Chapter 4
Materials and Methodology

The basic materials required for the compilation of an inventory of glaciers and glacial lakes are large-scale topographic maps and aerial photographs. Remote sensing data like those from the Land Observation Satellite (LANDSAT) Thematic Mapper (TM), Indian Remote Sensing satellite series 1D (IRS1D) Linear Imaging and Self Scanning Sensor (LISS3), and the Système Probatoire Pour l'Observation de la Terre (SPOT) multispectral (XS) for different dates are also used to study the activity of glaciers and for the identification of potentially dangerous glacial lakes. The combination of digital satellite data and the digital elevation model (DEM) of the area is also used for better and more accurate results for the inventory of glaciers and glacial lakes.

4.1 Topographic Maps

Glaciers and glacial lakes are mostly concentrated in the northern part of Bhutan. The spatial distribution of glaciers and glacial lakes was identified from topographic maps and verified by satellite images for the activity of the glaciers and glacial lakes. The topographic map series of the 1960s on a scale of 1:50,000 was based on vertical aerial photographs of the 1950s and field verification in the 1960s. The Survey of India published these topographic maps of Bhutan.

The coordinate system parameters for the maps of the Bhutan are as follows:

- Projection: Polyconic
- Ellipsoid: Everest (India 1956)
- Datum: Indian (India, Nepal)
- False easting: 2,743,196.4
- False northing: 914,398.80
- Central meridian: 90° 0' 00" E
- Central parallel: 26° 0' 00" N
- Scale factor: 0.998786

Altogether 78 topographic map sheets cover the whole of Bhutan (Figure 4.1). The maps required for the study of the glaciers and glacial lakes fall within 42 sheets (Table 4.1). Not all the original print copies were available for the present work. The topographic maps of the major part of the glacier and glacial lake area are not available; only photocopied map sheets were available for the northern part covering the glaciated area of the country. For some map sheets copies are not even available. For the areas without topographic map sheets and where the original topographic map sheets were not available, false colour composite satellite images on a scale of 1:50,000 of different dates (1993–99) were used for the present study.

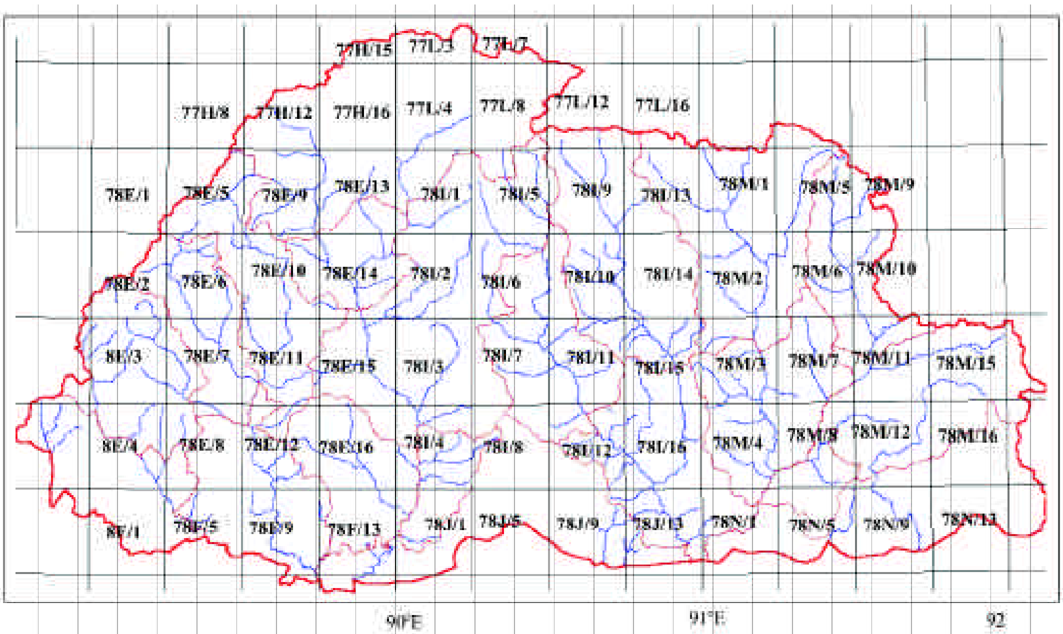

Figure 4.1: Index map for the 1:50,000 scale topographic maps of the Kingdom of Bhutan

Table 4.1: List of topographic maps of Bhutan

Grid number	Sheet number (total 78 sheets)*	Remarks
78E	**2**, **3**, **4**, **5**, **6**, 7, 8, **9**, **10**, 11, 12, **13**, 14, 15, and 16	Original map sheets
78I	**1**, **2**, 3, 4, **5**, **6**, **7**, 8, **9**, **10**, **11**, 12, **14**, **15**, and **16**	
78M	**2**, **3**, 4, **5**, **6**, 7, 8, 11, 12, 15, and16	
78F	1, 5, and 13	
78J	1, 5, 9, and 13	
78N	1, 5, and 13	
83A	**3**	
83B	1	
77H	**16**	Photocopied map sheets
77L	**4**, **8**, **12**, and **16**	
77P	**8**	
78M	**1**, **9**, and 10	
78A	16	
78N	9	
77H	**8**, **12**, and **15**	Unavailable map sheets
77L	**3**,**7**, and **11**	
77P	**4**	
78E	**1**	
78I	**13**	
78A	14 and **15**	
78B	13	
78F	9	
83A	**3**	

*Sheet numbers in bold are the topographic maps required for the study.

4.2 Aerial Photographs

Aerial photographs of Bhutan were not available for the present study.

4.3 Satellite Images

Various types of satellite image suitable for the present study are available from different data providers. The LANDSAT TM images covering the whole of Bhutan are shown in Figure 4.2 and Table 4.2. LANDSAT multi-spectral scanning (MSS) data in digital format from 1993, 1994, 1998, and 1999 were acquired for the present study. The LANDSAT TM satellite image scenes used are two full scenes of December 1993, five full scenes of December 1994, one full scene of November 1998, one full scene of December 1998, and one full scene of January 1999 (Table 4.3).

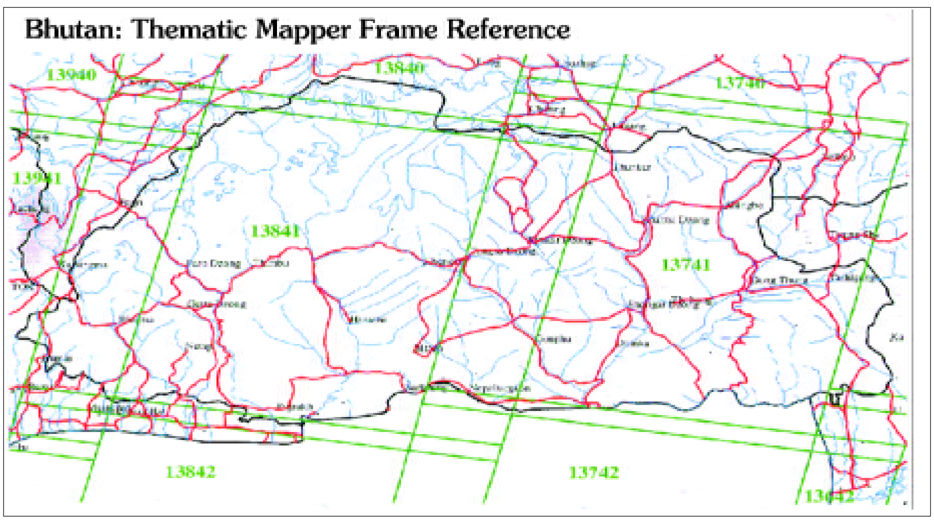

Figure 4.2: Index map of LANDSAT satellite images of Bhutan

Table 4.2: Index of LANDSAT TM images for Bhutan			
S. No	Path	Row	If not full scene
1	136	041	Q3
1	137	041	full scene
2	138	041	full scene
3	139	041	Q4
4	138	040	Q3 and Q4

Quadrants of the scenes	
Q1	Q2
Q3	Q4

Besides LANDSAT TM images, the satellite images of IRS1D LISS3 and SPOT as given below were also acquired.

Table 4.3: Acquired LANDSAT TM images used for the study				
S.Nr.	Path	Row	If not full scene	Year
1	136	041	Full scene	26 December 1993
2	138	040	Full scene	24 December 1993
3	137	040	Full scene	4 December 1994
4	137	041	Full scene	4 December 1994
5	138	040	Full scene	27 December 1994
6	138	041	Full scene	27 December 1994
7	139	040	Full scene	2 December 1994
8	138	041	Full scene	4 November 1998
9	139	041	Full scene	29 December 1998
10	137	041	Full scene	16 January 1999

IRS1D LISS3 images

Due to time constraints and relative costs in acquiring cloud free data, instead of LANDSAT TM, IRS1D LISS3 images of 1999–2000 with least cloud cover were acquired. Three scenes cover all the northern parts and the glaciated area of Bhutan (Table 4.4). The images acquired are of November and December 1999. To avoid the unnecessary area the scenes are shifted 30% up along the track (Table 4.4). The scene of 6 January 1999 covers 70% of 108/052 and 30% of 108/051. The scene of 16 December covers 70% of 110/052 and 30% of 110/051, and the scene of 19 December 1999 covers 70% of 109/052 and 30% of 109/051.

Table 4.4: IRS1D LISS3 satellite images of Bhutan acquired for the study				
S.Nr.	Path	Row	Date	Shift along track
1	108	052	6 Jan 1999	30% shift up to row 051
3	109	052	19 Dec 1999	30% shift up to row 051
5	110	052	16 Dec 1999	30% shift up to row 051

Table 4.5: Index of SPOT images of Bhutan required for the study		
S.Nr.	Path	Rows
1	K232	J295
2	K233	J295
3	K234	J295
4	K235	J295
5	K236	J295
6	K237	J295
7	K233	J294
8	K232	J294
9	K234	J294
10	K235	J294
11	K236	J294
12	K237	J294

SPOT images

Twenty scenes of SPOT images cover the whole of Bhutan. Out of these, only 12 are of the glaciated region. These are shown in Table 4.5.

The following high resolution images were also used for the study:

- One scene of SPOT3 high resolution visibility (HRV)1 panchromatic (PAN) of 25 December 1994 of Path/Row: 234/294
- One scene of IRS1D PAN of 3 January 1999 of Path/Row: 108/51

4.4 Inventory Method

The methodology for the mapping and inventory of the glaciers is based on 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) and 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 inventory of glaciers and glacial lakes has been systematically carried out for the drainage basins on the basis of topographic maps and satellite images. Topographic maps on a scale of 1:50,000 published by the Survey of India during the period from the 1950s to the 1970s are used. The following sections describe how the compilation of the inventories for both the glaciers and glacial lakes have been carried out.

Inventory of glaciers

The glacier margins on each map are delineated and compared with satellite images, and the exact boundaries between glaciers and seasonal snow cover are determined. The coding system is based on the subordinate relation and direction of river progression according to the World Glacier Inventory. The description of attributes for the inventory of glaciers are as given below

Numbering of glaciers

The lettering and numbering start from the mouth of the major stream and proceed clockwise round the basin. The inventory of glaciers is carried out throughout the river basins of Bhutan. For convenience, the major river systems are further divided into sub-basins.

Registration of snow and ice masses

All perennial snow and ice masses are registered in the inventory. Measurements of glacier dimensions are made with respect to the carefully delineated drainage area for each 'ice stream'. Tributaries are included in main streams when they are not differentiated from one another. If no flow takes place between separate parts of a continuous ice mass, they are treated as separate units.

Delineation of visible ice, firn, and snow from rock and debris surfaces for an individual glacier does affect various inventory measurements. Marginal and terminal moraines are also included if they contain ice. The 'inactive' ice apron, which is frequently found above the head of the valley glacier, is regarded as part of the valley glacier. Perennial snow patches of large enough size are also included in the inventory. Rock glaciers are included if there is evidence of large ice content.

Snow line

In the present study, the snow line specially refers to the **firn line** of a glacier, not the equilibrium line. The elevation of the firn line of most glaciers was not measured directly but estimated by indirect methods. For the regular valley and cirque glaciers from topographical maps, Hoss's method (i.e. studying changes in the shape of the contour lines from convex in the **ablation area** to concave in the **accumulation area**) was used to assess the snow line.

Accuracy rating table

The accuracy rating table proposed by Muller et al. (1977) on the basis of actual measurements (Table 4.6) is used in the present study. For the snow line an error range of 50–100m in altitude is entered as an **accuracy rating** of '3'. In the glacier inventory, different methods or a combination of methods are usually chosen for comparison with aerial photographs in order to assess the elevation of the firn line for different forms of glacier.

Table 4.6: Accuracy rating adopted from Muller et al. (1977)

Index	Area/length (%)	Altitude (m)	Depth (%)
1	0–5	0–25	0–5
2	5–10	25–50	5–10
3	10–15	50–100	10–20
4	15–25	100–200	20–30
5	>25	>200	>30

Mean glacier thickness and ice reserves

There are no measurements of glacial ice thickness for the Bhutan Himalayas. Measurements of glacial ice thickness in the Tianshan Mountains, China, show that the glacial thickness increases with the increase of its area (LIGG/WECS/NEA 1988). The relationship between ice thickness (H) and glacial area (F) was obtained there as

$$H = -11.32 + 53.21\,F^{0.3}$$

This formula has been used to estimate the mean ice thickness in the glacier inventory of the Arun and Bhote-Sunkoshi Basins of Nepal. The same method is also used here to find the ice thickness. The ice reserves are estimated by mean ice thickness multiplied by the glacial area.

Muller et al. (1977) roughly estimated the ice thickness values for Khumbu Valley in Nepal using the relationship between glacier type, form, and area (see Table 4.7). This method was used by WECS to calculate the thickness values for Rolwaling Valley in Nepal. The same method can also be used for the glaciers of the Bhutan Himalaya.

According to Muller et al. (1977), mean depth can be estimated with the appropriate model developed for each area by local investigators. For example, the following model was used for the Swiss Alps

$$\bar{h} = a + b\sqrt{F}$$

where $\bar{h}$ is the mean depth, F is the total surface area, and a and b are arbitrary parameters that are empirically determined.

Table 4.7: Relationship between glacier type, form, area, and depth given by Muller et al. (1977)

Glacier type	Form	Area (km^2)	Depth (m)
Valley glacier	Compound basin	1–10	50
		10–20	70
		20–50	100
		50–100	120
	Compound basins	1–5	30
		5–10	60
		10–20	80
		20–50	120
		50–100	120
	Simple basins	1–5	40
		5–10	75
		10–20	100
Mountain glacier	Cirque	0–1	20
		1–2	30
		2–5	50
		5–10	90
		10–20	120

Measured depth

The measured depth is shown on the data sheet only if the depths of large parts of the glacier bed are known from literature and field measurements.

Area of the glacier

The area of the glacier is divided into accumulation area and ablation area (the area below the firn line). The area is given in square kilometres. The delineated glacier area is digitised in the integrated land and water information systems' (ILWIS) format and the database is used to calculate the total area.

Length of the glacier

The length of the glacier is divided into three columns: total length, length of ablation and the mean length. The total (maximum) length refers to the longest distance of the glacier along the centre line. The mean value of maximum lengths of glacier tributaries (or firn basins) is the mean length.

Mean width

The mean width is calculated by dividing the total area (km^2) by the mean length (km).

Orientation of the glacier

The orientation of accumulation and ablation areas is represented in eight cardinal directions (N, NE, E, SE, S, SW, W, and NW). Some of the glaciers are capping just in the form of an apron on the peak, which is inert and sloping in all directions, is represented as 'open'. The orientations of both the areas (accumulation and ablation) are the same for most of the glaciers.

Elevation of the glacier

Glacier elevation is divided into **highest elevation** (the highest elevation of the crown of the glacier), **mean elevation** (the arithmetic mean value of the highest glacier elevation and the lowest glacier elevation), and **lowest elevation** (elevation of the glacier tongue).

Morphological classification

The morphological matrix-type classification and description is used in the study. It was proposed by Muller et al. (1977) for the TTS to the WGI. Each glacier is coded as a six-digit number, the six digits being the vertical columns of Table 4.8. The individual numbers for each digit (horizontal row numbers) must be read on the left-hand side. This scheme is a simple key for the classification of all types of glaciers all over the world.

Each glacier can be written as a six-digit number following Table 4.8. For example, '520110' represents '5' for a valley glacier in the primary classification, '2' for compound basins in Digit 2, '0' for normal or miscellaneous in frontal characteristics in Digit 3, '1' for even or regular in longitudinal profile in Digit 4,

Table 4.8: Classification and description of glaciers

	Digit 1	Digit 2	Digit 3	Digit 4	Digit 5	Digit 6
	Primary classification	Form	Frontal characteristic	Longitudinal profile	Major source of nourishment	Activity of tongue
0	Uncertain or miscellaneous	Uncertain or miscellaneous	Normal or miscellaneous	Uncertain or miscellaneous	Uncertain or miscellaneous	Uncertain
1	Continental ice sheet	Compound basins	Piedmont	Even: regular	Snow and/or drift snow	Marked retreat
2	Ice field	Compound basin	Expanded foot	Hanging	Avalanche and/or snow	Slight retreat
3	Ice cap	Simple basins	Lobed	Cascading	Superimposed ice	Stationary
4	Outlet glacier	Cirque	Calving	Ice fall		Slight advance
5	Valley glacier	Niche	Confluent	Interrupted		Marked advance
6	Mountain glacier	Crater				Possible surge
7	Glacieret and snow field	Ice apron				Known surge
8	Ice shelf	Group				Oscillating
9	Rock glacier	Remnant				

‘1’ for snow and/or drift snow in the major source of nourishment in Digit 5, and 0 for uncertain tongue activity in Digit 6.

The details for the glacier morphological code values according to TTS are explained below.

Digit 1 Primary classification

0 Miscellaneous: Any not listed.
1 Continental ice sheet: Inundates areas of continental size.
2 Ice field: More or less horizontal ice mass of sheet or blanket type of a thickness not sufficient to obscure the sub-surface topography. It varies in size from features just larger than glacierets to those of continental size.
3 Ice cap: Dome-shaped ice mass with radial flow.
4 Outlet glacier: Drains an ice field or ice cap, usually of valley glacier form; the catchment area may not be clearly delineated (Figure 4.3a).
5 Valley glacier: Flows down a valley; the catchment area is in most cases well defined.
6 Mountain glacier: Any shape, sometimes similar to a valley glacier, but much smaller; frequently located in a cirque or niche.
7 Glacieret and **snowfield**: A glacieret is a small ice mass of indefinite shape in hollows, river beds, and on protected slopes developed from snow drifting, avalanching and/or especially heavy accumulation in certain years; usually no marked flow pattern is visible, no clear distinction from the snowfield is possible, and it exists for at least two consecutive summers.
8 Ice shelf: A floating ice sheet of considerable thickness attached to a coast, nourished by glacier(s), with snow accumulation on its surface or bottom freezing (Figure 4.3b).
9 Rock glacier: A glacier-shaped mass of angular rock either with interstitial ice, firn, and snow or covering the remnants of a glacier, moving slowly downslope. If in doubt about the ice content, the frequently present surface firn fields should be classified as ‘glacieret and snowfield’.

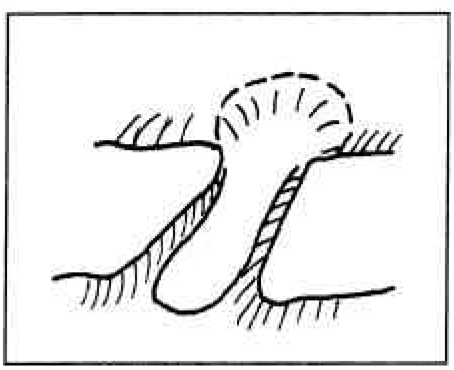
Figure 4.3a: Outlet

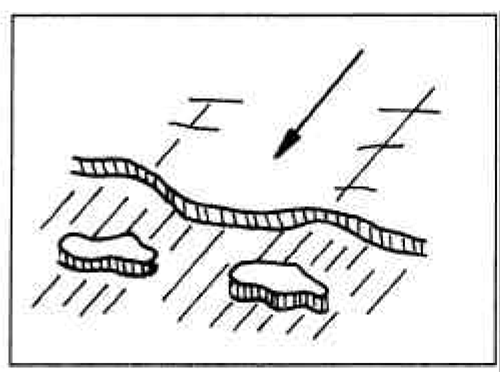
Figure 4.3b: Ice shelf

Digit 2 Form

1 Compound basins: Two or more tributaries of a valley glacier, coalescing (Figure 4.4a).
2 Compound basin: Two or more accumulation basins feeding one glacier (Figure 4.4b).
3 Simple basin: Single accumulation area (Figure 4.4c).
4 Cirque: Occupies a separate, rounded, steep-walled recess on a mountain (Figure 4.4d).
5 Niche: Small glacier formed in initially a V-shaped gully or depression on a mountain slope (Figure 4.4e).
6 Crater: Occurring in and /or on a volcanic crater.
7 Ice apron: An irregular, usually thin ice mass plastered along a mountain slope.
8 Group: A number of similar ice masses occurring in close proximity and too small to be assessed individually.
9 Remnant: An inactive, usually small ice mass left by a receding glacier.

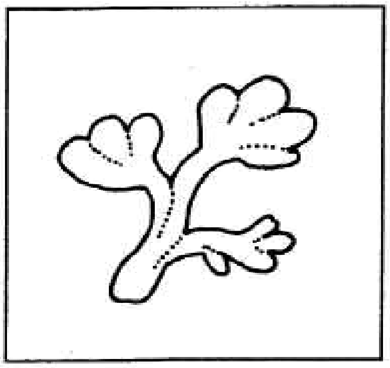

Figure 4.4a: Compound basins

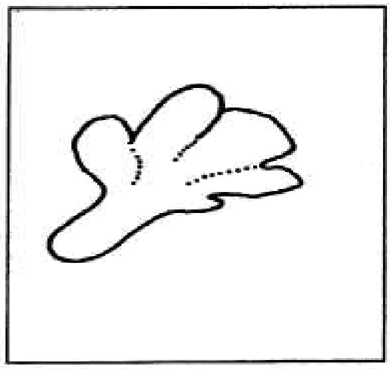

Figure 4.4b: Compound basin

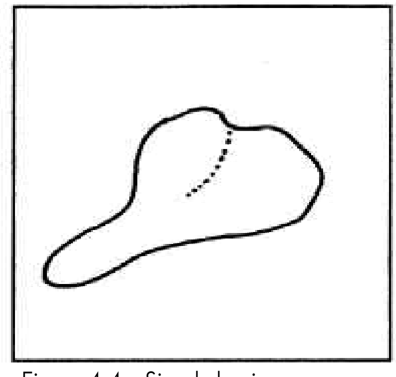

Figure 4.4c: Simple basin

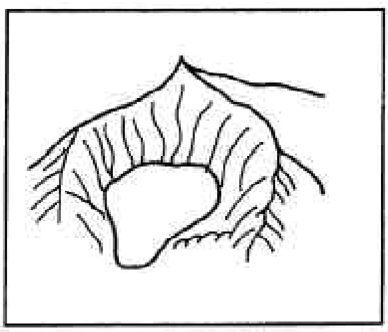

Figure 4.4d: Cirque

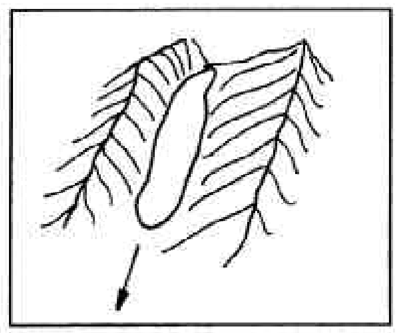

Figure 4.4e: Niche

<u>Digit 3 Frontal characteristics</u>

1 **Piedmont**: Ice field formed on low land with the lateral expansion of one or the coalescence of several glaciers (Figures 4.5a and b).
2 **Expanded foot**: Lobe or fan of ice formed where the lower portion of the glacier leaves the confining wall of a valley and extends on to a less restricted and more level surface. Lateral expansion markedly less than for Piedmont (Figure 4.5c).
3 **Lobed**: Tongue-like form of an ice field or ice cap (see Figure 4.5d).
4 **Calving**: Terminus of glacier sufficiently extending into sea or occasionally lake water to produce icebergs.
5 **Confluent**: Glaciers whose tongues come together and flow in parallel without coalescing (Figure 4.5e).

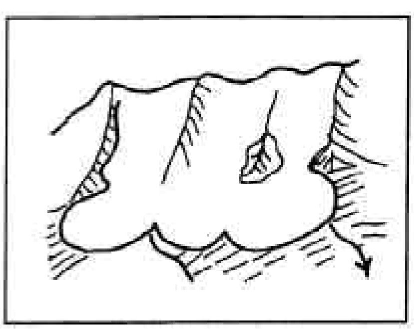

Figure 4.5a: Piedmont

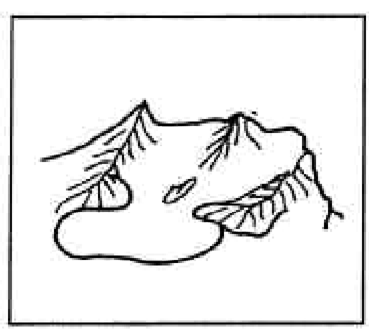

Figure 4.5b: Piedmont

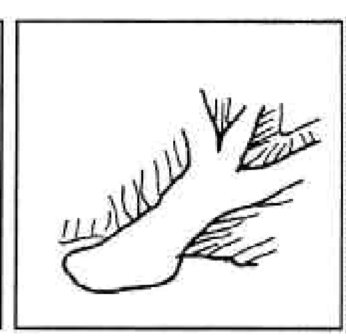

Figure 4.5c: Expanded

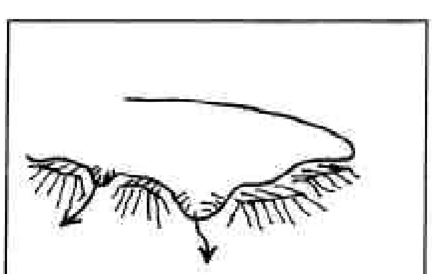

Figure 4.5d: Lobed

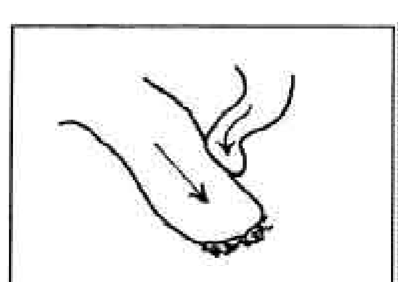

Figure 4.5e: Confluent

Digit 4 Longitudinal profile

1 **Even /regular**: Includes the regular or slightly irregular and stepped longitudinal profile.
2 **Hanging**: Perched on a steep mountain slope, or in some cases issuing from a steep hanging valley.
3 **Cascading**: Descending in a series of marked steps with some crevasses and seracs.
4 **Ice fall**: A glacier with a considerable drop in the longitudinal profile at one point causing a heavily broken surface.
5 **Interrupted**: Glacier that breaks off over a cliff and reconstitutes below.

Digit 5 Major source of nourishment

The sources of nourishment could be uncertain or miscellaneous (0), snow and/or drift snow (1), avalanche and/or snow (2), or superimposed ice (3) as indicated in Table 4.8.

Digit 6 Activity of tongue

A simple-point qualitative statement regarding advance or retreat of the glacier tongue in recent years, if made for all glaciers on Earth, would provide the most useful information. The assessment of an individual glacier (strongly or slightly advancing or retreating etc) should be made in terms of the world picture and not just that of the local area; however, it seems very difficult to establish the quantitative basis for the assessment of the tongue activity. A change of frontal position of up to 20m per year might be classed as 'slight' advance or retreat. If the frontal change takes place at a greater rate it would be called 'marked'. Very strong advances or surges might shift the glacier front by more than 500m per year. Digit 6 expresses qualitatively the annual tongue activity. If observations are not available on an annual basis then an average annual activity is given.

Moraines: Two digits to be given.
Digit 1: moraines in contact with present-day glacier.
Digit 2: moraines further downstream.

0 no moraines
1 terminal moraine
2 lateral and/or medial moraine
3 push moraine
4 combination of 1 and 2
5 combination of 1 and 3
6 combination of 2 and 3
7 combination of 1, 2, and 3
8 debris, uncertain if morainic
9 moraines, type uncertain or not listed.

Remarks: The remarks can, for instance, consist of the following information.

- Critical comments on any of the parameters listed on the data sheet (e.g. how close is the snow line to the firn line, comparison of year concerned with other years).
- Special glacier types and glacier characteristics which, because of the nature of the classification scheme, are not described in sufficient detail (e.g. 'melt structures', glacier-dammed lakes).
- Additional parameters of special interest to the basins concerned (e.g. area of altitudinal zones, inclination etc).
- It is often useful to divide the snow line into several sections (because of different exposition or nourishment). In such cases, the snow line data of each section can be recorded separately.
- Literature on the glacier concerned.
- Any other remarks

The inventory database form (see Annex I) used for compilation of the inventory of glaciers includes map/satellite codes, aerial photographs, and basin numbers, as well as the glacier parameters described above.

Inventory of glacial lakes

The attributes used for the present inventory and their details are given in the lake inventory form (Annex II). Similar lake inventories were done in the Pumqu (Arun) and Poiqu (Bhote/Sunkoshi) Basins in Tibet (China) by LIGG/WECS/NEA (1988).

The permanent snow line in the northern belt of the Himalayas is higher than 4,000 masl. All the glacial lake boundaries are demarcated in the topographic maps.

Changes in climatic conditions have had an impact on the high mountain glacial environment. Many of the big glaciers have melted rapidly and given birth to a large number of glacial lakes. Due to the rapid rate of ice and snow melt, possibly caused by global warming, the accumulation of water in these lakes has been increasing rapidly. The isolated lakes above 3,500 masl are assumed to be remnants of the glacial lakes left due to the retreat of the glaciers.

The glacial lake inventory has been systematically compiled for the drainage basins on the basis of topographic maps and satellite images.

Brief descriptions of major attributes for the lake inventory are given below.

Numbering of glacial lakes

The numbering of lakes starts from the outlet of the major stream and proceeds clockwise round the basin.

Longitude and latitude

Reference longitude and latitude are designated for the approximate centre of the glacial lake.

Area

The area of the glacial lake is determined from the digital database after digitisation of the lake from the topographic maps and satellite images.

Length

The length is measured along the long axis of the lake, and estimated to one decimal place in km units (0.1 km).

Width

The width is normally calculated by dividing the area by the length of the lake, down to one decimal place in km units (0.1 km).

Depth

The depth is measured along the axis of the cross section of the lake. On the basis of the depth along the cross section the average depth and maximum depth are estimated. The data are collected from the literature.

Orientation

The drainage direction of the glacial lake is specified as one of eight cardinal directions (N, NE, E, SE, S, SW, W, and NW). For a closed glacial lake, the orientation is specified according to the direction of its longer axis.

Altitude

The altitude is registered by the water surface level of the lake in masl.

Classification of lakes

Genetically glacial lakes can be divided into the following.

- Glacial erosion lakes, including cirque lakes, trough valley lakes, and erosion lakes.
- Moraine-dammed lakes, including end moraine lakes and lateral moraine lakes.
- Blocking lakes formed through glaciers and other factors, including the main glacier blocking the branch valley, the glacier branch blocking the main valley, and the lakes formed through snow avalanche, collapse, and debris flow blockade.
- Ice surface and sub-glacial lakes.

In the glacial lake inventory, end moraine-dammed lakes, lateral moraine lakes, trough valley lakes, glacial erosion lakes, and cirque lakes are represented by the letters M, L, V, E, and C respectively; B represents blocking lakes.

Activity

According to their stability, the glacial lakes are divided into three types: stable, potential danger, and outburst (when there have been previous bursts). The letters S, D, and O represent these types respectively.

Types of water drainage

Glacial lakes are divided into drainage lakes and closed lakes according to the drainage pattern. The former refers to lakes from which water flows to the river and joins the river system. In the latter, water does not flow into the river. Ds and Cs represent those two kinds of glacial lakes respectively.

Chemical properties

This attribute is represented by the degree of mineralisation of the water, mg l^{-1}.

Other indices

One important index for evaluating the stability of a glacial lake is its contact relation with the glacier. So an item of distance from the upper edge of the lake to the terminus of the glacier has been added and the code of the corresponding glacier registered. Since an end moraine-dammed lake is related to its originating glacier, this index is only referred to end moraine dammed lakes. As not enough field data exist, the average depth of glacial lakes is difficult to establish in most cases. Based on field data, and as an indication only, the average depth of a glacial lake formed by different causes can be roughly estimated as follows: cirque lake, 10m; lateral moraine lake, 30m; trough valley lake, 25m; blocking lake and glacier erosion lake, 40m; lateral moraine lake, 20m. The water reserves of different types of glacial lakes can be obtained by multiplying their average depth by their area (LIGG/WECS/NEA 1988).

The inventory database form (see Annex II) used for compilation of the inventory of glacial lakes includes map/satellite image codes, aerial photographs, and basin numbers, as well as the lake parameters (attributes) described above.