4 Remote Sensing and GLOF Risk Assessment

Introduction

Remote sensing of glaciers began with terrestrial and aerial photography during the mid 20th century. The Landsat Multispectral Scanner (MSS) was one of the first satellite data systems used for glacier mapping by the United States Geological Survey (USGS) in the early 1970s. Since then, satellite data from different sensors have been used as soon as they became available. Today the discipline embraces a large variety of data types from laser scanner data to very high resolution satellite imagery that can be applied to the mapping of changes in area or surface zonation of glaciers. Recent development in satellite sensors (higher spatial and spectral resolution) and better image processing software (advanced classification techniques) has made an algorithm-based semi-automated classification approach possible.

Use of statistical and remote sensing-based approaches has proved an important addition to the earlier deterministic, return period, and qualitative geomorphic analyses. Such tools have been used, for example, to investigate the probability of catastrophic drainage of moraine-dammed lakes in southwestern British Columbia, Canada (McKillop and Clague 2007). Glacial lake hazard assessment has been undertaken in the Swiss Alps using three scale levels of remote sensing with a progressive focus on critical glacial lakes (Huggel et al. 2002). In very remote regions, such as the Cordillera Carabaya in the Peruvian Andes, remote sensing has proven to be of great value, being virtually the only tool available to fill gaps in information (Huggel et al. 2003).

In the Hindu Kush-Himalayas, remote sensing methods using space borne imagery with or without aerial photographs and in situ field surveys, have been widely applied for the assessment of glaciers and glacial lake hazards by different researchers (Yamada 1998a, 1998b; Reynolds 1998; Mool et al. 2001a, 2001b; Huggel et al. 2002; Bolch et al. 2008; Fujita et al. 2009; Watanabe et al. 2009). The appropriateness of different types of data for use in GLOF risk assessment, their use in developing a new and more accurate inventory of glaciers and glacial lakes for the Hindu Kush-Himalayan region, and application in monitoring are discussed in the following.

Using remote sensing data in GLOF risk assessment

Given the enormous extent and unusually challenging accessibility of the HKH region, application of remote sensing (and continued refinement of methodology) is a fundamental requirement for any assessment of the potentially large scale and widespread hazard posed by the rapid formation of new glacial lakes and the continued enlargement of existing ones. Because of the numbers involved, only a very small percentage of such lakes will ever be visited in the field. This creates the essential challenge.

Before any progress can be made in assessing the magnitude of the problem, however, or in the development of methods to reduce downstream vulnerability or mitigate the effects of glacial lake outbursts, the sources of possible danger must first be identified and precisely located. While many sources of potential danger have already been noted, the entire situation is extremely volatile – new glacial lakes form while existing ones continue to expand. A replicated monitoring system is the first task for long-range application of remote sensing.

Emphasis must be placed on the relatively small number of lakes that can be identified as especially vulnerable to sudden outbreak. This is not only because of the degree of danger to which people and infrastructure may be exposed, but also to ensure the most efficient use of the limited resources available (as already recommended in the early report produced by

WECS in 1987). Glacial lakes must be ranked in order of their apparent level of instability. This process has two aspects: (1) evaluation of the current degree of lake instability from a purely geophysical point of view; and (2) determination of the potential for downstream damage and loss of life in the event of actual lake outburst. The two foci must be examined separately and then combined.

1. Repeat remote sensing of particular glacial lakes is essential. It is clear that priority attention should be given to the larger ones, and/or to those known for various reasons to have enlarged rapidly in recent years and to exhibit other characteristics that suggest instability. The relatively small number of such lakes out of the huge number that were identified by first-pass remote sensing should become candidates for special attention. Nevertheless, this will constitute only a first approximation.
2. It follows that the largest and potentially unstable glacial lakes that are in closest proximity to human activities must be ranked as requiring special attention. Local grazing and cultivation, settlements, and so on, also modern infrastructure, such as hydroelectric facilities, roads and bridges, and popular trekking routes that lead to the various major tourist destinations, must be evaluated.

If lakes, from a purely geophysical/remote sensing survey, are far removed from human activity then, by any definition, they should not be classed as a potential hazard.

Repeated remotely sensed images of high resolution can be used to observe the changes in Himalayan glacial lakes such as expansion mechanisms for monitoring purposes, as shown during the studies of Imja Lake (Fujita et al. 2009; Watanabe et al. 2009). But sole reliance on remote sensing data is inadequate as it cannot furnish the necessary repeat bathymetric information, changes in the height of the damming moraine, or changes in lake level, which are also needed.

Reliable determination of the degree of glacial lake instability, at least in most cases, will require detailed glaciological and geotechnical in situ field investigation. Enough is known about the development of Imja Lake, for example, to conclude that rate of lake expansion alone is not a reliable guide for determination of the degree of instability (Watanabe et al. 2009). That is one reason why it is essential to use remote sensing applications for an initial ranking – to reduce the expense, both in time of available experienced field persons and in cost. Furthermore, highly sensitive remote sensing, utilising the more powerful imagery and software for its examination that is continually becoming available, must be evaluated. Even then, it is unlikely that the need for field investigation will be eliminated.

Selection of appropriate type of remotely-sensed data

Thus the best approach to GLOF risk studies is to use a step-by-step, multi-scale, and multi-level process starting from a regional scale (preliminary reconnaissance) and proceeding to a local scale (detailed information gathering) (Mool et al. 2001a; Huggel et al. 2002). The level of study determines the type of remote sensing data to be used, especially in terms of resolution. Two types of resolution are important: spatial, i.e. distance or area, and temporal, i.e. in time. The spatial resolution of the sensor determines the degree of detail that can be detected, or the smallest size of a feature that can be mapped or sampled. This is categorised in terms of high resolution, medium resolution, low resolution, and very low resolution. The temporal resolution determines variations in size through time – hours, days, months, and so on. There are very few objects and/or phenomena in nature that do not change with respect to one another through the course of time, but the rate of change is different for different phenomena. The temporal resolution has to be in agreement with the rate of hazard development. In other words, changes observed during annual visits of a sensor, for example, might be sufficient to monitor development of a glacial lake, whereas a repeat time of a few days would be necessary for ice avalanches or landslide-induced lakes (Kääb et al. 2005; Bajracharya et al, 2009). Besides the various degrees of resolution, other factors, such as the spatial coverage, i.e., the ground area or width of the ground track sensed, the timing of data acquisition, stereo interferometric or ranging capability, and usability of data, also govern the extent to which remote sensing methods can be successfully applied (Kääb 2005).

The first step in preparing an inventory is to develop a database for a large area. This can be achieved using medium resolution satellite images (e.g., Landsat TM, IRS [Indian Remote Sensing], or ASTER [Advanced Spaceborne Thermal Emission and Reflection Radiometer] images), a digital elevation model (DEM), and ancillary information. Following this, the potentially dangerous lakes can be identified from the inventory data and other defined criteria. At this stage, multi-source data and multi-temporal satellite images are used combined with a DEM (digital elevation model) using GIS tools. The critical (potentially dangerous) lakes can then be ranked, using high resolution images such as IKONOS, QuickBird, or OrbView for detailed local-scale investigations and supporting information related to possible impact on the downstream areas. The last step comprises detailed field investigation leading to assessment of the need for an early warning system and mitigation measures.

Use of remote sensing data for the Himalayan Inventory

ICIMOD, in collaboration with national and international partners, developed the first regional inventory of glaciers and glacial lakes between 1999 and 2005 using various levels of remote sensing, topographic maps, aerial photographs, GIS tools, and satellite images as described in Chapter 2. This first study focused on the Himalayas of Bhutan, India, Nepal, and Pakistan, followed by selected basins in China.

The methodology was based on the guidelines for compilation and assembly of data for the World Glacier Inventory (WGI), developed by the Temporary Technical Secretary (TTS) at the Swiss Federal Institute of Technology (ETH), Zurich in 1977. It involved visual interpretation and manual digitisation of glacier boundaries followed by integration of non-spatial data. The inventory was carried out systematically for the drainage basins on topographic maps. In areas for which there were no topographic maps, satellite images were used. The data represented a wide temporal range and was derived from different map and satellite image sources. Thus the results do not represent a clear comparative picture for a specific point in time. Nevertheless, it provided a necessary first reconnaissance approach (Mool et al. 2001a, 2001b; Bajracharya et al. 2009). This first inventory still had considerable geographic gaps, however, including much of the northeastern Indian Himalaya and Myanmar.

As mentioned above, a new inventory is now being prepared for the whole region, from Afghanistan in the west to Myanmar in the east, based on the principles outlined in the preceding sections. The inventory is being carried out by ICIMOD in conjunction with the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI) of the Chinese Academy of Sciences (CAS) based in Lanzhou. A similar project, undertaken by the same institutional collaboration, aims to cover the Tibetan Plateau in China. Finalisation of the reports is expected by the end of 2010. This will provide coverage of the entire HKH region and give an authoritative and up-to-date status of glacial lakes. Further firming up of partnership activities will enhance this process. Equally there is a long history of glaciological research in the northwestern regions of the Hindu Kush-Himalayas by 'western' scholars (e.g., Hewitt, Bishop, Schroder, Winiger, and others), in addition to a large contribution by several Japanese scientists, that should be incorporated in the studies. Their continued collaboration should also be encouraged.

The new inventory process

When generating a clear comparative assessment, it is important that the source and source date of the data be as similar as possible. Keeping this in mind, a new rapid methodology has been developed for preparing the inventory of glaciers and glacial lakes that includes generation of a database from a single source with a narrow temporal range.

The readily available data sets are satellite images which are downloadable free of cost, such as Landsat 5 TM, and Landsat 7 TM/ETM+. The scene of a Landsat TM image gives the synoptic view of a land surface area 185 km by 170 km. Landsat TM is a single system which can provide satellite images covering the entire area of the HKH region. The information mapped from Landsat TM images with a spatial resolution of 30 metres pixel size is minimally compatible with a 1:50,000 scale map. However, management of good quality images with single-year coverage of the entire area has proven difficult and it has become necessary to use a wider temporal range, covering a number of years, although much narrower than for the initial inventory. Satellite images (Landsat 5, 7, TM/ETM+) of 2005 ±3 years were selected; they provide the status of glaciers and glacial lakes and baseline information that gives an acceptable range for scientific analysis. In some cases, such as the Myanmar area, images from 2000/2001 had to be used due to limited usability of selected images of 2005 ±3 years.

This new mapping inventory for glaciers is being carried out using a semi-automated approach. Glacier outlines are mapped using multi-spectral (optical) satellite data and 'Definion' software. Parameters were selected based on the 'Guidelines for the compilation of glacier inventory data from digital sources' that were reviewed by several members of the working and user group of 'GlobGlacier' (a global project supported by the European Space Agency to assist global glacier monitoring) and the GLIMS community (Global Land Ice Measurement from Space supported by NASA). The structure of the inventory closely follows the original guidelines of Müller et al. (1977) for the World Glacier Inventory (WGI), and includes the data source and dates of imagery used (Bajracharya et al. 2009).

In contrast to the situation with glacier mapping, there is no global scientific forum concerned with establishing a standard approach to mapping and database development for glacial lakes. For this, ICIMOD has developed its own mapping method and definition of associated information, which will support compilation of a standardised glacier and glacial lake information dataset for the entire HKH region. Briefly the method is as follows. As with glaciers, glacial lake identification and mapping is carried out using a semi-automated approach with satellite images. The same satellite images are used as for the glacier mapping (Landsat 5, 7, TM/ETM+, from 2005±3 years). Glacial lakes are delineated using Arc/GIS and ERDAS Imagine software; Google Earth is used to verify or check lakes in shadow areas. Identification and mapping of water bodies including glacial lakes was found to be easier in the output image of the Normalized Difference Water Index (NDWI, defined as NDWI = [BNIR - BSWIR)/BNIR+BSWIR]) using NIR (near infrared) and SWIR (short wave infrared) bands of Landsat TM or ETM+, thus this method was adopted. There is a limitation in this method as many lakes in the HKH region are snow covered or frozen from November to March, and in some cases it can be difficult to delineate lakes from glaciers. In these cases, lakes are delineated manually as the lake surface is relatively level and smooth compared to the surroundings or glaciers. Post-classification data management and parameterisation is undertaken in a GIS environment. Additional data sets, such as DEM and topographic maps are used to substantiate some important parameters.

This approach provides baseline information for glaciers and glacial lakes. It will also contribute considerably to monitoring studies of snow and ice in the HKH region as the results can be compared, at least to some extent, with those in the first regional inventory. In future, the method can be repeated for later years to provide an exact assessment of change. This new approach to inventory, based on space-borne imagery, will fulfil the need for a mapping method able to deliver data rapidly that is consistent with the established international inventory system. In this way, vital support will be provided for global climate change research and adaptation studies.

Although the data sets are not strictly equivalent, a brief comparison was made between the results of the 2001 inventory for Nepal (based on combination of information from topographic maps that used data compiled from 1950 to the 70s and satellite images from between 1984 and 1994 (see Chapter 2) with the results of the 2009 inventory (using data from satellite images of 2005±3) (ICIMOD 2009b, unpublished report). The total number of glacial lakes decreased from 2,323 in the 2001 study to 1,466 in the 2009 study, with a small decrease in total area from 75.6 sq.km to 64.8 sq.km, and increase in average size (Table 3). Most of the changes appeared to result from the fact that many of the very small supra-glacial lakes mapped during the first inventory had amalgamated to form fewer but larger lakes in the second inventory, while some small lakes had disappeared. Some lakes of mappable size identified in ablation valleys or push moraines in the 2001 study had also disappeared in the later study. Differences in the mapping techniques used, and especially the inconsistent data sources of the first inventory, probably also account for some of the differences identified. Nevertheless, the changes demonstrate the rapidly changing situation, and confirm the need for periodic repeat surveys at set time intervals across the entire region.

The risk assessment process

The basic inventory of glacial lakes over the whole region is Level One in the risk assessment process. Level Two requires identification of those lakes that may pose a potential danger, in other words it assesses the hazard potential of the lakes detected in the images. For this, simple detection of the lakes and lake characteristics must also be complemented by information about the related hazards. In the first inventory, 126 of the 7,966 lakes recorded for Bhutan, India, Nepal, and Pakistan were tagged as potentially dangerous (Table 2). The classification was based on processes and records of past events, geomorphological and geotechnical characteristics of the lakes, lake surroundings, and other physical details (see Chapter 2). Many of the criteria were derived from remotely sensed data, because investigation of a large number of lakes widely distributed over a vast geographic area is inhibitive of field inspection. Geomorphic features and processes are very distinctive on the high spatial resolution satellite images, and aerial photographs and physical parameters of glaciers, glacial lakes, and associated moraines can be estimated easily using stereoscopic views. Use of high spatial resolution satellite images and medium- to large-scale aerial photographs is the best approach available short of detailed field investigation and other forms of evaluation.

Table 3: **Comparison of glacial lakes of Nepal: 2001 survey and 2009 survey[a]**
(ICIMOD unpublished report, 2009b)

Sub basin	Glacial lakes 2001		Glacial lakes 2009		Comparison 2001/2009	
	Number	Area (km²)	Number	Area (km²)	Number (%)	Area (%)
Koshi River Basin						
Tamor	356	7.32	209	6.57	-41.29	-10.22
Arun	109	2.53	81	3.28	-25.69	29.53
Dudh Koshi	473	13.1	243	13. 19	-48.63	0.89
Likhu	14	0.22	13	0.31	-7.14	43.78
Tamakoshi	57	1.26	24	2.15	-57.89	71.07
Sunkoshi	35	0.41	17	0.31	-51.43	-25.73
Indrawati	18	0.28	12	0.11	-33.33	-60.79
Sub-Total	1062	25.1	599	25.92	-43.60	3.30
Gandaki River Basin						
Trishuli	117	2.03	50	1.68	-57.26	-17.44
Budhi Gandaki	37	0.64	12	0.71	-67.57	10.78
Marsyangdi	78	6.28	22	5.16	-71.79	-17.90
Seti	10	0.26	6	0.11	-40.00	-56.54
Kali Gandaki	96	3.29	26	1.88	-72.92	-42.86
Sub-Total	338	12.50	116	9.53	-65.68	-23.73
Karnali River Basin						
Bheri	152	9.16	56	6.94	-63.16	-24.26
Mugu Karnali	280	8.56	218	5.03	-22.14	-41.29
Tila	71	4.97	73	3.58	2.82	-28.01
Humla Karnali	345	13.01	346	12.19	0.29	-6.29
Kawari	44	1.57	24	0.77	-45.45	-50.70
West Seti	15	0.40	25	0.65	66.67	63.00
Sub-Total	907	37.67	742	29.16	-18.19	-22.59
Mahakali Basin						
Mahakali	16	0.38	9	0.137	-43.75	-63.95
Grand Total	**2,323**	**75.64**	**1,466**	**64.75**	**-36.89**	**-14.36**

[a] Note: data for the 2001 survey were derived from topographic maps based on survey data from the 1950s and 60s and satellite images of between 1984 and 1994; data for the 2009 survey were derived from satellite images from 2005±3 (see text)

In the new inventory, image analysis and GIS modelling based on multi-source data such as satellite imagery and digital elevation models (DEM) are applied to derive important parameters for hazard assessment. Slope information is derived from stereo satellite/photo pairs. The Shuttle Radar Transmission Mission (SRTM) DEM from the National Geospatial Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA) is used as a base. This DEM maps earth topography using radar signals reflected from the ground at 30 m spatial resolution, although only 90 m data are actually available. In some cases more precise DEMs were used that have recently become available, generated from an imaging instrument flying on Terra Satellite, ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) which has long track stereo capabilities.

Level Three in the risk assessment entails rating or ranking of the potentially dangerous lakes. A detailed approach was developed for the 2009/10 study of the Nepal Himalayas based on factors related to the physical stability of lake surroundings and the moraine dams (i.e., likelihood of failure) , and socioeconomic parameters (i.e., potential impact). The possibly dangerous lakes were first identified from high spatial resolution satellite images and then ranked using detailed study of the images together with other GIS data.

The key parameters applied in the ranking of lakes are changes in boundary conditions of the identified glaciers (frontal retreat and thinning) and lakes (enlargement) over time. Lakes less than 0.02 sq.km in area are not considered dangerous.

The next parameter is the distance between the lake and the glacier and whether or not the two are in contact, close, or less than 1,500 m apart. Lakes more than 1,500 m from the associated glacier are not considered dangerous. The rating of moraines themselves includes height, width and steepness. Steepness is rated as very steep (>45 degrees), steep (25 to 45 degrees), or gentle (<25 degrees). Surroundings of the lake area include factors such as rock or debris slides and hanging glacier avalanche paths.

The socioeconomic parameters include size of settlements (small, <10 houses; medium, 10 to 50 houses; and large, >50 houses); number and type of bridges (wooden, suspension, motorable, and highway bridges); distance from hydropower projects (number and capacity of hydropower projects in megawatts); area of agricultural land; and any other important infrastructure or activities of economic value such as trekking trails, community service centres such as schools and health centres, religious gathering sites, camp sites, and so on. Preliminary information on these parameters was derived from topographic and thematic maps.

The physical parameters were used to identify lakes potentially at risk, and together with the socioeconomic and physical parameters to rank them into categories as follows: 1) lakes requiring detailed field investigation and mapping, 2) lakes which require close monitoring such as reconnaissance field surveys, and 3) lakes where observation is needed over time. This prioritisation is usually a minimum prerequisite before deciding to carry out on-site mitigation measures.

Further investigation is then carried out on lakes identified as Category 1 or 2. This entails application of very high resolution remote sensing data, geophysical studies, and other field work. In the Nepal 2009 inventory case study, six lakes were assessed as Category 1. Detailed field investigations of three lakes, Tsho Rolpa, Imja, and Thulagi, and their moraine dams and surrounding area, were carried out, and the results used for dam-break modelling. Socioeconomic surveys were carried out for the downstream areas (Khanal et al. 2009). The final results, including the updated inventory, are in preparation for publication.

This methodological approach will be extended to other countries in the region as resources become available. In some areas, actual field inspection is likely to prove difficult, if not impossible. More detailed information for these parts can be obtained through intensive application of a variety of specialised methods (especially remote sensing and GIS) by the institutions responsible for the individual regional sections.

The approach can be used to obtain a comprehensive GLOF risk assessment in a time- and cost-effective manner through the application of space technology in combination with other tools. The space- and airborne techniques have limitations with regard to depth penetration; ground-based geophysical surveys such as bathymetric and borehole surveys are needed for below-surface investigation. Remote sensing techniques cannot replace specific ground-based site investigation or individual lake investigation, but space-borne and/or air-borne images are inexpensive and easily accessible sources of data that can be used to identify the very few lakes for which field surveys, which are both expensive and difficult, are needed.

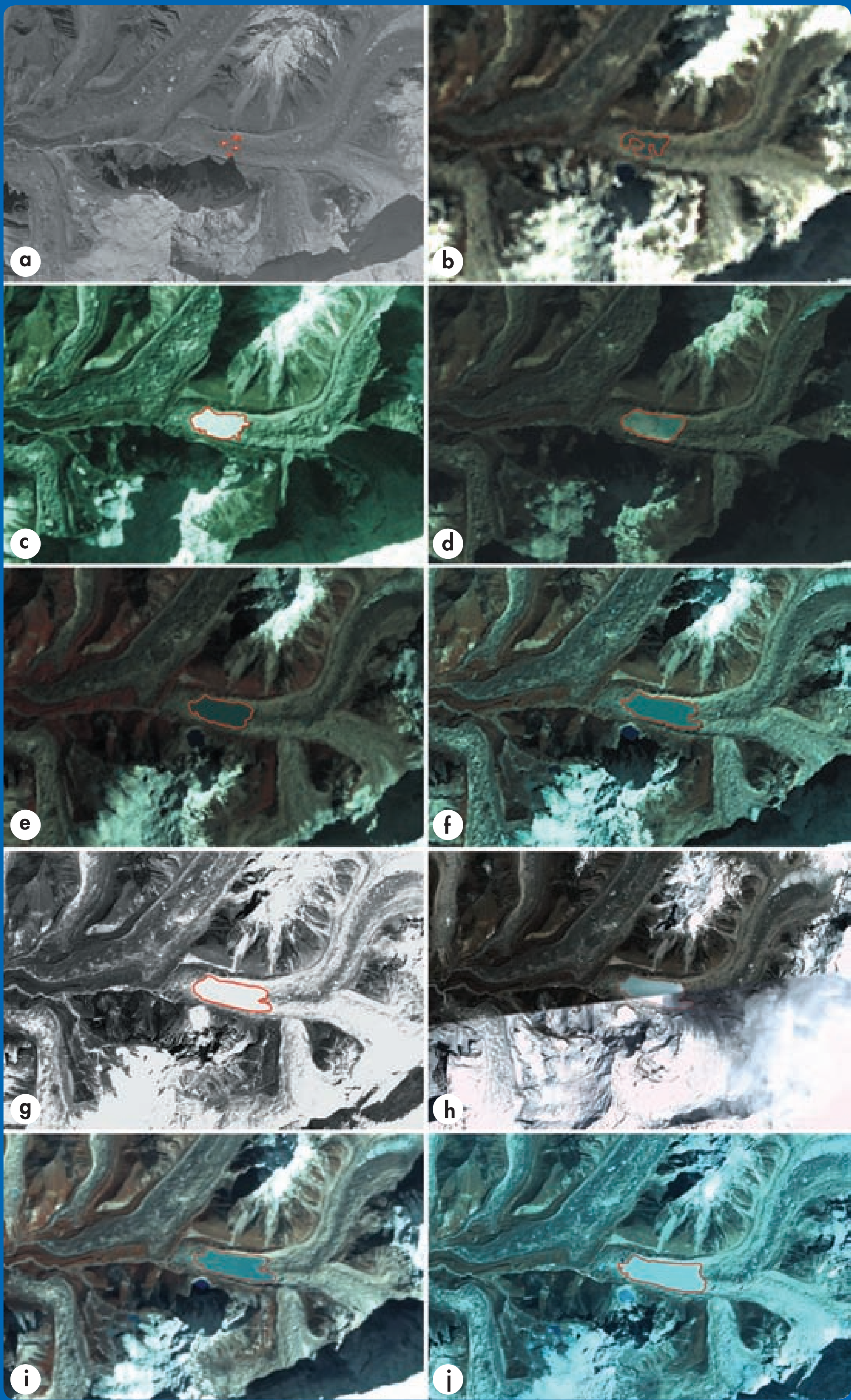
Remote sensing for GLOF risk monitoring

Glacial lakes are still being created and many that exist continue to grow. The formation and growth of lakes need to be monitored on a routine basis to determine possible instability and potential threats to downstream communities and infrastructure. Such monitoring, combined with measurement of the distribution and temporal variation of snow cover using satellite imagery, is essential for GLOF risk assessment and mitigation.

Monitoring of glacial lake growth can be accomplished using time series satellite images. An example is given in Figure 7, which shows satellite images taken between 1962 and 2009 of Imja lake in Nepal.

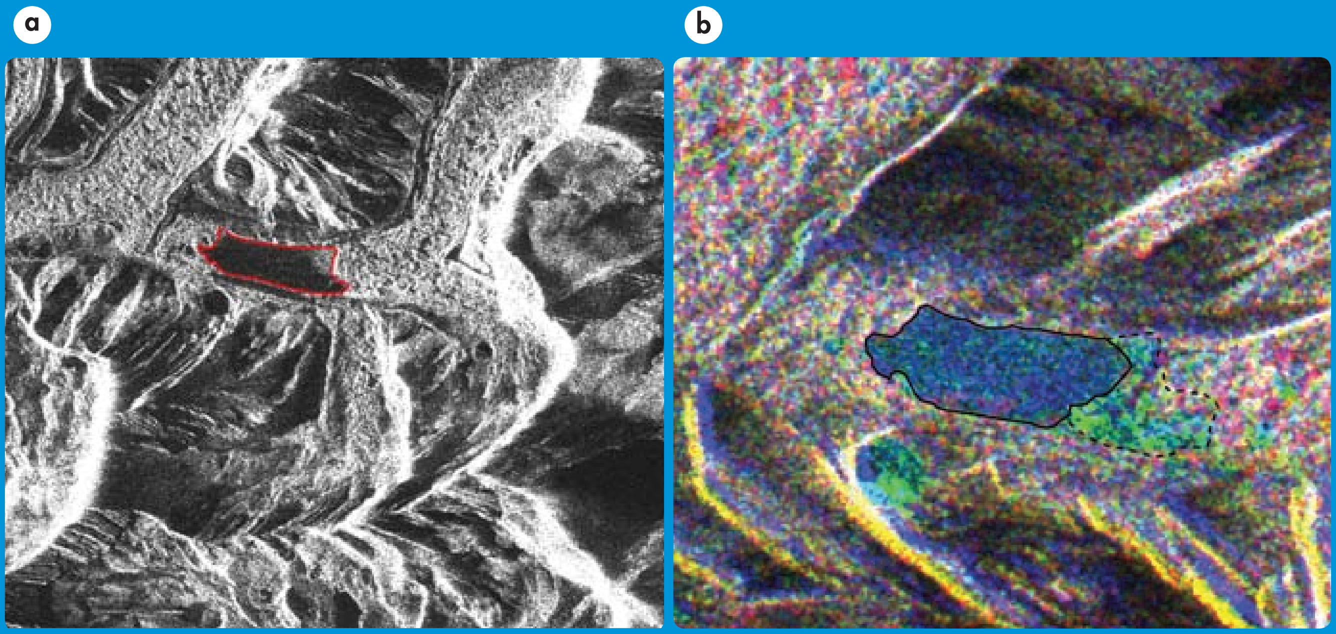
Satellite images can also be used for regular updating of the inventory database. This facilitates tracking of any changes that may occur. However, clouds can obstruct satellite image reception, particularly during the monsoon season, and information gaps may occur. Microwave remote sensing, that can penetrate cloud cover, is being employed to offset this problem. ICIMOD, with support of the European Space Agency (ESA), is continually monitoring Imja lake and its vicinity using the regular temporal RADAR dataset, i.e., Synthetic Aperture Radar (SAR) and Advanced Synthetic Aperture Radar (ASAR) data (Bajracharya et al. 2007). Use of these technologies, together with TerraSAR X data, is effective during obscured atmospheric conditions (Figures 8a, b, c).

Figure 7: **Time series satellite images of different spatial resolution of Imja glacial lake and its surroundings in Sagarmatha National Park, Nepal**

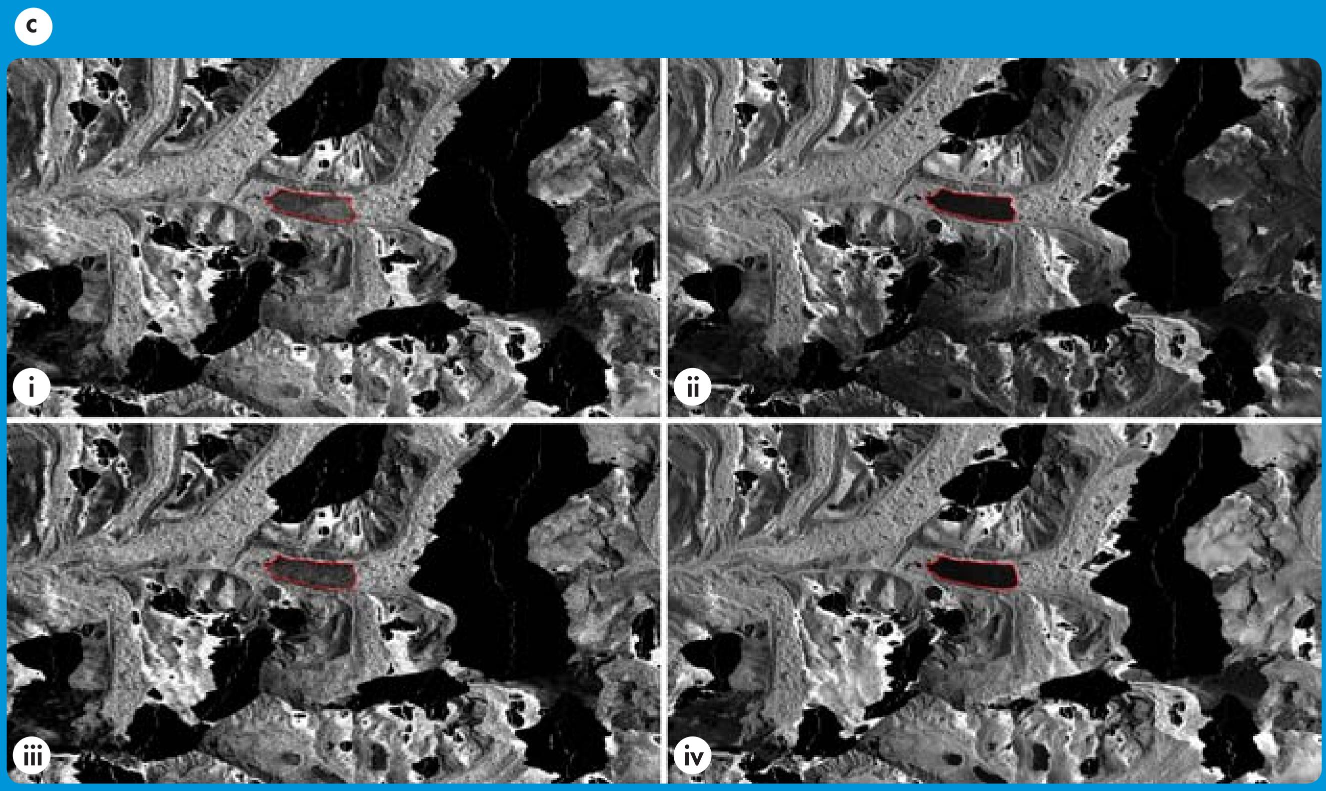


a) Corona (15 Dec 1962); b) Landsat MSS (15 Oct 1975); c) Space Shuttle (02 Dec 1983);
d) Landsat 5 TM (11 Dec 1989); e) Landsat 5 TM (22 Sep 1992); f) Landsat 7 ETM+ (30 Oct 2000);
g) LISS 3 (19 March 2001); h) Google Earth (Feb 2003); i) Landsat 5 TM (5 Nov2005);
j) ALOS AVNIR-II (11 Mar 2009).

Figure 8: **Remote sensing images of Imja glacial lake in Nepal,**
a) Microwave image of ALOS PALSAR March 14, 2008; b) Colour composite image obtained by superimposing ESA ASAR RADAR images taken in 1993 (red), 1996 (green), and 2005 (blue), the unbroken polygon represents the lake area in 1993 while the dashed polygon represents the increase in area by 2005; c) Monitoring of lake through microwave remote sensing data of ESA TerraSAR and ASAR satellite images at different times i) 30 April 2009 ESA ASAR, ii) 22 October 2009 ESA ASAR, iii) 7 June 2009 Terra SAR-X , iv) 17 October 2009 Terra SAR-X

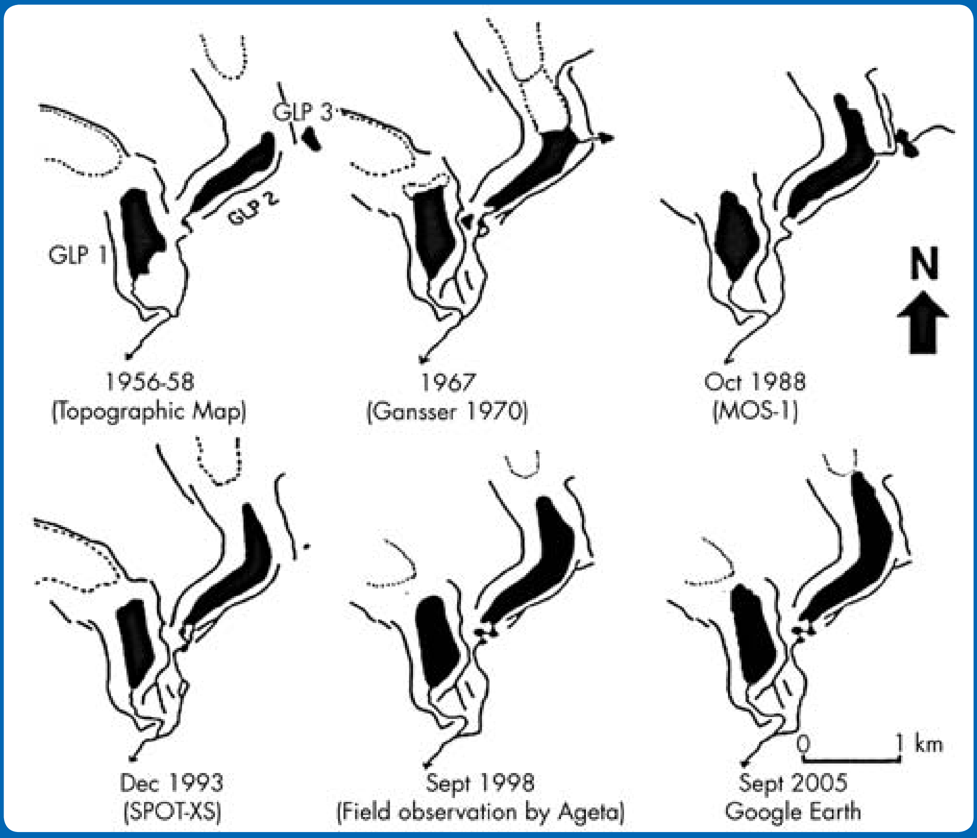


Bajracharya et al. (2007)



A similar approach using satellite imagery has been employed in Bhutan for the two Tarina lakes: Tarina Tso and Mouzom Tso. Figure 9 shows changes in the size and shape of the lakes in different years, as detected from a comparison of satellite images, photographs, topographic data and other information (modified from Ageta et al. 2000, in Bajracharya et al. 2007). The upper lake, Mouzom Tso, grew from 1967 to 1988 and was then blocked by a cliff in the upstream area. The lower Tarina lake expanded from 1956 to 1967. The lakes then diminished in area, possibly due to an outburst event in 1989/90 (DGM 1996), but further expansion was reported in subsequent years. Growth of both lakes continued until they reached the upstream bedrock wall, which prevented further expansion. Overtopping by a surge wave due to icefall into these lakes has been identified as an associated risk (Ageta et al. 2000; Bajracharya et al. 2007).

Figure 9: **Map showing the growth of the Tarina Tso glacial lake in Bhutan based upon topographic maps, satellite images, flight observation and other ancillary information**



modified from Ageta et al. (2000) in Bajracharya et al. (2007)

Remnant of GLOF event from Nare glacial lake, Nepal, in 1977 as seen in April 2009,
Tyangboche and Mt Ama Dablam in the background