SPATIAL DATABASE DEVELOPMENT OF GLACIERS AND GLACIAL LAKES IN THE IDENTIFICATION OF POTENTIALLY DANGEROUS GLACIAL LAKES OF NEPAL USING REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEMS

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ABSTRACT:
Spatial and attribute database of the glaciers and glacial lakes of whole Nepal had developed by ICIMOD in collaboration with UNEP/RRC-AP in 2001 using remote sensing and geographic information systems techniques. There are altogether 3,252 glaciers covering an area of 5,322 square kilometer with approximately 481 km^3 of ice reserves. The Mahakali River basin comprises 87 glaciers with an area of 143 square kilometer, and the estimated ice reserve of 10 km^3. The Karnali River basin consists of 1,361 glaciers with 1,740 square kilometer area and the estimated ice reserve is 128 km^3. There are all together 1,025 glaciers covering an area of 2,030 square kilometer and ice reserve of 191 km^3 in the Gandaki River basin. Similarly the Koshi River basin comprises 779 glaciers with an area of 1,410 square kilometer and the estimated ice reserve is 152 km^3. Prior to the present study, there is no inventory of glacial lakes in the country. Lakes at an elevation higher than 3,500 masl are assumed as the glacial lakes in the present study. Some of the lakes are isolated and far behind the ice mass, which may or may not be the glacial origin. The Mahakali River basin, Karnali River basin, Gandaki River basin, and Koshi River basin consist of 16 lakes, 907 lakes, 338 lakes and 1,062 lakes respectively. Among the 2323 glacial lakes of Nepal, 20 glacial lakes are identified as potentially dangerous.

INTRODUCTION

Nepal is a mountainous country, where mountains and hills occupy more than 80% of the area. The mountains are vulnerable to various hazards associated with landslides and river erosion due to fragile geological conditions, great elevation differences and steep sloping terrain. Apart from that, the region is also quite susceptible to disastrous hazards due to glacial lake outburst floods (GLOF). In general, about 3% of the area above 5,000 metres above sea level (masl) is mostly covered by snow and ice throughout the year forming the glaciers. The glaciers, some of which are found to create many glacial lakes in the down valleys close to the glaciers. They are formed mostly due to the moraine damming of melt water of snow and ice cover. The sudden break of a moraine may generate the discharge of large volume of water and debris causing floods. Downstream impacts of these GLOFs are reported to be highly destructive in nature and leaded to long-term secondary environmental degradation in the valleys, both physically and socio-economically.

A digital database of glaciers and glacial lakes is necessary to identify the potentially dangerous glacial lakes. Geographic Information System (GIS) is the most appropriate tool for spatial data input and attribute data handling. It is a computer-based system that provides the capabilities to handle data input, data management (data storage and retrieval), data manipulation and analysis, and data output.

Integrated Land and Water Information System (ILWIS) is used for the spatial and attribute database development and analysis. ILWIS has the capabilities of image processing and geographic information system. Analysis and modeling in a GIS requires input of relevant data with the correct map projection system. A map projection defines the relationship between the map coordinates and the geographic coordinates (latitude and longitude). Nepal is situated in-between 80º to 88º15´ East and 26º to 30º 30´ North. The area is divided into two grid zones (Zone IIA and Zone IIB) according to the Survey of India Map Series (originally prepared by the Ordnance Survey, Britain's National Mapping Agency). The area east of 82º falls in Grid Zone IIB and west of 82º in Grid Zone IIA. The coordinate systems for the maps published by the Survey of India for both of the grid zones are given in Table 1

Table 1: Coordinate system for the topographic maps published by the Survey of India from 1950s to 1970s

S No.	Coordinate systems	For Grid Zone IIB	For Grid Zone IIA
1	Projection	Lambert conformal conic	
2	Ellipsoid	Everest (India 1956)	
3	Datum	India (India, Nepal)	
4	False easting	2743196.40	
5	False northing	914398.80	
6	Central meridian	90° 00' 00" E	
7	Central parallel	26° 00' 00" N	
8	Scale factor	0.998786	
9	Standard parallel 1	23° 09' 28.17" N	21° 30' 00" N
10	Standard parallel 2	28° 49' 8.18" N	30° 00' 00" N
11	Minimum *X* Value	1920240	1823188
12	Maximum *X* Value	2651760	2000644
13	Minimum *Y* Value	914398	1306643
14	Maximum *Y* Value	1188720	1433476

All the polygons representing glaciers and glacial lakes are numbered and points showing the location of glaciers and glacial lakes were digitized. They were used later for identification of the glaciers and glacial lakes. In an object oriented GIS, polygon maps with identifier domains of the objects have a related attribute table with the same domain. The domain defines the possible contents of a map, a table, or a column in a table (attribute). An attribute table is linked to a map through its domain. An attribute table may contain several columns. Most of the attributes were derived from the topographic maps, aerial photographs, satellite images, reports, field data, etc. Attributes such as area, location (latitude, longitude) etc were derived from the spatial database. If other necessary digital spatial data layers, such as digital elevation models (DEM), are available, it is possible to generate terrain parameters such as elevation, slope, length etc as measuring units for glaciers and glacial lakes. Other attributes, such as aspect, mean length, elevation, map code, name, etc. were manually entered in the attribute database. Additional attributes, such as mean elevation, volume etc were derived using logical calculations.

USE OF REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEM

Glaciers and glacial lakes are generally located in remote areas, where access is through tough and difficult terrain takes several days to reach the area. The inventories and field investigation of glaciers, glacial lakes and glacial lakes outburst floods using conventional methods, requires extensive time and resources together with hardship in the field. Inventories and monitoring of the glaciers, glacial lakes and extent of GLOF impact along the downstream can be done quickly and precisely using time series satellite images and aerial photographs. Use of these images and photographs for the evaluation of physical conditions of the area provides greater accuracy. The multi-stage approach using remotely sensed data and field investigation increases the ability and accuracy of the work. Visual and digital image analysis techniques integrated with techniques of GIS are very useful for the study of glaciers, glacial lakes and GLOFs.

The basic materials used in the compilation of database of glaciers and glacial lakes are based on the topographic maps published by the Survey of India in the period from 1950s to 1970s at a scale of 1 inch to 1 mile and by the Survey Department of His Majesty's Government of Nepal in 1996 at a scale of 1:50,000. The aerial photographs at a scale of 1:50,000 for eastern Nepal were taken in 1992 and for western Nepal in 1996. Digital data sets of the Land Observation Satellite (LANDSAT)-5 Thematic Mapper (TM) and Indian Remote Sensing Satellite Series 1D (IRS1D) Linear Imaging and Self Scanning Sensor (LISS) 3 were used mostly for the present study. Some data sets of Système Probatoire d'Observation de la Terre (SPOT) Multi-Spectral (XS) and SPOT Panchromatic (PAN) and the prints of the satellite images in the form of planimetric maps at a scale of 1:250,000 published by the Remote Sensing Centre of Nepal in 1984 were also used in the study.

Snow and ice are the frozen state of water. Early work with satellite data indicated that snow and ice could not be reliably mapped because of the similarity in spectral response between snow and clouds due to limitations in the then available data set. Today satellite remote sensing systems' data are available in more spectral bands (e.g. LANDSAT TM in seven bands). It is now possible to differentiate snow and cloud easily in the middle infrared portion of the spectrum, particularly in the 1.55 - 1.75µm and 2.10 - 2.35µm wavelength bands (bands 5 and 7 of LANDSAT TM). As shown in Figure 1, in these wavelengths, the clouds have a very high reflectance and appear white on the image, while the snow has a very low reflectance and appears black on the image. In the visible, near infrared, and thermal infrared bands, spectral discrimination between snow and clouds is not possible, while in the middle infrared it is. The reflectance of snow is generally very high in the visible portions and decreases throughout the reflective infrared portions of the spectrum. The reflectance of old snow and ice is always lower than that of fresh snow and clean/fresh glacier in all the visible and reflective infrared portions of the spectrum. Compared to clean glacier and snow (fresh as well as old), debris covered glacier and very old/dirty snow have much lower reflectance in the visible portions of the spectrum and higher in the middle infrared portions of spectrum.

To identify the physical conditions of individual glaciers and glacial lakes, different image enhancement techniques are useful. However, complemented by the visual interpretation method (visual pattern recognition), with the knowledge and experience of the terrain conditions. Different colour composite (FCC) and individual spectral bands images highlight different land-cover features using the knowledge of image interpretation keys: colour, tone, texture, pattern, association, shape, shadow etc.

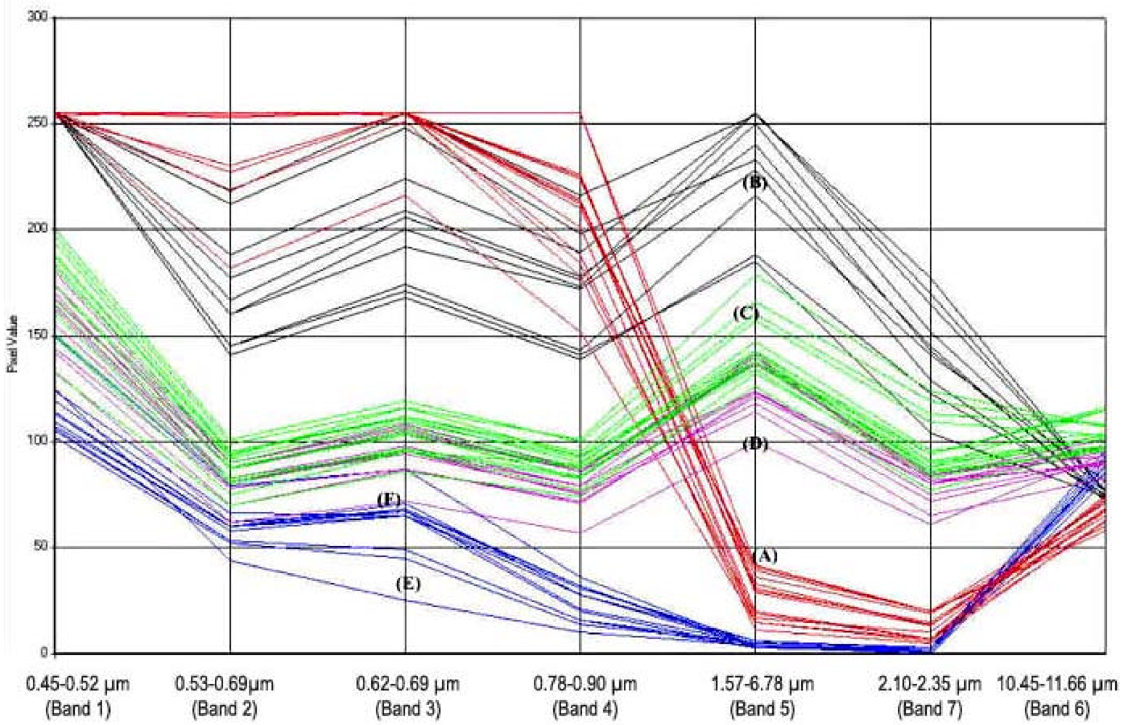


Figure 1: Spectral reflectance characteristics of snow/ice, clean glaciers, debris covered glaciers, clouds, and water bodies. Reflectance in terms of pixel value based on a September 22, 1992, LANDSAT TM seven-band data set of the Tama Koshi and Dudh Koshi areas of Nepal.

(A) lines - clean glaciers and fresh snow; (B) lines - clouds; (C) lines - recent debris from GLOFs; (D) lines - debris covered glacier; (E) lines - clean/melted and (F) - silty and/or partly frozen water (lake)

reflectance values. Glaciers appear white in individual bands and white to light blue in colour composite with variable sizes of linear and regular shape having fine to medium texture, whereas, in the thermal band, they appear grey to black. The distinct linear and dendritic pattern associated with slopes and valley floors of the high mountains covered with seasonal snow can be distinguished in the glaciers in the mountains.

The lake water in colour composite images ranges in appearance from light blue to blue to black. In the case of frozen lakes, it appears white. Sizes are generally small, having circular, semi-circular, or elongated shapes with very fine texture and are generally associated with glaciers in the case of high lying areas, or rivers in the case of low lying areas. In general, erosion lakes and some cirque lakes are not necessarily associated with glaciers or rivers at present. The debris flow path along the drainage channel gives a white to light grey and bright tone.

Knowledge of the physical characteristics of the glaciers, glacial lakes, and their associated features is always necessary for the interpretation of the images. For example, the end moraine damming the lake may range from a regular curved shape to a semi-circular crescent shape. The frozen lake and glacier ice field may have the same reflectance, but the frozen lake always has a level surface and is generally situated in the ablation areas of glaciers or at the toe of the glacier tongue, and there is greater possibility of association with drainage features downstream.

The technique of digital image analysis facilitates image enhancement and spectral classification of the ground features and, hence, greatly helps in the study of glaciers and lakes. Monitoring of the lakes and glaciers can be done visually as well as digitally. In both the visual interpretation and digital feature extraction techniques, the analyst's experience and adequate field knowledge are necessary.

An ice-cored moraine dam usually has a hummock dissected end moraine with smaller ponds in some cases, which show a coarse texture in satellite images. The lateral moraine ridges are generally of a smooth, narrow, linear appearance and are easily identifiable on the images.

The technique of integrating remote-sensing data with GIS does help a lot with identification and monitoring of lakes and glaciers. The DEM of an area generated, either using stereo satellite images, aerial photographs, or digitization of topographic map data, can play a big role in deciding the rules for discrimination of features and land-cover types in GIS techniques and for better perspective viewing and presentations. DEM itself can be used to create various data sets of the area (e.g. slope, aspect). For example, even though glacial lakes are covered by snow, the lake surfaces are flat, and glaciers, snow, and ice give some slope angle. In this case, decision rules for integrated analysis in GIS can be assigned, that is, if the slope is not so pronounced, then those areas are recognized as the frozen glacial lakes. DEM should be compatible with and of reliable quality when compared with other data sets. The satellite images or orthophotos can be draped over the DEM for interpretation or presentation.

INVENTORY OF GLACIERS AND GLACIAL LAKES

The methodology for the inventory of glaciers is based on the instructions for compilation and assemblage of data for the World Glacier Inventory (WGI) developed by the Temporary Technical Secretary (TTS) at the Swiss Federal Institute of Technology, Zurich (Muller et al. 1977). The methodology for the inventory of glacial lakes is based on that developed by the Lanzhou Institute of Glaciology and Geocryology, the Water and Energy Commission Secretariat and the Nepal Electricity Authority (LIGG/WECS/NEA 1988). The Nepal Himalaya revealed 3,252 glaciers and 2,323 lakes above 3500 masl. The glaciers cover an area of 5,323 square kilometer with an estimated ice reserve of 481 km^3. The Koshi River basin comprises 779 glaciers and 1,062 lakes. The glaciers in the basin cover an area of 1,409.84 square kilometer with an estimated ice reserve of 152.06 km^3. The Gandaki River basin consists of 1,025 glaciers and 338 lakes. The glaciers in the basin cover an area of 2,030.15 square kilometer with an estimated ice reserve of 191.39 km^3. The Karnali River basin consists of 1,361 glaciers and 907 lakes, the glaciers cover an area of 1,740.22 square kilometer and an estimated ice reserve of 127.72 km^3. Only 35% of the Mahakali River basin lies within the territory of Nepal comprising 87 glaciers and 16 lakes. The area covered by these glaciers is 143.23 square kilometer with an estimated ice reserve of 10.06 km^3.

POTENTIALLY DANGEROUS GLACIAL LAKES

The potentially dangerous glacial lakes were identified shown in Table 2 and Figure 2 with the help of remote sensing and logical calculation in the geographic information systems (Mool et al 2001a and Mool et al 2001b). The features depicted from the aerial photographs and time series satellite images are condition of lakes, stability of dam, associated mother glaciers, and topographic features around the lakes and glaciers. The important features for the identification of the potentially dangerous glacial lakes are mentioned below:

Activity of supraglacial lakes

Groups of closely spaced supraglacial lakes of smaller size at glacier tongues merge as time passes and forms bigger lakes such as Tsho Rolpa Glacial Lake. The lake was associated with many supraglacial lakes in the topographic map of 1959 (published by Survey of India in 1974). The merging of supraglacial lakes in the Tsho Rolpa Glacial Lake has formed a bigger lake in the topographic map of 1981, aerial photograph of 1992, and topographic map of 1996. Some new lakes of considerable size are also formed at glacier tongues such as the lake at Lower Barun Glacier. The lake is not visible in the topographic map published by the Survey of India in 1967 nor is it visible in the topographic map published by Nepal-Kartenwerk der Arbeitsgenmeinschaft für vergleichende Hochgebirgsforschung No.2 in 1981. The lake is more distinct and sufficiently large enough in the topographic map of 1996 published by the Department of Survey, Nepal. These activities of supraglacial lakes are an indication that the lakes are becoming potentially dangerous.

Position of lakes

The potentially dangerous lakes are generally at the lower part of the ablation area of the glacier near to the end moraine, and the mother glacier should be sufficiently large to create a potentially dangerous lake environment. The valley lakes with an area bigger than 0.1 sq.km and a distance less than 0.5 km from the mother glacier of considerable size are considered as potentially dangerous. The Cirque lakes even smaller than 0.1 square kilometer associated with mother glaciers (in contact or distance less than 0.5 km) with steep hanging glaciers are taken as potentially dangerous. Even the lakes smaller in size but associated with steep hanging glacier may pose a danger to the lake.

Dam conditions

The natural conditions of the moraine damming the lake determine the lake stability. The stability of lake will be less if the moraine dam has following characteristics features:

- narrow crest area
- outlet not well defined or no drainage outflow
- steep sloping moraine walls
- ice cored
- very tall moraine dam (from toe to crest)
- mass movement or potential mass movement in the inner slope and/or outer slope
- breached and closed in the past and refilled again with water
- seepage flow at moraine walls

Condition of associated mother glacier

Generally, the bigger valley glaciers with tongues reaching an elevation below 5,000 masl have well-developed glacial lakes. The active retreating and steep hanging glaciers on the banks of lakes may cause the lake potentially dangerous. The following general characteristics of associated mother glaciers can create danger to moraine-dammed lakes:

- hanging glacier in contact with the lake,
- bigger glacier area,
- fast retreating,
- debris cover at glacier tongue area,
- steep gradient at glacier tongue area,
- presence of crevasses and ponds at glacier tongue area,
- toppling/collapses of glacier masses at the glacier tongue, and
- ice blocks draining to lake.

Physical conditions of surroundings

Besides the damming moraines, mother glaciers, and lake conditions, other physical conditions of the surrounding area as given below may also cause the lake to be potentially dangerous:

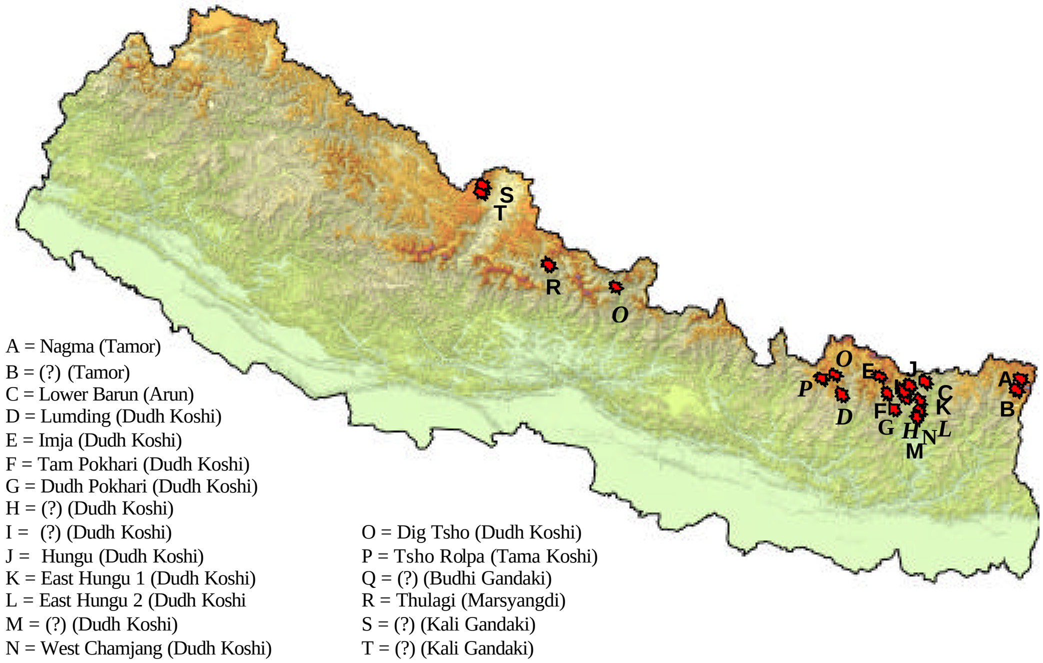
- potential rock fall/slide (mass movements) site around the lake which can fall into the lake suddenly
- snow avalanches of large size around the lake which can fall into the lake suddenly
- neo-tectonic and earthquake activities around or near the lake area
- climatic conditions of successive years being a relatively wet and cold year followed by a hot and wet or hot and arid year
- sudden advance of a glacier towards the lower tributary or mother glacier having a well-developed lake at its tongue

Table 2: Name and location of potentially dangerous glacial lakes of Nepal

S No.	Lake No	Lake Name	Latitude	Longitude	Altitude (m)	Area (sq. m)
1.		Lower Barun	27° 45.31'	87° 06.31'	4550	
2.	Kdu_gl 28	Lumding Tsho	27° 46.51'	86° 37.53'	4846	104943
3.	Kdu_gl 55	Dig Tsho	27° 52.41'	86° 36.61'	4364	143249
4.	Kdu_gl 350	Imja Tsho	27° 54.00'	86° 55.40'	5023	48811
5.	Kdu_gl 399	Tam Pokhari	27° 44.33'	86° 50.76'	4431	138846
6.	Kdu_gl 422	Dudh Pokhari	27° 41.21'	86° 51.68'	4760	274296
7.	Kdu_gl 442		27° 47.70'	86° 54.81'	5266	133752
8.	Kdu_gl 444		27° 48.23'	86° 56.61'	5056	112398
9.	Kdu_gl 449	Hungu	27° 50.17'	86° 56.26'	5181	198905
10.	Kdu_gl 459	East Hungu 1	27° 47.92'	86° 57.95'	5379	78760
11.	Kdu_gl 462	East Hungu 2	27° 48.30'	86° 58.65'	5483	211877
12.	Kdu_gl 464		27° 46.86'	86° 57.22'	5205	349396
13.	Kdu_gl 466	West Chamjang	27° 45.24'	86° 57.33'	4983	6446
14.	Kta_gl 26	Tsho Rolpa	27° 52.03'	86° 28.41'	4556	231693
15.	Ktr_gl 146		27° 48.83'	87° 45.09'	4876	179820
16.	Ktr_gl 191	Nagma Pokhari	27° 52.10'	87° 52.02'	4907	18971
17.	Gbu_gl 9		28° 35.79'	84° 38.09'	3590	81520
18.	Gka_gl 38		29° 2.76'	83°40.52'	5419	149544
19.	Gka_gl 67		29° 12.79'	83° 41.79'	5452	1015173
20.	Gmar_gl 70	Thulagi	28° 29.69'	84° 29.01'	3825	223385

Based on different criteria, actively retreating glaciers and potentially dangerous lakes can be determined using the developed spatial and attribute database complemented by multi-temporal remote-sensing data sets. Once the activity of glaciers and the potentially dangerous status of lakes are determined, the use of medium- to large-scale aerial photographs provides the best tool for detailed geomorphic studies and other evaluation. The photograph image characteristics, shape, shadow, tone, colour, texture, pattern, and relation to surrounding objects were used for aerial photo interpretation. Geomorphic features and processes of the area are very distinctive in their appearance on the aerial photographs. Physical parameters of the glaciers, glacial lakes, and associated moraines can easily be estimated by stereoscopic viewing.

Figure 2: Name and locations of potentially dangerous glacial lakes of Nepal



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