Observed changes in Himalayan glaciers

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In the Himalaya, large areas are covered by glaciers and seasonal snow. They are an important source of water for the Himalayan rivers. In this article, observed changes in glacial extent and mass balance have been discussed. Various studies suggest that most of the Himalayan glaciers are retreating though the rate of retreat varies from glacier to glacier, ranging from a few meters to almost 61 m/year, depending upon the terrain and meteorological parameters. In addition, mapping of almost 11,000 out of 40,000 sq. km of glaciated area, distributed in all major climatic zones of the Himalaya, suggests an almost 13% loss in area in the last 4–5 decades. The glacier mass balance observations and estimates made using methods like field, AAR, ELA and geodetic measurements, suggest a significant increase in mass wastage of Himalayan glaciers in the last 3–4 decades. In the last four decades loss in glacial ice has been estimated at 19 ± 7 m. This suggests loss of 443 ± 136 Gt of glacial mass out of a total 3600–4400 Gt of glacial stored water in the Indian Himalaya. This study has also shown that mean loss in glacier mass in the Indian Himalaya is accelerated from –9 ± 4 to –20 ± 4 Gt/year between the periods 1975–85 and 2000–2010. The estimate of glacial stored water in the Indian Himalaya is based on glacier inventory on a 1 : 250,000 scale and scaling methods; therefore, we assume uncertainties to be large.

Keywords: Glacial stored water, glacier retreat, mass balance, snow.

Introduction

THE Himalayan region has one of the largest concentrations of glaciers and large areas of the Himalayan mountain range are also covered by snow during winter. Therefore, this region is also known as the 'Third Pole'. Many major rivers and their numerous tributaries originate from these snow and glacier-bound regions. Melt water from snow and glaciers makes these Himalayan rivers perennial, and has helped in the flourishing of several civilizations along the banks of these rivers for ages. However, this source of water ought not be considered permanent, as the geological history of the Earth suggests constant variations in glacial extent due to change in climate. Moreover, natural changes in the climate would have altered due to greenhouse effect caused by man-made changes in the Earth's environment. Some hypotheses suggest that the alteration may have started long before the beginning of the Industrial Revolution[1]. Invention of agriculture about 11,000 years ago may be attributed to large-scale deforestation and rice cultivation. However, this pace of change might have been accelerated from the beginning of the Industrial Revolution leading to an increase in average global temperature by 0.6° ± 0.2°C from 1900 (ref. 2). In the Fifth Assessment[3] published by the Intergovernmental Panel on Climate Change (IPCC) in 2013, the global mean surface warming (relative to 1986–2005) in the late 21st century for different warming scenarios vary between 1°C and 4°C. This would have profound effect on the Himalayan glaciers. However, the Himalayan region is highly rugged and detailed information is available only for a few glaciers. Therefore, predictions were made based on limited data and it has created significant confusion in the scientific community and public in general.

In one of its assessments a controversial statement made by IPCC was 'Glaciers in the Himalaya are receding faster than in any other parts of the world. If present rate continues, the likelihood of them disappearing by year 2035 and perhaps sooner is very high if the Earth keeps warming at the current rate.'[4] This argument was followed by another statement in a discussion paper of the Ministry of Environment and Forests, Government of India, 'A large mountain glacier would take 1000 to 10,000 years to respond to warming today, while small mountain glaciers take 100 to 1000 years to respond. Thus, one explanation for the glacier retreat could be: they are responding to natural warming that occurred either during the Medieval warm period in the 11th century or to an even warmer period that occurred 6000 years ago[5]'. Both the statements are not supported by scientific evidences and are speculative in nature. Therefore, understanding of the present status of Himalayan glaciers and development of models to assess future changes are important. This has led to a significant interest of the scientific community in understanding Himalayan glaciers. Therefore, in this article recent work related to observed changes in glacial extent and glacier mass balance is reviewed.

Observed changes in glacial extent

Glacier inventory in the Himalaya is carried out by numerous agencies with various methodologies and in

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different study areas. Inventory by the Geological Survey of India (GSI) has used topographic maps, aerial photographs and satellite images. During the inventory 9040 glaciers covering an area of 18,528 sq. km were mapped. However, the inventory was carried out for only the Indian Himalaya and 535 glaciers covering an approximate area of 8240 sq. km in Gilgit region were not mapped[6]. In the Indian Himalaya, glacier inventory was also carried out using satellite images indicating the areal extent of 23,308 sq. km (ref. 7). Our best estimate for areal extent of the glaciers in the Indian Himalaya is 25,041 ± 1726 sq. km. The uncertainties are large, as the GSI inventory area of Gilgit region is estimated using level-I inventory and in the inventory by Kulkarni and Buch[7], small glaciers and ice fields were not included. Another inventory was carried out by the International Centre for Integrated Mountain Development (ICIMOD) for the Hindu Kush–Himalaya (HKH) region using data from Landsat and Shuttle Radar Topography Mission (SRTM)[8]. During the inventory 54,252 glaciers covering an area of 60,054 sq. km were mapped. A glacier inventory of the Indus, Ganga and Brahmaputra basins was made by the Space Applications Centre (SAC), ISRO, using LISS-III images of the Indian Remote Sensing satellite. During the inventory, 32,392 glaciers covering an area of 71,182 sq. km were mapped[9]. Variation in the number of glaciers and glaciated area is possibly large due to different reference areas, scale of mapping and also possibly due to the methodologies used. However, further studies are needed to understand and estimate the uncertainties in each estimate.

The changes that occur in the glacial extent and length are normally reported for glaciers in the Himalayan region. The changes are some times reported for individual glaciers, but many a times overall changes for the group of glaciers are also reported. An individual glacier is normally studied using field and satellite data. The overall changes in areal extent are generally reported using remote sensing data with limited field studies.

Changes in glacier terminus were reported for glaciers such as the Samudra Tapu, Chhota Shigri, Parbati, Satopant, Bhagirathi, Gangotri, AX010, Pensilungpa[10–16]. These studies are based on field studies and also data acquired from remote sensing techniques. Studies suggest that almost all glaciers are retreating and the rate of retreat varies from a few metres to as high as 61 m/year. The long-term rate of retreat, for a period of 40 years is available for 81 glaciers. The list of glaciers and their rates of retreat is given in Table 1. The location of glaciers and amount of retreat between 1960 and 2000 is given in Figure 1. The mean loss of glacial length for four decades is approximately 621 ± 468 m. The large standard deviation suggests large variation in glacier retreat. This indicates that glaciers in different regions of the Himalaya respond differently (Figure 1). Factors like area–altitude distribution, mass balance, slope and debris cover contribute to variation in rates of retreat[17,18]. In general, loss in length is higher in Western Himalaya than in Sikkim. Limited data on retreat of individual glaciers are available for Karakoram, Nepal, Bhutan and Arunachal Pradesh.

The snout monitoring carried out in the Karakoram mountain range suggests that snout of more than 50% of glaciers is either advancing or are stable[19]. However, conclusions based on monitoring of only the snout could be misleading, as slope and length can influence retreat, even if loss in mass is the same. This was used to explain differential rate of retreat of Zemu and Gangotri glaciers[20]. In addition, if glacier snout is covered by debris, it can decrease melting at the snout but continue to have increased melting at higher altitudes leading to fragmentation or disintegration of glaciers (Figure 2)[21]. This phenomenon has now been observed not only in the Himalaya, but also in other parts of the world[4,22,23].

Retreat of individual glaciers may be influenced by local geomorphic and climatic parameters and may not represent regional changes in climatic condition. Therefore, it would be important to assess long-term overall changes in glacial extent. Recently, studies were carried out to understand overall changes in glacial extent in different parts of the Himalaya[23–28]. These include western, central, eastern Himalaya and Tibetan regions. In the Indian Himalaya almost 7200 sq. km of total 23,000 sq. km area is mapped for the retreat and almost 11,000 sq. km of total 40,000 sq. km area of the complete Himalayan range is mapped (Figure 3). The studies suggest almost 4–30% overall loss in glacier area in the last 40 years, depending upon numerous terrain and geomorphological parameters (Table 2). Studies in Tibet and Garhwal Himalaya suggest that rate of retreat has accelerated in the present decade[23,25], but, has remained constant in the Mount Everest region[24]. Studies using Landsat TM images of 1998 and 2009, for 70 glaciers in the Baspa and Parbati river basins that form a part of the Indus basin, suggest that the glaciers continue to retreat in the present decade (Figure 4). A 299.5 sq. km area was mapped for the retreat and a loss of 18.6 sq. km was observed in 11 years starting from 1998 (Table 2).

Observed changes in mass balance

Mass balance of a glacier is one of the key parameters to understand the influence of climate change. Measurements of mass balance using field parameters are a difficult and major task. Therefore, these observations were carried out on a few glaciers namely, Neh Nar, Ruling, Gara, Gor Garang, Shaune Garang, Chhota Shigri, Dunagiri, Tipra Bank, Dokariani, Nardu and Change Khangme in India and AX010 glacier in Nepal[29–31]. These glaciers are distributed in different parts of the Himalaya. However, continuous mass balance data are not available for a

Table 1. List of glaciers and their rate of retreat

Glacier ID	Glacier	Period	Retreat rate (m/decade)	Reference
1	Zanskar glacier 1	1999–2004	80	26
2	Parkachik	1990–2003	–110	26
3	Zanskar glacier 3	1990–2003	220	26
4	Zanskar glacier 4	1975–2003	270	26
5	Zanskar glacier 5	1990–2003	40	26
6	Zanskar glacier 6	1990–2003	290	26
7	Zanskar glacier 8	1975–2003	10	26
8	Zanskar glacier 7	1975–2003	80	26
9	Zanskar glacier 9	1975–2006	320	26
10	Zanskar glacier 10	1975–2006	610	26
11	Drang Drung	1975–2008	90	26
12	Zanskar glacier 12	1990–2003	40	26
13	Zanskar glacier 13	1992–2002	20	26
14	Miyar	1961–1996	160	29
15	Triloknath	1968–1996	180	29
16	Panchi nala I	1963–2007	110	29
17	Panchi nala II	1963–2007	120	29
18	Beas Kund	1963–2003	190	29
19	Sonapani	1906–1957	180	29
20	Samudra Tapu	1962–2000	200	11
21	Hamtah	1961–2005	80	29
22	Jobri	1963–2003	30	29
23	Chhota Shigri	1962–1995	70	29
24	Sara ugma	1963–2004	410	29
25	Bara Shigri	1906–1995	300	29
26	Man Talai (Gl. No. 115)	1989–2004	230	29
27	Bilare Bange	1962–1997	30	47
28	Shaune Garang	1962–1997	260	47
29	Janapa Garang	1962–1997	200	47
30	Tikku	1960–1999	220	29
31	Jhajju Bamak	1960–1999	280	29
32	Jaundar Bamak	1960–1999	370	29
33	Bandarpunch	1960–1999	260	29
34	Dokriani	1962 –2007	170	29
35	Gangotri	1935–1996	188	29
35	Gangotri	1962–1999	338	48
35	Gangotri	1935–2004	220	14
35	Gangotri	1965–2006	200	41
35	Gangotri	1962–2000	397	28
35	Gangotri	2004–2007	119	29
36	Gl. No. 3 (Arwa)	1932–1956	80	29
37	Satopanth	1962–2006	220	13
38	Bhagirathi Kharak	1962–2001	167	29
38	Bhagirathi Kharak	1962–2006	73	13
39	Trishul bank	1960–2003	220	29
40	Devasthan Bank	1960–2003	260	29
41	Uttari Rishi Bank	1960–2003	340	29
42	Dakshini Rishi Bank	1960–2003	170	29
43	Dakshini Nanda Devi Bank	1960–2003	130	29
44	Milam	1948–1997	170	29
45	Pindari	1906–2001	152	29
45	Pindari	1845–1906	263	42
45	Pindari	1906–1966	184	53
45	Pindari	1966–2007	64	40
46	Poting	1306–1957	50	29
47	Burphu	1966–1997	50	29
48	Shankalpa	1886–1957	70	29
49	Jhulang	1962–2000	110	49
50	Meola	1912–2000	190	29
51	Chipa	1961–2000	270	49
52	Nikarchu	1962–2002	90	29

(*Contd*)

Table 1. (*Contd*)

Glacier ID	Glacier	Period	Retreat rate (m/decade)	Reference
53	Adikailash	1962–2002	130	29
54	Rekha Samba	1974–1999	120	44
55	AX010	1978–1989	30	54
56	AX030	1978–1989	0	54
57	DX080	1978–1989	50	54
58	EB050	1978–1989	30	54
59	Kongma	1978–1989	30	54
60	Kongma Tikpe	1978–1989	30	54
61	Chukhung	1978–1989	90	54
62	Rathong	1976–2005	180	5
63	Onglaklong	1976–2005	100	5
64	Talung	1976–2005	40	5
65	Tongshiong	1976–2005	140	5
66	Zemu	1976–2005	140	5
67	Changsang	1976–2005	220	5
68	E. Langpo	1976–2005	240	5
69	Jongsang	1976–2005	380	5
70	South Lhonak	1962–2008	420	50
71	Lhonak	1976–2005	270	5
72	N. Lhonak	1976–2005	130	5
73	Chuma	1976–2005	80	5
74	Tasha	1976–2005	20	5
75	Tashal	1976–2005	40	5
76	Yulhe	1976–2005	–10	5
77	Changme	1976–2005	30	5
78	Rulak	1976–2005	20	5
79	Tista	1976–2005	150	5
80	Kangkyong	1976–2005	80	5
81	Tenabawa	1976–2005	40	5

In this table retreat of glaciers is given. Multiple sources of data were used. These are Landsat, ASTER, GPS, Field measurements[26], Survey of India topographic maps, IRS PAN and LISS-III[11], IRS 1C[47], CORONA and LISS III[13,50], toposheets and satellite geocoded data[48], GPS survey[14], Corona, Hexagon, IRS PAN and Cartosat-1[41], PAN and LISS III and topographical map[28] while refs 42, 53, 40, 49, 44, 54 have done field studies. For others, sources are not available.

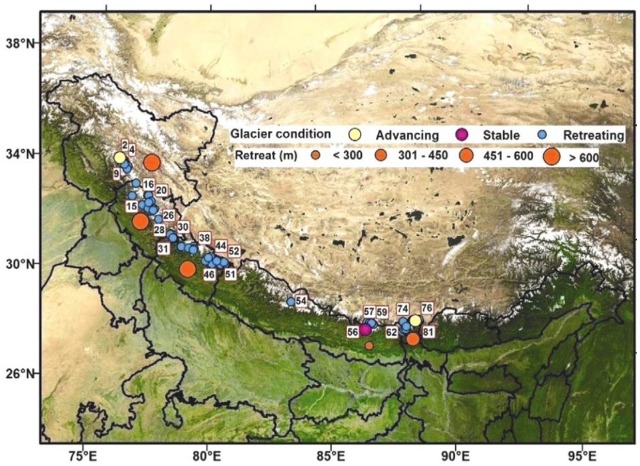

Figure 1. Location of glaciers and amount of retreat between 1960 and 2000. The number represent names of glacier, as given in Table 1.

long-term. Generally for a glacier, mass balance data are available only for a period of a decade and for some glaciers it is available for few years only. To overcome this difficulty, mass balance was estimated for Gara, Gor Garang and Shaune Garang glaciers using accumulation area ratio (AAR) and equilibrium line altitude (ELA)[32,33]. The altitude of transient snowline was estimated using area weighted method[34]. Satellite data of AWiFS and TM sensors of IRS and Landsat respectively, of June, July, August and September were used. The elevation of transient snowline for the year 2009 for Shaune Garang glacier in Baspa basin, India is shown in Figure 5. This has helped in generating mass balance data for additional years. The cumulative loss in glacier mass balance is plotted in Figure 6. The plot is based on mass balance estimates made using field, ELA and AAR methods for Gara, Gor Garang, Shaune Garang, Chhota Shigri, Dokriani, Chorabari, Hamta glaciers. The mean and cumulative mass balance will change, if data from other regions such as Sikkim and Karakoram are available. The mass balance data for 1996 and 1997 are not available and therefore data has been interpolated. In addition, satellite-based geodetic method was used to estimate mass balance of many glaciers in western Himalayas[35].

This analysis suggests an overall loss of 19 ± 7 m of glacier ice for a period between 1975 and 2011 (Figure 6). The study has also shown that mean loss in glacier mass in Indian Himalaya accelerated from –9 ± 4 to –20 ± 4 Gt/year from the decade 1975–85 to 2000–2010.

Table 2. Loss in area in the different regions of Hindu Kush Himalaya

ID	Basin/region	Period	Areal extent (sq. km)	Loss in area (sq. km)	Number of glaciers	Reference
1	Bhut	1962–2001/4	469	47	189	27
2	Zanskar	1962–2001/4	1023	92	671	27
3	Kang Yatze Massif	1969–2010	96	14	121	52
4	Warwan	1962–2001/4	847	178	253	27
5	Miyar	1962–2001/4	568	45	166	27
6	Bhaga	1962–2001/4	363	109	111	27
7	Samudra Tapu	1962–2000	73	8	1	11
8	Chandra	1962–2001/4	696	139	116	27
9	Parbati	1962–2001/4	493	99	90	27
		1998–2009	154.3 ± 0.39	8	51	Present study
10	Baspa	1962–2001/4	173	33	19	27
		1998–2009	145.2 ± 0.27	19	19	Present study
11	Dokriani	1962–1995	8	1	1	43
12	Bhagirathi	1962–2001/4	1365	191	212	27
13	Alaknanda	1968–2006	324.7 ± 8.4	18	69	23
14	Naimona'nyi region	1976–2003	84	7	NA	55
15	Mt Everest region	1976–2006	3212 ± 0.019	502	NA	24
16	AX010	1978–1999	1	0	1	45
17	Sagarmatha national park	1950–1990	404	19	NA	51
18	Tista	1997–2004	403	11	57	27
19	Bhutan Himalaya	1963–1993	147	12	66	46

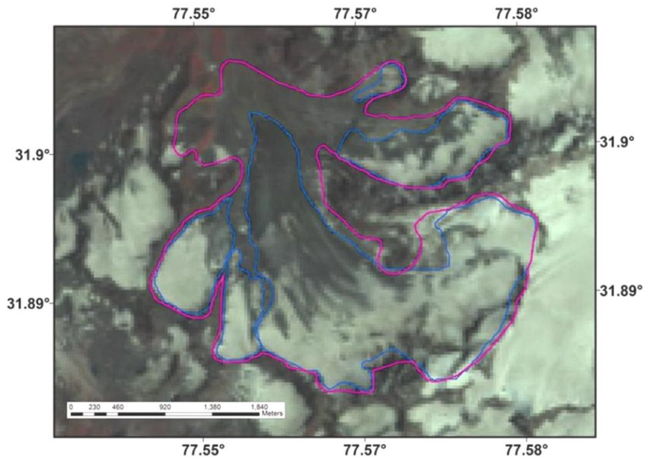

Figure 2. Landsat TM satellite imagery dated 13 August 2009 showing fragmentation of glaciers in Parbati river basin, Himachal Pradesh, India between 1962 (pink) and 2009 (blue).

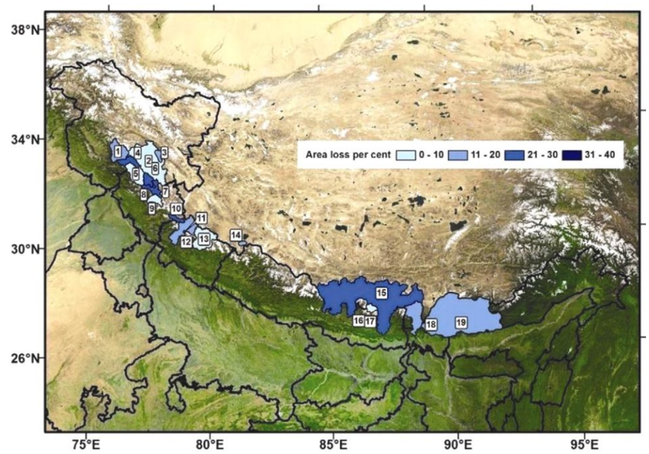

Figure 3. Glacial area loss (%) in different regions of the Himalaya from 1960 to 2000. The number represents names of basins/regions, as given in Table 2.

This is a significant acceleration in mass loss, considering the amount of water stored in the Indian Himalaya.

The important indicator of mass balance is ELA. The ELA in western Himalaya has shifted upward by 300 m in the last 40 years[27]. This has significantly affected the accumulation area of many glaciers located in low altitude and due to lack of formation of new ice, these glaciers are likely to face terminal retreat (Figure 7)[36].

Further, the results of the analysis suggest loss of 443 ± 136 Gt of glacial mass in the Indian Himalaya between 1975 and 2011. The loss in mass is estimated considering overall loss of 19 ± 7 m of glacier ice and glacier area of 23,308 sq. km. The glacier area was estimated[7] using satellite images of 1987 and 1988 (ref. 7). The amount of glacial stored water in the Indian Himalaya has also been estimated using glacier inventory on a 1 : 250,000 scale and different scaling methods[7,28,37]. The estimate varies between 3600 and 4400 Gt of glacial stored water in the Indian Himalaya (Table 3). The estimate of glacial stored water needs further revision, as earlier studies have shown that if information about inventory on 1 : 50,000 scale, slope and movement is used, then estimates will be substantially lower[38]. However, due to lack of data on the Indian Himalaya, this technique could not be applied in the present study.

Discussion and conclusion

In this study the mass of glacial stored water in the Indian Himalaya is estimated using glacier inventory on a

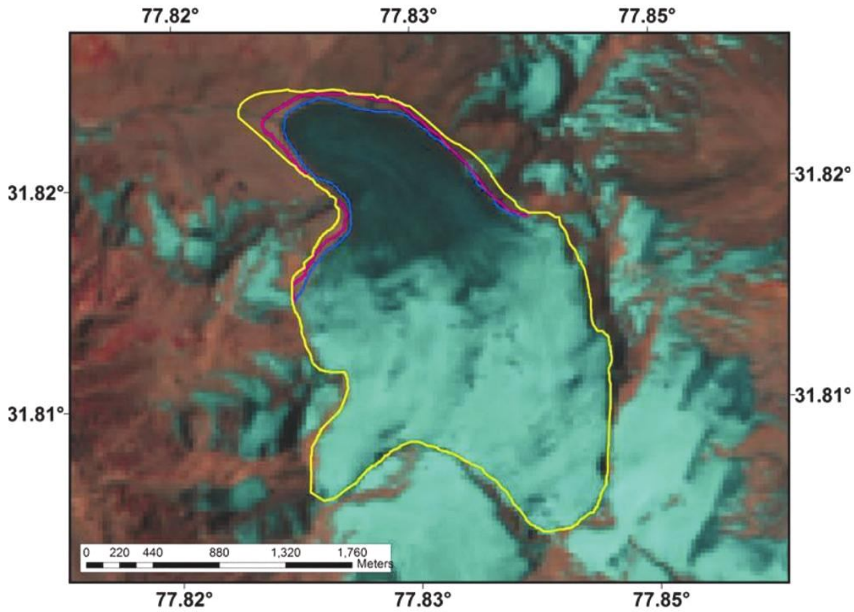

Figure 4. Landsat TM satellite imagery dated 13 August 2009 showing retreat of glaciers in Parbati river basin, Himachal Pradesh, India between 1962 (yellow), 1998 (pink) and 2009 (blue).

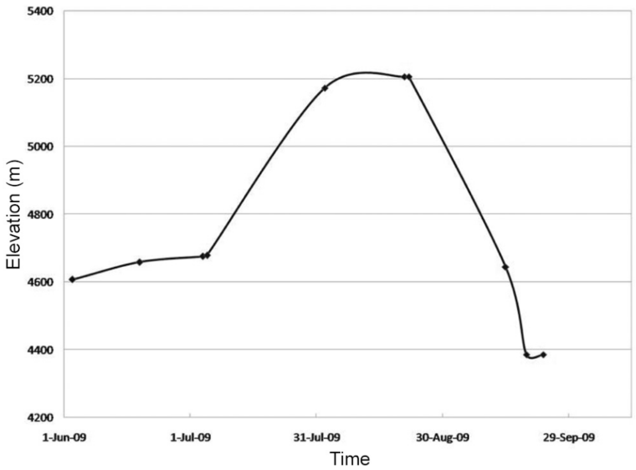

Figure 5. Elevation of transient snowline on Shaune Garang glacier, Baspa basin, India.

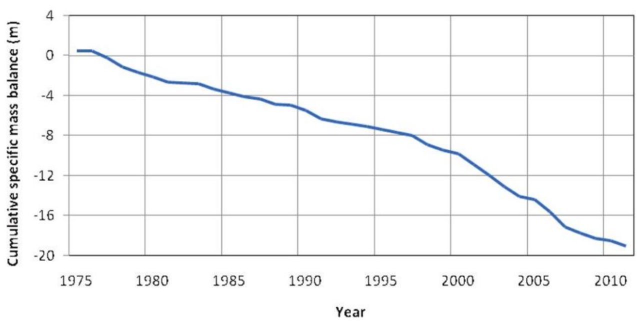

Figure 6. Cumulative loss in glacial ice from 1975. The mass balance data were estimated using field, ELA and AAR methods for Gara, Gor Garang, Shaune Garang, Chhota Shigri, Dokriani, Chorabari and Hamta glaciers.

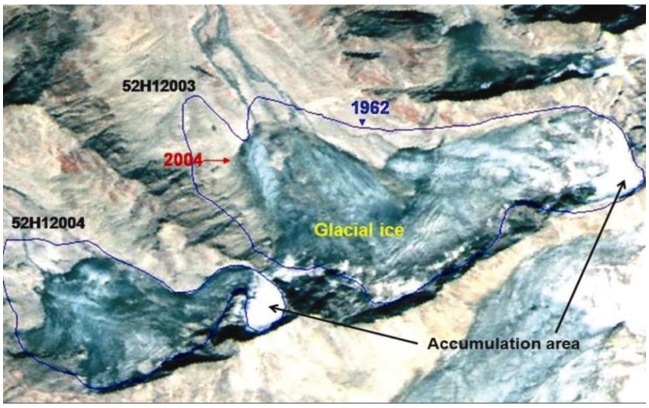

Figure 7. Satellite imagery of IRS LISS-IV sensor of 2004 showing glaciers with negligible accumulation area.

1 : 250,000 scale and using scaling method[7]. This suggests total glacier stored water in the Indian Himalaya is 3600–4400 Gt. The estimates can be further improved, if more detailed inventory and better techniques in which slope and velocity of glacial ice are used[38].

Studies suggest that glaciers in the Himalaya are retreating. Rate of retreat is different for different regions. Based on mapping of almost 11,000 sq. km glaciated area, distributed in all major climatic zones of the Himalaya, suggest an overall 13% of glaciated area has been lost during the last 4–5 decades.

The glacier mass balance observations and estimates made by combining methods like field, AAR, ELA and geodetic measurements suggest a significant increase in mass wastage of Himalayan glaciers in the last 3–4

Table 3. Basin-wise glacier stored water in Indian Himalaya. The estimates were made from different scaling techniques

Basin	Glacier area (sq. km) (1)	Mass (Gt) (2)	Mass (Gt) (3)
Alaknanda	1,036	144	110
Beas	379	53	40
Bhagirathi	883	177	143
Brahmaputra	224	21	15
Chenab	2,567	375	290
Indus	8,081	1,562	1,273
Jhelum	158	11	8
Ravi	105	11	7
Satluj	296	28	20
Sharda	772	94	71
Shyok	5,651	1,469	1,251
Siang	57	6	5
Tista	431	59	45
Yamuna	136	18	13
Shaksgam	2,198	422	338
Sulmar	340	30	22
Total	23,314	4,480	3,651

1. Areal extent[7].
2. Scaling method[37].
   Formula used for estimation of volume:
   $[V] = -11.32 + 53.21 \times [A]^{0.3}$
   where V is the volume of glacier, and A is its surface area.
3. Scaling method[39].
   Formula used for estimation of volume:
   $[V] = 0.03 \times [A]^{1.36}$
   where V is the volume of the glacier, and A is its surface area.

decades. The cumulative loss in glacial ice during the last four decades has been estimated at 19 ± 7 m. This suggests loss of 443 ± 136 Gt of glacial mass out of total 3600–4400 Gt of glacial stored water in the Indian Himalaya. The estimate of glacial stored water in the Indian Himalaya is based on glacier inventory on a 1 : 250,000 scale and scaling methods; therefore, uncertainties are expected to be large. The study has also shown that mean loss in glacier mass in the Indian Himalaya has accelerated from –9 ± 4 to –20 ± 4 Gt/year from the decade 1975–1985 to 2000–2010. This loss is significant considering the amount of water stored in the glaciers of the Indian Himalaya. If the loss continues at this high rate, it may influence the livelihood of people living in the mountains.

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