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 Stéréo Système Probatoire de 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 Nepal. 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 maps used were published by the Survey of India in the period from the 1950s to the 1970s on a scale of 1 inch to 1 mile (i.e. 1:63,360) and by the Survey Department of His Majesty's Government of Nepal (HMGN) in 1996 on a scale of 1:50,000. The topographic maps of the Survey Department were based on aerial photographs from 1992 and field verification in 1996. New topographic maps of the glaciated region of western Nepal were not published in the period of the study. As such, the topographic maps of the period from the 1950s to 1970s were used as a base map (Tables 4.1 and 4.2).

Table 4.1: List of used topographic maps published by the Survey of India

Grid number	Sheet number (total 92 sheets)
78A	1, 2 and 3
72M	1, 2, 5, 6, 9, 10, 13 and14
71L	4, 12 and 16
72I	1, 5, 6, 9, 10, 13 and 14
71H	2,3,4,7,8,11,12 and 16
71D	1, 2, 3, 5, 6, 7, 10, 11, 14 and 15
62O	2, 3,4,6, 7, 8, 12,15 and 16*
62P	1, 2, 5, 6, 9,10, 13 and 14
62J	3, 4 and 8
62K	1, 2, 4, 5, 6, 7, 8, 9, 10, 11, 12, 14, 15 and 16
62L	9, 10, 13 and 14
62 F	4, 7, 8*, 11*12,15 and 16
62 G	1, 5, 6, 9, 10 and 13
62B	14*
62 C	13

Table 4.2: List of used topographic maps published by the Survey Department of HMGN

Grid number	Sheet number (total 33 sheets)
2885	09, 10, 11, 13, 14, 15 and 16
2886	13,15 and 16
2785	04
2786	01,02,03,04,06,07,08 and 12
2787	01,02,03,04,05,06,07,08,10,11 and 12
2788	01*, 05* and 09*

* Not available due to restrictions on distribution by HMGN

4.2 Aerial Photographs

The aerial photographs (1:50,000 scale) used for the study were taken in 1992 for eastern Nepal and in 1996 for western Nepal. The list of aerial photographs is given in Table 4.3 for eastern Nepal and in Table 4.4 for western Nepal.

103.	51	55,56,57,58,59,	78A/1	5
104.	52	7,8,9,10,11		5
105.	102	17,		1
106.	50	11,12,13	78A/2	3
107.	67	6,7,8,55		4
108.	102	7,11		2
109.	45	54,55	78A/3	2
110.	46	46,47		2
111.	102	3,4,5,6		4
The total number of aerial photographs for eastern Nepal is 640.				

S. No.	Flight No.	Photograph No.	Toposheet No.	Total
1.	62	6,7,8,9,10,11,12,13,14	71H/4	9
2.	L165	35,36,37,38	71H/2	4
3.	L164	44,45,46,47		4
4.	L218	22,23,24,25,26,27		6
5.	L163	3,4,5,6,	71H/3	4
6.	L164	37,38,39,40,41,42,43	71D/14	7
7.	L163	7,8,9,10,11,12,13		7
8.	L162	11,12,13,14,15,16	71D/15	6
9.	L161	3,4,5,6,7		5
10.	L218	18,19,20		3
11.	L166	39,40,41,42,43	71D/10	5
12.	L165	22,23,24,25,26		5
13.	L164	30,31,32,33,34,35,36		7
14.	L163	14,15,16,17,18,19,20,21		8
15.	L162	4,5,6,7,8,9,10	71D/11	7
16.	L161	8,9,10,11,12,13		6
17.	L110	9,10,11,12,13,14,15,16,17,18,19,20		11
18.	L109	59,60,61,62,63,64,65,66,67		9
19.	L135	8,9	71D/5	2
20.	L134	55,56,57,58,59,60,61		7
21.	L167	6,7,8,9,10,11		6
22.	L166	33,34,35,36,37,38	71D/6	6
23.	L165	16,17,18,19,20,21		6
24.	L164	25,26,27,28,29		5
25.	L163	22,23,24,25,26,27		6
26.	L162	1,2,3	71D/7	3
27.	L133	1,2,3,4		4
28.	L133	9,10,11,12,13,14,15,16,17	71D/3	9
29.	L133	18,19,20,21,22,23,24	62P/15	7
30.	L136	46,47,48,49,50,51,52	71D/1	7
31.	L135	10,11,12,13,14,15,16,17		8
32.	L134	47,48,49,50,51,52,53,54,55		9
33.	L167	12,13,14,15,16,17		6
34.	L141	50,51,52,53	71C/3	4
35.	L217	2,3,4,5,6,7,8,9,10,11,12	Diagonal 71C/4	11
36.	L140	49,50,5152,53	71C/4	5
37.	L139	36,37,38,39,40,41,42		7
38.	L138	7,8,9,10,11		5
39.	L137	5,6,7,8,9,10,11		7
40.	L142	4,5,6,7,8	62O/15	5
41.	L141	44,45,46,47,48,49		6
42.	L216	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15		15
43.	L140	43,44,45,46,47,48	62O/16	6
44.	L139	43,44,45,46,47,48		6
45.	L138	12,13,14,15,16,17,18		7
46.	L137	12,13,14,15,16,17,18		7
47.	L140	35,36,37,40,41,42	62O/12	6
48.	L139	49,50,51,52,53,54,55,56		8
49.	L138	19,20,21,22,23,24,25	62O/12	7
50.	L137	19,20,21,22,23,24,25,26		8
51.	L147	8,9	62O/2	2
52.	L146	30,31,32,33,34,35,36,37		8
53.	L145	5,6,7,8,9,10,11		7
54.	L144	26,27,28,29	62O/3	4
55.	L143	25, 26,27,28		4
56.	L142	26,27,28		3
57.	L141	25, 26,27,28		4
58.	L144	30,31,32	62O/7	3
59.	L143	28,29,30,31,32		5
60.	L142	20,21,22,23,24,25		6

Table 4.4 Cont….

S. No.	Flight No.	Photograph No.	Toposheet No.	Total
61.	L141	29,30,31,32,33,34,35		7
62.	L140	28,29,30,31,32,33,34	62O/8	7
63.	L139	57,58,59,60,61,62,63		7
64.	L138	26,27,28,29,30,31,32		7
65.	L137	27,28,29,30,31,32		6
66.	L140	22,23,24,25,26,27	62O/4	6
67.	L139	7,8,9,10,11,12,13		7
68.	L138	33,34,35,36,37,38,39		7
69.	L137	33,34,35,36,37,38,39		7
70.	L146	38	62O/6	1
71.	L145	2,3,4		3
72.	L136	19,20,21,22,23,24,25	62P/1	4
73.	L135	38,39,40,41,42,43		6
74.	L134	19,20,21,22,23,24,25		7
75.	L167	36,37,38,39,40,41		6
76.	L166	1,2,3,4,5,6,7	62P/2	7
77.	L115	54,55,56,57,58	62P/5	5
78.	L136	26,27,28,29,30,31,32		7
79.	L135	31,32,33,34,35,36,37		7
80.	L134	26,27,28,29,30,31,32		7
81.	L167	29,30,31,32,33,34,35		7
82.	L136	33,34,35,36,37,38,39	62P/9	7
83.	L135	25,26,27,28,29,30		6
84.	L134	33,34,35,36,37,38,39,40		8
85.	L167	23,24,25, 26,27,28,29		7
86.	L166	15,16,17,18,19,20	62P/10	6
87.	L165	41,42,43,44,45,46		6
88.	L136	40,41,42,43,44,45	62P/13	6
89.	L135	18,19,20,21,22,23,24		7
90.	L134	41,42,43,44,45,46,47		7
91.	L167	18,19,20,21,22		5
92.	L166	21,22,23,24,25,26	62P/14	6
93.	L165	5,6,7,8,9,10		6
94.	L164	60,61,62,63,64,65,66		7
95.	L163	36,37,38,39,40,41,42		7
96.	L166	8,9,10,11,12,13,14	62P/6	7
97.	L165	47,48,49,50,51,52,53		7
98.	L164	49,50,51,52,53,1,2,3		7
99.	L135	50,51,52,53,54,55	62L/9	6
100.	L134	5,6,7,8,9,10,11		7
101.	L173	1,2,3,4,5,6,7		7
102.	L116	25,26,27,28,29,30,31,32	62L/10	8
103.	L136	13,14,15,16,17,18	62L/13	6
104.	L135	44,45,46,47,48,49		6
105.	L134	12,13,14,15,16,17,18		7
106.	L173	8,9,10,11,12,13		6
107.	L113	8,9,10,11,12,13,14,15	62L/14	8
108.	L114	13,14,15,16,17,18,19,20		8
109.	L115	7,8,9,10,11,12,13,14	62L/14	8
110.	L152	9,10,11,12,13,14,15	62K/1	7
111.	L151	12,13, 14,15,16,17		6
112.	L150	18,19,20, 21,22,23		6
113.	L149	39,40,41,42,43,44	62K/1	6
114.	L148	23,24,25,26,27,28	62K/2	6
115.	L147	29,30,31,32,33,34		6
116.	L128	36,37,38,39,40	62K/3	5
117.	L144	1,2,3		3
118.	L127	5,6,7,8,9,10,11,12		8
119.	L141	32,33,34		3
120.	L144	4,5,6,7,8,9,10	62K/7	7

Table 4.4. Cont…..

S. No.	Flight No.	Photograph No.	Toposheet No.	Total
121.	L143	1,2,3,4,5,6,7		7
122.	L127	1,2,3,4		4
123.	L141	1,2,3,4,5,6,7		7
124.	L144	11,12,13,14,15,16,17	62K/11	7
125.	L143	8,9,10,11,12,13,14,15		8
126.	L141	8,9,10,11,12,13,14,15		8
127.	L144	18,19,20,21,22,23	62K/15	6
128.	L143	16,17,18,19,20,21,22,23		8
129.	L141	16,17,18,19,20,21,22		7
130.	L148	7,8,9	62K/14	3
131.	L147	7,8,9,10,11,12,13,14,15		9
132.	L148	10,11,12,13,14,15,16	62K/10	7
133.	L147	16,17,18,19,20,21,22		3
134.	L145	20,21,22		7
135.	L148	17,18,19,20,21,22,23	62K/6	7
136.	L147	23,24,25,26,27,28,29		7
137.	L145	23,24,25,26,27,28,29,30		8
138.	L124	5,6,7,8	62K/4	4
139.	L123	23,24,25,26,27		5
140.	L140	5,6,7	62K/8	3
141.	L124	1,2,3,4,		4
142.	L123	28,29,30,31		4
143.	L139	27,28,29,30		4
144.	L138	53,54,55,56,57,58		6
145.	L137	52,53,54,55,56,57		6
146.	L140	8,9,10,11,12,13,14	62K/12	7
147.	L139	21,22,23,24,25,26		6
148.	L138	47,48,49,50,51,52		6
149.	L137	46,47,48,49,50,51		6
150.	L140	15,16,17,18,19,20,21	62K/16	7
151.	L139	14,15,16,17,18,19,20		7
152.	L138	40, 41,42,43,44,45,46		7
153.	L137	40, 41,42,43,44,45		6
154.	L152	22,23	62K/9	2
155.	L150	5,6,7,8,9,10,11		7
156.	L149	52,53,54,55,56,57,58		7
157.	L152	15,16,17,18,19,20,21	62K/5	7
158.	L151	18,19,20,21,22,23		6
159.	L150	12,13,14,15,16,17		6
160.	L149	45,46,47,48,49,50,51		7
161.	L170	8,9,10,11,12	62G/1	5
162.	L169	14,15,16,17,18,19		6
163.	L168	13,14,15,16,17,18,19		7
164.	L149	14,15,16,17,18,19,20		7
165.	L170	13,14,15,16,17,18	62G/5	6
166.	L169	8,9,10,11,12,13		6
167.	L168	8,9,10,11,12		5
168.	L149	21,22,23,24,25,26		6
169.	L170	19,20,21	62G/9	3
170.	L152	1,2,3	62G/9	3
171.	L151	1,2,3,4,5		5
172.	L169	5,6,7		3
173.	L168	1,2,3,4,5,6,7		7
174.	L150	30,31,32		3
175.	L149	27,28,29,30,31,32,33		7
176.	L152	5,6,7,8	62G/13	4
177.	L151	6,7,8,9,10,11		6
178.	L148	41,42,43	62G/6	3
179.	L147	46,47,48		3
180.	L148	34,35,36,37,38,39,40	62G/10	7

S. No.	Flight No.	Photograph No.	Toposheet No.	Total
181.	L147	40,41,42,43,44,45		6
182.	L146	19,20,21,22,23,24,25		7
183.	L145	20,21,22,23,24,25,26		7
184.	L158	6,7,8,9	62J/3	4
185.	L157	6,7,8,9		4
186.	L214	4,5,6,7,8		5
187.	L156	25,26,27,28	62J/4	4
188.	L155	6,7,8,9,10,11,12		7
189.	L154	28,29,30,31,32		5
190.	L153	24,25,26,27,28,29,30		7
191.	L153	31,32,33,34,35	62J/8	5
192.	L159	1,2,3	62F/7	3
193.	L158	24,25,26		3
194.	L159	4,5,6,7,8,9	62F/11	6
195.	L158	17,18,19,20,21,22,23		7
196.	L157	17,18,19,20,21,22,23,24		8
197.	L159	10,11	62F/15	2
198.	L158	10,11,12,13,14,15,16		7
199.	L157	10,11,12,13,14,15,16		7
200.	L155	37,38,39	62F/4	3
201.	L154	2,3,4,5		4
202.	L171	7,8,9,10		4
203.	L215	5,6,7,8,9,10,11,12,13,14,15	Digonal 62F/4	11
204.	L156	9, 10,11	62F/8	3
205.	L155	27,28,29,30,31,32		6
206.	L154	10,11,12,13,14,15		6
207.	L153	5,6,7,8,9,10,11		7
208.	L156	12,13,14,15,16,17	62F/12	6
209.	L155	20,21,22,23,24,25,26		7
210.	L154	16,17,18,19,20,21		6
211.	L153	12,13,14,15,16,17,18		7
212.	L156	18,19,20,21,22,23,24	62F/16	7
213.	L155	13,14,15,16,17,18,19		7
214.	L154	22,23,24,25,26,27,28		7
215.	L153	19,20,21,22,23,24		6
216.	L205	1,2,3,4,5,6,7,8,9,10,11,12	62B/16	12
217.	L155	40,41,42		3
218.	L171	1,2,3,4,5,6		6
219.	L172	10,11,12,13,14		5
220.	L170	2,3,4,5,6,7	62C/13	6
221.	L169	20,21,22,23,24		5
222.	L168	19,20,21,22,23		5
223.	L149	7,8,9,10,11,12		6
The total number of aerial photographs for western Nepal is 1,344.				

4.3 Satellite Images

Various types of satellite image suitable for the present study are available from different organisations, institutes, and data providers. Prints of the satellite images in the form of planimetric maps on a scale of 1:250,000 published by the Remote Sensing Centre of Nepal in 1984 have been used for the inventory of glaciers and glacial lakes. LANDSAT MSS data in digital format from March–April 1994, resampled in 50m pixel size, are available at ICIMOD and have been used for the study. The list of planimetric maps is given in Table 4.5

Thirteen full or partial scenes of LANDSAT TM are required to cover the whole of Nepal as shown in Figure 4.1 and Table 4.6. For the present study, eight scenes have been used. They are given in Table 4.7.

Table 4.5: List of satellite image planimetric maps of Nepal

Planimetric maps on a scale of 1: 250,000					
NH44-6	NH44-7				
NH44-10	NH44-11	NH44-12	NH45-9		
NH44-14	NH44-15	NH44-16	NH45-13	NH45-14	
	NG44-3	NG444	NG45-1	NG45-2	NG45-3
			NG45-5	NG45-6	NG45-7

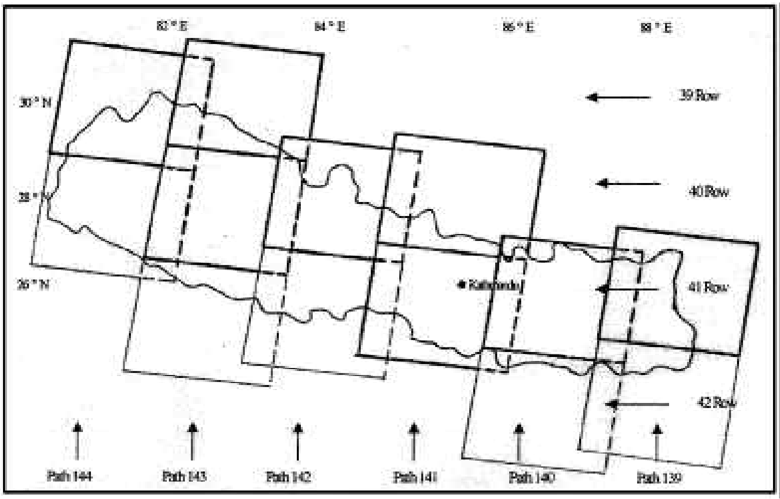

Figure 4.1: Index map of LANDSAT satellite images (arrows indicate the path and row of a scene)

1	139	041	Q1
2	140	041	Q1 and Q2
3	141	041	Q1 and Q2
4	141	040	Q3 and Q4
5	142	040	Q1, Q2 and Q3
6	143	140	Q2
7	143	039	Q3 and Q4
8	144	039	Q3 and Q4

1	144	39	Q3	8 November 1990
2	144	39	Q4	8 November 1990
3	144	40	Q1	8 November 1990
4	144	40	Q2	8 November 1990
5	144	40	Q3	8 November 1990
6	144	40	Q4	8 November 1990
7	143	39	Q3	17 November 1990
8	143	39	Q4	17 November 1990
9	143	40	Q1	17 November 1990
10	143	40	Q2	17 November 1990
11	143	40	Q3	17 November 1990
12	143	40	Q4	17 November 1990
13	143	41	Q1	17 November 1990
14	141	41	Q2	17 November 1990
15	142	40	Q1	15 December 1991
16	142	40	Q2	15 December 1991
17	142	40	Q3	15 December 1991
18	142	40	Q4	15 December 1991
19	142	41	Q1	26 November 1990
20	142	41	Q2	26 November 1990

Table 4.7 Cont.....

21	142	41	Q3	26 November 1990
22	142	41	Q4	26 November 1990
23	142	41	Q2	28 October 1991
24	141	40	Q3	28 October 1991
25	141	40	Q4	21 December 1990
26	141	41	Q1	21 December 1990
27	141	41	Q2	21 December 1990
28	141	41	Q3	21 December 1990
29	141	41	Q4	21 December 1990
30	140	41	Q1	17 December 1991
31	140	41	Q2	17 December 1991
32	140	41	Q3	17 December 1991
33	140	40	Q4	17 December 1991
34	140	42	Q1	17 December 1991
35	140	42	Q2	17 December 1991
36	139	41	Q1	24 November 1991
37	139	41	Q3	24 November 1991
38	139	42	Q1	24 November 1991
39	139	42	Q2	24 November 1991
40	140	42	(full scene)	? January 1998
41	142	41	(full scene)	? January 1998

Due to time constraints in acquiring cloud free data and relative costs, instead of LANDSAT TM, IRS1D LISS3 images from 1999–2000 with least cloud cover were acquired. Nine scenes, as given in Table 4.8, cover all northern parts and the glaciated area of Nepal.

Some selected SPOT scenes available from different organisations were acquired. The list of required SPOT images is given in Table 4.9.

1	099	050	18 January 2000	
2	100	050	05 January 1999	
3	101	052 and 051	02 January 1999	30%shift down to row 051
4	102	050 and 051	18 February 1999	30%shift up to row 051
5	103	051	15 February 1999	
6	104	051	03 January 2000	
7	105	051 and 052	15 January 1999	40%shift up to row 051
8	106	051 and 052	12 January 1999	40%shift up to row 051
9	107	052	19 January 2000	

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 Glacer 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, aerial photographs, and satellite images. Topographic maps on a scale of 1:63,360 and 1:50,000 published respectively by the Survey of India during the period from the 1950s to the 1970s and the Survey Department of Nepal in 1996 respectively are used.

1	J289	K215
2	J290	K214, K215, K216 and K217
3	J291	K218, K219, K220 and K221
4	J292	K219, K220 and K221
5	J293	K222, K223 and K224
6	J294	K225, K226, K227, K228, K229 and K230
7	J295	K227, K228, K229 and K230

The following sections describe how the compilation of the inventories for both the glaciers and glacial lakes has been carried out.

Inventory of glaciers

The glacier margins on each map are delineated and compared with aerial photographs, 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 descriptions of attributes for the inventory of glaciers are given below.

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 Nepal. For convenience, the major river systems are further divided into sub-basins.

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 4.10) 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.

	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 Nepal 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. 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 using the relationship between glacier type, form, and area (see Table 4.11). The same method was used by WECS to calculate the thickness values for Rolwaling Valley.

According to Muller et al. (1977), mean depth can be estimated with the appropriate model developed for each area by local investigators.

Table 4.11: 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

For example, the following model was used for the Swiss Alps

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

where *h* is the mean depth, *F* is the total surface area, and *a* and *b* are arbitrary parameters that are empirically determined.

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 centreline. 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 glaciers

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**.

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 4.12. 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 4.12. 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, '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.

Table 4.12: 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				

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 4.2a).
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 4.2b).
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'.

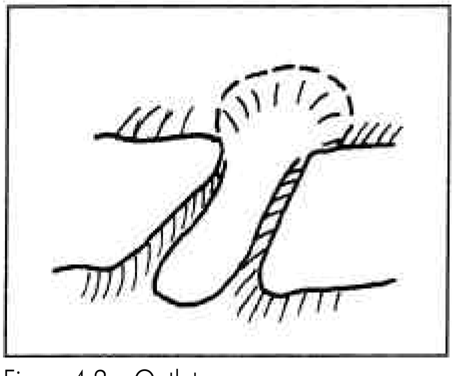

Figure 4.2a: Outlet

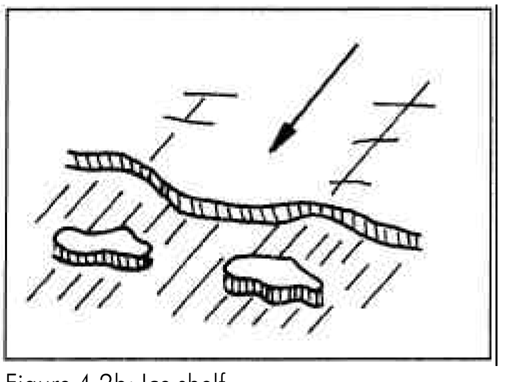

Figure 4.2b: Ice shelf

Digit 2 Form

1 ***Compound basins***: Two or more tributaries of a valley glacier, coalescing (Figure 4.3a).
2 ***Compound basin***: Two or more accumulation basins feeding one glacier (Figure 4.3b).
3 ***Simple basin***: Single accumulation area (Figure 4.3c).
4 ***Cirque***: Occupies a separate, rounded, steep-walled recess on a mountain (Figure 4.3d).
5 ***Niche***: Small glacier formed in initially a V-shaped gully or depression on a mountain slope (Figure 4.3e).
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.

Digit 3 Frontal characteristics

1 ***Piedmont***: Ice field formed on low land with the lateral expansion of one or the coalescence of several glaciers (Figures 4.4a 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 4.4c).
3 ***Lobed***: Tongue-like form of an ice field or ice cap (see Figure 4.4d)
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 4.4e).

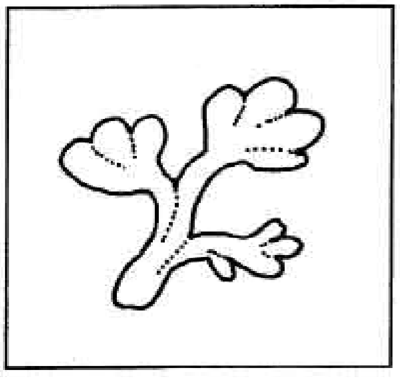
Figure 4.3a: Compound basins

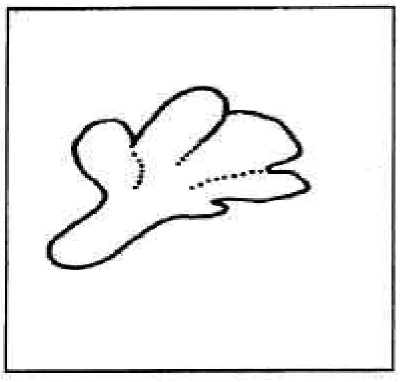
Figure 4.3b: Compound basin

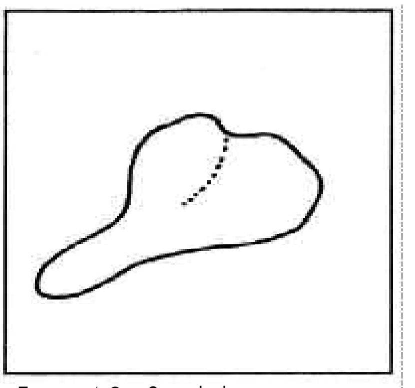
Figure 4.3c: Simple basin

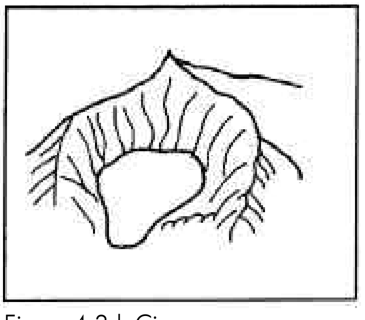
Figure 4.3d: Cirque

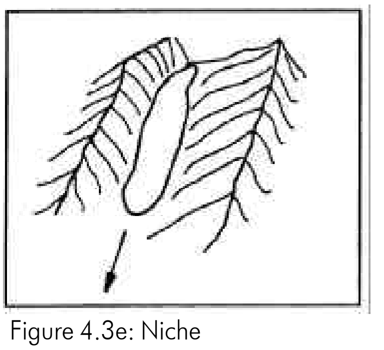
Figure 4.3e: Niche

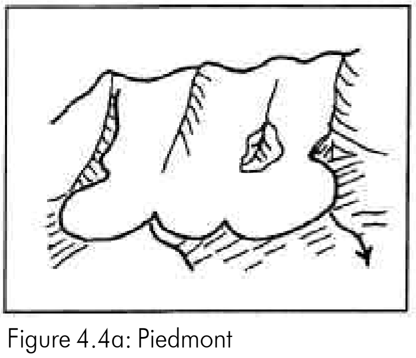
Figure 4.4a: Piedmont

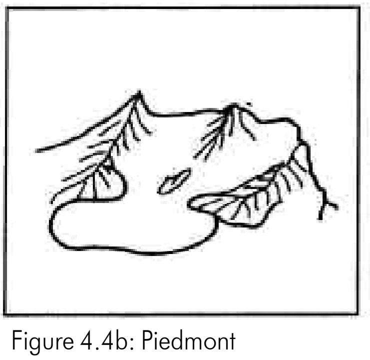
Figure 4.4b: Piedmont

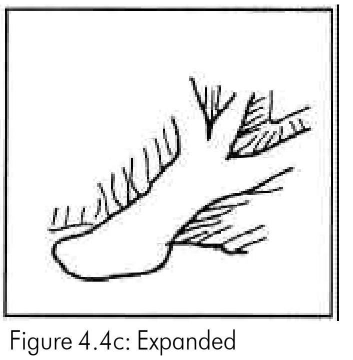
Figure 4.4c: Expanded

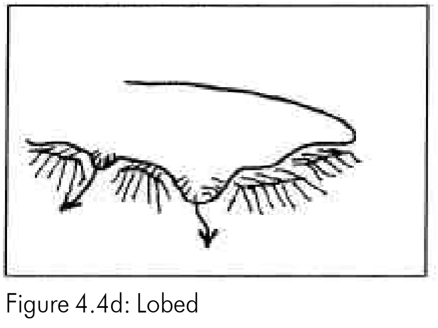
Figure 4.4d: Lobed

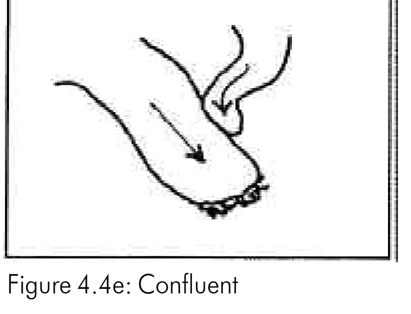
Figure 4.4e: Confluent

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 4.12.

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 glacial lakes on each map are delineated and compared with aerial photographs and satellite images. The descriptions of attributes for the glacial lakes' inventory based on LIGG, WECS and NEA (1988) are given below.

Numbering of glacial lakes

For the study of the glacial lakes, the Nepal Himalayas are divided into four major river basins: The Mahakali River Basin, The Karnali River Basin, The Gandaki River Basin, and The Koshi River Basin. Further divisions into sub-basins within the major river basins are made.

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.

The global climatic change during the first half of the twentieth century had a tremendous impact on the high mountainous glacial environment. Many of the big glaciers melted rapidly and gave birth to a large number of glacial lakes. Due to the faster rate of ice and snow melting, possibly caused by global warming, the accumulation of water in these lakes has been increasing rapidly. The isolated lakes above 3,500m are assumed to be the remnants of the glacial lakes left due to the retreat of the glaciers.

The attributes used for the present inventory are similar to the lake inventories that were done in the Pumqu (Arun) and Poiqu (Bhote-SunKoshi) Basins in Tibet, China (LIGG/WECS/NEA 1988).

The numbering of the 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.

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 (also divided into neo end moraine and paleo end moraine 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.