Chapter 13
Conclusions

Databases of the glaciers and glacial lakes of Bhutan, based on medium- to large-scale topographic maps, have not been developed prior to the present study. For the glacier inventory the study used the methodology developed by the Temporary Technical Secretary for the World Glacier Inventory (Muller et al. 1977), and for the glacial lake inventory, the methodology developed by the Lanzhou Institute of Glaciology and Geocryology (LIGG) (LIGG/Water and Energy Commission Secretariat [WECS]/Nepal Electricity Authority [NEA] 1988) was used with modification.

Creating inventories of and monitoring glaciers and glacial lakes can be done quickly and correctly using a combination of satellite images and aerial photographs simultaneously with topographic maps. The multi-stage approach of using remotely sensed data and field data increases the ability and accuracy of the work. The integration of visual and digital image analysis with a geographic information system (GIS) can provide very useful tools for the study of glaciers, glacial lakes, and Glacial Lake Outburst Floods (GLOFs).

Analysts' experiences and adequate field knowledge of the physical characteristics of glaciers, glacial lakes, and their associated features are necessary for the interpretation of topographic maps, satellite images, and aerial photographs. Evaluation of spectral responses by different surface cover types in different bands of satellite images is necessary. Different techniques of digital image enhancement and spectral classification of ground features are useful for the study of glaciers and lakes. With different spectral band combinations in false colour composite (FCC) and individual spectral bands, glaciers and glacial lakes were studied using the knowledge of image interpretation keys.

The Digital Elevation Model (DEM) is useful in deciding the rules for discrimination of features and land-cover types in GIS techniques and for better perspective viewing and presentations. DEM suitable for the present study of the whole country is not yet available.

The topographic maps published by the Survey of India in the 1950s–1970s on a scale of 1:50,000, based on aerial photographs and field verification are the only map series that cover the whole of Bhutan on medium scale. Based on this map series, spatial and attribute databases of glaciers and glacial lakes were developed.

The inventory of glaciers and glacial lakes of Bhutan as a whole is divided into the following six basins.

- Amo Chu (Torsa) Basin
- Wang Chu Basin
- Puna Tshang Chu (Sankosh River) Basin
- Manas River Basin
- Nyere Ama Chu Basin
- Northern basin, rivers flowing from Bhutan towards Tibet, China

The Amo Chu, Nyere Ama Chu, and Northern Basins have no sub-basins of significant size. For the inventory of glaciers and glacial lakes the Wang Chu Basin is divided into the Thim Chu, Pa Chu, and Ha Chu Sub-basins; the Puna Tshang Chu Basin is divided into the Mo Chu, Pho Chu, and Dang Chu Sub-basins; and the Manas Chu Basin is divided into the Mangde Chu, Chamkhar Chu, Kuri Chu, and Dangme Chu Sub-basins. Thus, 13 basins and sub-basins were covered by the study.

The Amo Chu and Nyere Ama Chu Basins and the Ha Chu and Dang Chu Sub-basins do not have glaciers within their watersheds. In Bhutan there are 677 glaciers altogether with an area of 1,316.71 sq.km. The estimated ice reserve is 127.25 km^3. The Wang Chu Basin consists of 36 glaciers with an area of 48.92 sq.km and an estimated ice reserve of 3.55 km^3; the Puna Tsang Chu Basin consists of 272 glaciers with an area of 503.11 sq.km and an estimated ice reserve of 43.21 km^3; and the Manas Chu Basin consists of 310 glaciers with an area of 376.95 sq.km and an estimated ice reserve of 28.77 km^3

Prior to the present study, there was no inventory of lakes of the whole country. In this study any lakes in contact with or near a glacier, or occupying a basin produced by glacial erosion or deposition, were termed 'glacial lakes'. However, some of the lakes inventoried were isolated and far behind the ice mass, and their water may or may not actually be derived from glacial meltwater. Altogether 2,674 lakes were identified as glacial lakes in Bhutan.

Among the glacial lakes studied, Raphstreng Tsho in eastern Lunana received the greatest attention due to the 1994 GLOF events.

The characteristic features used to identify potentially dangerous lakes in general are:

- moraine-dammed glacial lakes in contact or very near to large glaciers,
- merging of supraglacial lakes at the glacier tongue such as Raphstreng Tsho and Lugge Tsho Lakes of the Pho Chu Basin,
- some new lakes of considerable size formed at glacier tongues,
- lakes rapidly growing in size, and
- rejuvenation of lakes after a past glacial lake outburst event.

Twenty-four glacial lakes have been identified as potentially dangerous lakes from the study of topographic maps, literature, and satellite images available. The potentially dangerous lakes identified are located within four sub-basins: the Chamkhar Chu, Mangde Chu, Mo Chu, and Pho Chu Sub-basins. Among the potentially dangerous lakes, three lakes belong to the Chamkhar Chu Sub-basin, one lake to the Kuri Chu Sub-basin, seven lakes to the Mangde Chu Sub-basin, five lakes to the Mo Chu Sub-basin, and eight lakes to the Pho Chu Sub-basin.

Among the dangerous lakes, Lugge Tsho and some unidentified lakes have been found to have had outburst events.

It is recommended that the potentially dangerous lakes identified be further investigated and field surveys carried out.

The 1995 Indo-Bhutan joint expedition to Lunana carried out hydrometeorological and topographical surveys and geotechnical, geological, and foundation investigations. The team recommended short- and long-term mitigation measures.

Based on the reconnaissance study, the water levels of subsidiary lakes I and II of Raphstreng Tsho were reduced by 0.94m and 1.5m respectively in October 1996. In 1996, Water and Power Consultancy

Services (India) Ltd (WAPCOS) recommended lowering the lake water level 4m (WAPCOS 1997). To implement the above recommendation work was carried out in 1997 and 1998.

It is concluded that the present day risk for an outburst from Raphstreng is low, but the risk of an outburst of Thorthormi Glacial Lake in the future is considered high and it could occur in 15–20 years considering the present trend of climate change (Häuslar et al. 2000). Häuslar and Leber (1998) proposed that special risk engineering at Lugge Tsho outlet and a more sound GLOF risk assessment east of Thanza be carried out.