data; (*d*) final lake layer prepared from the LISS III data.

In view of the possibilities for the formation of glacial lakes, the second lake layer is processed through the slope layer prepared from Cartosat-1 DEM. The location of glacial lakes in Sikkim Himalaya is characterized by steep slope and hence the criteria of slope $<10^\circ$ was assigned for the possible location of glacial lakes. This decision generated the final lake layer of the study area. Figure 6 shows the 2010 satellite data and the final lake layer prepared through the present methodology.

Figure 6(*a*) shows ICIMOD database of glacial lakes, and near the lake "143", the feature "#" is represented as part of glacier in ICIMOD database, but basically the feature is a large glacial lake as it can be seen in the NDWI image and final lake layer. This misclassification in ICIMOD database might have occurred due to certain error in the visual inventory. The present NDWI approach clearly shows that this method can distinguish clearly glaciers and glacial lakes because of the difference in reflectance characteristics.

The present classification shows glacial lakes with spatial extent more than one pixel size (23.5 m) of the LISS III data. The advantages of this methodology lie in (1) distinguishing shadow areas and glacial lakes precisely and (2) clear demarcation of lake boundary over non-lake features. Apart from the quality of the scene, the uncertainty of glacial lake area is computed with an error of ± 1pixel (23. 5 m) along the perimeter of the glacial lake. This uncertainty attributes to the lake pixel mixing with the adjacent non-lake pixels. This error is conservative when compared with the Fujita *et al*. (2009) who proposed an error of ± 0.5 pixel for the Imja lake, Everest region. One more disadvantage of this methodology is that the application of this technique fails if the glacial lakes covered under snow/ice and lakes under permanent mountain shadows.

The present automated satellite-based glacial lake inventory shows the benefit of space-based database in monitoring the glacial lakes in the remote, uninhibited areas of the Sikkim Himalaya. The formation and enlargement of many glacial lakes is a matter of concern for the tectonically active Sikkim Himalaya. If an earthquake of higher magnitude occurs in close proximity to a potentially dangerous glacial lake, it can create devastating GLOF events and associated hazards. Glacial lake outburst flood events in the Indian Himalaya are poorly recorded due to lack of authentic databases and instrumentation. The present technique can generate a background database of glacial lakes of the Sikkim Himalaya for further analysis in a short span of time.

6. Conclusion

This study shows the utility of remote sensing-based observations for a rapid and qualitative assessment of glacial lakes in the inaccessible terrain of Sikkim Himalaya. Normalised difference water index-based approach automatically identified the glacial lakes from the other features with best possible way. The expansion of lakes from 2003 to 2010 indicates the environmental changes applicable to the Himalayan terrain. The growth of the lakes indicates possible developments of the hazard situation. The changes in glacial lake environment suggests that a detailed inventory and field survey should be carried out in this part of the Himalaya and GLOF early warning mechanism be established in potentially dangerous locations.

Acknowledgements

The authors thank the Director and Deputy Director (RSA) of NRSC for the support throughout the course of research. The authors also thank the ICIMOD, Kathmandu, for providing the glacial lakes digital database of the Sikkim Himalaya and Mrs. G. Meenakumari, Scientist, NRSC, for the technical support. The authors acknowledge the constructive comments of the reviewers for improving the quality of the manuscript.

References

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

Bolch, T., Buchroitner, M.F., Peters, J., Baessier, M. and Bajracharya, S., 2008, Identification of glacier motion and potentially dangerous glacial lakes in the Mt. Everest region/Nepal using space borne imagery. *Natural Hazards and Earth System Sciences*, **8**, pp. 1329–1340.

Campbell, J.G., 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 (Kathmandu, Nepal: ICIMOD & APN).

Fujita, K., Sakai, A., Nuimura, T., Yamaguchi, S. and Sharma, R.R., 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. *Environmental Research Letters*, **4**, 4045205.

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. *Journal of Glaciology*, **54** (185), pp. 220–228.

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*, **1** (4), pp. 339–347.

Huggel, C., Kaab, A., Haeberli, W., Teysseire, P. and Paul, F., 2002, Remote sensing based assessment of hazards from glacier lake outburst: a case study in the Swiss Alps. *Canadian Geotechnical Journal*, **39**, pp. 316–330.

Komori, J., 2008, Recent expansions of glacial lakes in the Bhutan Himalayas. *Quaternary International*, **184**, pp. 177–186.

Kulkarni, A.V., Rathore, B.P., Singh, S.K. and Bahuguna, I.M., 2011, Understanding changes in the Himalayan cryosphere using remote sensing techniques. *International Journal of Remote Sensing*, **32** (3), pp. 601–615.

Markham, B.L. and Barker, J.L., 1987, Thematic Mapper bandpass solar exo-atmospheric irradiances. *International Journal of Remote Sensing*, **8** (3), pp. 517–523.

Mcfeeters, S.K., 1996, The use of normalized difference water index (NDWI) in the delineation of open water features. *International Journal of Remote Sensing*, **17**, pp. 1425–1432.

Mool, P.K. and Bajracharya, S.R., 2003, *Tista Basin, Sikkim Himalaya Inventory of Glaciers, Glacial Lakes, and the Identification of Potential Glacial Lake Outburst Floods (GLOFs) Affected by Global Warming in the Mountains of Himalayan Region*, p. 145 (Kathmandu, Nepal: ICIMOD).

Pandya, M.R., Singh, R.P., Chaudhari, K.N., Murali, K.R., Kirankumar, A.S., Dadhwal, V.K. and Parihar, J.S., 2007, Spectral characteristics of sensors onboard IRS-1D and P6 satellites: estimation and their influence on surface reflectance and NDVI. *Journal of Indian Society of Remote Sensing*, **35** (4), pp. 333–350.

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*, **56**, pp. 137–152.

Reynolds, J.M., 2000, On the formation of supraglacial lakes on debris-covered glaciers. In Symposium at Seattle 2000 – Debris-Covered Glaciers, M. Nakawo, C.F. Raymond and A. Fountain (Eds), IAHS Publication **264**, pp. 153–161 (Wallingford, UK: International Association for Hydrological Sciences)

Richardson, S. and Reynolds, J., 2000, An overview of glacial hazards in the Himalayas. *Quaternary International*, **65** (66), pp. 31–47.

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*, **45** (6), pp. 1401–1408.

Ukita J., Narama C., Tadono T., Yamanokuchi, T., Omiyama N., Kawamoto S., Abe C., Uda T., Yabuki H., Fujita K. and Nishimura K., 2011, Glacial lake inventory of Bhutan using ALOS data: Part I. Methods and preliminary results. *Annals of Glaciology*, **52** (58), pp. 65–71.

Wang W., Yao T. and Yang, X., 2011, Variations of glacial lakes and glaciers in the Boshulamountain range, southeast Tibet, from the 1970s to 2009. *Annals of Glaciology*, **52** (58), pp. 9–17.

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

Yamada, T. and Sharma, C., 1993, Glacier lakes and outburst floods in the Nepal Himalaya. In *Proceedings of the Kathmandu Symposium*, November 1992, G.J. Young (Ed), IAHS Publication **218**, pp. 319–330 (Wallingford, UK: International Association for Hydrological Sciences)

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 Science Bulletin*, **55** (20), pp. 2072–2078.