Estimation of glacial retreat and mass loss in Baspa basin, Western Himalaya

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Abstract Glaciers are one of the valuable natural resources in Indian Himalaya. A large number of people depend on glacier melt for social and industrial activities. Therefore, monitoring the glacial changes becomes crucial. In the present study, retreat and mass balance of 19 glaciers in Baspa basin were analysed. An overall de-glaciation of 24 % ($41.1 \pm 8.37 \text{ km}^2$) was observed between 1962 and 2014. Mass balance was estimated by Accumulation Area Ratio and Equilibrium Line Altitude (ELA) methods. The mean ELA estimate varies between 5147 ± 178 and 5405 ± 173 m. Negative mass balance was observed and the estimated mass loss is 3.6 mega tonne ($3.6 \times 10^6 \text{ m}^3$), for a period of 9 years between 1998 and 2014. In addition, temperature and precipitation data obtained at Rakham observatory (3050 m) were analysed for a period of 29 years, between 1984 and 2013. The analysis showed an increasing trend in annual mean temperature, decreasing trend in precipitation and a higher rise in minimum temperatures of both summer and winter. Thus, the overall observations suggest continuous loss of glacier area and mass, which may influence the glacier's health and run-off in Baspa basin.

Keywords Mass loss · Retreat · Baspa · Rakham

1 Introduction

Glaciers are the major source for numerous rivers originating in Indian Himalaya. Large number of people is relied on these rivers for irrigation, domestic supplies and Hydro-power generation [1–3]. In the present scenario, except Karakoram, all the glaciers in the Himalaya are retreating, with a rate of few meters to almost 60 m year^{-1} [1, 4–6]. The rate of retreat varies among the glaciers depending on geomorphological characteristics [2, 5, 7–11]. However, recent studies have shown that the retreat rate of Himalayan glaciers has accelerated due to deposition of black carbon, changes in debris cover and slope [11–18].

The sustainability of a glacier can be assessed by mass balance [19–21]. The field mass balance studies are limited in Indian Himalaya due to the rugged terrain, harsh weather conditions and difficulty in providing logistics support. Thus, field data exists only for few glaciers (Fig. 1) and limited to a short period [4, 22–25]. The paucity in field data was addressed by Remote Sensing (AAR, ELA and Geodetic) methods to study the glacier mass balance in Indian Himalaya [26–33]. The observations reported on mass balance suggest a higher mass loss in Indian Himalaya for the past two decades [6, 9]. Thus, all the observations suggest that the Himalayan glaciers are losing mass at a higher rate over the past few decades [1, 3]. In addition, the weather records showed an increase in mean temperature of 2°C with a decreasing trend in precipitation between 1984 and 2007 [35–37]. Furthermore, Intergovernmental Panel on Climate Change (IPCC) Coupled Model Inter-comparison Project Phase (CMIP5) also

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Fig. 1 Field mass balance data are available only for 14 glaciers in Indian Himalaya and limited for a short period [1, 4, 22–24, 43, 51–53]

suggests that, the global mean temperature is projected to increase by 1.7–5.7 °C, with an increase of 3.5–5.5 °C in Indian sub-continent by the end of 2100 [38–40]. Thus, the rise in temperature and accelerated mass loss will have a profound effect on the areal extent and mass balance of glaciers in the Indian Himalaya, in near future [6, 38]. The present study consider Baspa basin as study area, since (1) Glaciers in this basin are well mapped and relationship between mass balance and accumulation area ratio (AAR) is well established [26, 29] (2) Run-off in this basin is mostly contributed by snow melt rather than rainfall [41, 42] and (3) the melt-runoff from the glaciers plays an important role in the power generation of Karcham Wangtoo Hydro-electric plant, with a capacity of 300 MW [42]. Hence, this study aims to (1) Estimate the glacial retreat between 1962 and 2014 (2) Analyze the mass balance changes between 1998 and 2014 and (3) Evaluate temperature and precipitation trends in Baspa valley.

2 Study area and methodology

Baspa is a major tributary of Satluj River, located in Kinnaur district of Himachal Pradesh, India (Fig. 2). The river originates at Arsomang and Baspa Bamak glaciers and travels 72 km through the valley before joining the Satluj River at Karcham [42]. The total area covered by the basin is 1050 km², with an altitude range varying from 1800 to 6400 m.s.a.l. Out of the total basin area, 22 % (238.65 km²) area is covered by 89 glaciers, in the altitude range between 3720 and 5900 m.s.a.l [43]. Among total glaciers, 19 glaciers covering 72 % areal extent is selected for the study (Fig. 2).

The pre-processing of satellite data, generation of digital database and mapping glacial extents were carried out using ERDAS Imagine (V. 2011) and ARC GIS (V. 9.3.2)

software's. The areal extents of 19 glaciers in the year 1962 were obtained from the study Kulkarni and Alex [44]. The glacier outlines for the same glaciers in 1998 and 2014 were mapped using 24 August 1998 (Landsat 5 TM) and 20 August 2014 (Landsat 8 OLI) imagery (Source: <http://earthexplorer.usgs.gov/>). The scenes at the end of the ablation period (August/September period) were preferred, since the glaciers will be fully exposed and snow cover is at its minimum extent [9, 44]. To enhance the spatial resolution of images, pan sharpening method (principal component) is applied. For Landsat 5 TM (24 Aug 1998), the pan band is obtained from Landsat 7 ETM + (20-09-1999) and for Landsat 8 imagery, the pan band on 20 Aug 2014 was used. The glacier margins are delineated using a semi-automatic approach, which includes the visual interpretation and band ratio (Normalized Difference Snow Index—NDSI) techniques [5, 46]. Contrast [linear, photography adjustment] and brightness enhancements were applied on standard True Color Composite images [Band combination: Green (0.52–0.60), Red (0.63–0.69) and NIR (0.76–0.90)] to aid in visual interpretation and identify the glacier margins, accurately [44]. The band ratio (NDSI) was used to identify the snow cover under shadow [46]. The ice divides (ice margins) are interpreted by overlaying the satellite image on the Cartosat Digital Elevation Model (obtained from NRSC, <http://bhuvan.nrsc.gov.in/data/download/index.php>) [9]. Snout positions on satellite images are identified using the geomorphic characteristics like (a) black tone due to the shadow of ice wall (b) origin of river (c) red tone of vegetation present near the terminal moraines and (d) moraine-dammed lakes [9, 30]. After defining the snout positions and glacial extents, the glacier outlines were manually interpreted and then areas were calculated. The mapping uncertainties were estimated using Eq. 1 [12]. To assess the accuracy of glacier outlines, a field visit was conducted to Naradu glacier in September 2014.

Fig. 2 Location of glaciers and meteorological station in Baspa valley, Himachal Pradesh, India

$$\text{Mapping uncertainty } a = N \times \frac{A}{2} \quad (1)$$

where N is number of pixels along the glacier boundary and A is the area of pixel.

A Regression relationship was well established between specific mass balance (cms) and accumulation area ratio (AAR) for the glaciers located in Baspa basin with a good correlation ($r^2 = 0.80$) and it suggests the AAR representing zero mass balance is 0.5 [29, 44]. In this study, the same regression relationship (Eq. 2) was used to estimate the mass balance for a period of 9 years between 1998 and 2014, where systematic data is available.

$$\text{AAR} = \frac{\text{Accumulation Area}}{\text{Total glacier Area}} \quad (2)$$

$$Y = 243.01 \times \text{AAR} - 120.187 \quad (3)$$

where Y is the specific mass balance in water equivalent (cm) and X is Accumulation Area Ratio.

Depending on the Equilibrium Line Altitude (altitude of snowline at the end of ablation period), the

accumulation area varies from year to year. Thus, the snow lines were demarcated and accumulation areas were mapped for all the 9 years, between 1998 and 2014. The altitude of snowlines were calculated using the hypsography derived (in 100 m) from Cartosat Digital Elevation Model and multi-temporal satellite imagery (Supplementary Table 1). Equations 2 and 3 were used to estimate the AAR and mass balance of glaciers. Further, the loss in ice volume (m^3) was estimated using the mass balance and areal extents.

To understand the response of glacier to change in climate, temperature and precipitation [snowfall and rainfall] data at Rakchham (3050 m) were analyzed for a period of 29 years, between 1984 and 2013. Hence, anomalies describe climate variability more accurately than absolute temperatures over larger areas [47]; the anomalies were estimated for annual mean temperature and precipitation including snowfall. Linear trends were plotted and Mann–Kendall test was performed to check the statistical significance of the trends [48, 49].

3 Results and discussion

3.1 Observed changes in glacier terminus

Retreat was observed for all the 19 glaciers between 1998 and 2014. Maximum retreat was observed for Janapa Garang i.e., 330 ± 21 m and minimum was observed for Sanchay glacier i.e., 12 ± 21 m. The glaciers like Shaune Garang, Janapa Garang, Jorya Garang, Naradu Garang, Bilare Bange and Baspa Bamak has also shown higher retreat. A rise of 122 ± 21 meters was observed in the mean snout altitude, between 1998 and 2014 (Supplementary Table 2). The area loss and shift in snout position of Baspa bamak are shown in the Fig. 3. The earlier studies carried on Baspa basin suggests that the glaciers have experienced retreat between 1962 and 1997. The rate of retreat for the Janapa Garang, Jorya Garang, Naradu Garang, Bilare Bange and Baspa Bamak glaciers are 696, 425, 550, 90 and 380 m, respectively [29, 44]. The field study conducted in September 2014 also suggests that Naradu Garang glacier have experienced retreat [53I07008] (Fig. 4). During the field visit, the geomorphological features like terminus position, terminal moraines, debris covered ice, supra-glacial lake and accumulation area were investigated and positions were recorded using Garmin GPS map 76CSX (Fig. 4). Presently, the terminus is at 310

$18^{\circ}15.1''\text{N}$ and $78^{\circ}25'34.3''\text{E}$ with an altitude of 4508 ± 8 meters (Fig. 4), whereas the terminus position identified using satellite imagery is 4516 ± 21 m.

3.2 Observed changes in glacier extent

For the year 1962, areal extent of 19 glaciers was reported as 173 km^2 [28]. Difference in areal extent of the same glaciers surveyed by Survey of India (SoI) and Geological Survey of India (GSI) is considered as the uncertainty in mapping the glacial area for the year 1962 [45], and it is estimated to $\pm 15.17 \text{ km}^2$. For 1998 and 2014, the areal extents of the same glaciers are estimated to 145.2 ± 10.1 and $131.7 \pm 8.37 \text{ km}^2$, respectively. An overall deglaciation of 24 % ($41.1 \pm 8.37 \text{ km}^2$) was observed for a period of 52 years, between 1962 and 2014. An area loss of $27.8 \pm 7.72 \text{ km}^2$ is observed between 1962 and 1998 (36 years) and $13.3 \pm 5.20 \text{ km}^2$ between 1998 and 2014 (16 years). The areal extent, uncertainty in mapping (mapping error) and loss in area of individual glaciers from 1962 to 2014 are given in the Table 1. The annual loss in area is observed to be 0.45 % and was increased to 0.6 % a^{-1} , after 1998. The studies carried in various parts of the Himalaya also suggest that the glaciers are losing area at an average rate of 0.4 % per year and the rate of loss increased

Fig. 3 **a** and **b** Area loss of 53111014 and 53107005 glaciers ($\sim 1 \text{ km}^2$), observed between 1962 and 2014. **c** Area loss and shift in snout position of Baspa Bamak (53112002). A retreat of 230 ± 21 m has been observed between 1998 and 2014

Fig. 4 Aerial extent of Naradu glacier in 2014. The features identified in the field investigation are marked in this figure. The position of the snout was identified on the satellite imagery by observing ice-cliff shadow and the origin of river. The difference in snout positions identified in the field and on satellite imagery is ~ 10 m

Table 1 Glacier area, loss in area and mapping uncertainty for 19 glaciers between 1962 and 2014

S. No.	Database Id	1962			Area $\pm$ uncertainty		Loss in area + uncertainty	
		Area by SOI (km ²)	Area by GSI (km ²)	Uncertainty for the year 1962 (km ²)	1998 (km ²)	2014 (km ²)	1962–1998 (km ²)	1998–2014 (km ²)
1	53I07001	10.5	8.2	2.3	8.7 $\pm$ 0.67	8 $\pm$ 0.61	1.8 $\pm$ 0.35	0.8 $\pm$ 0.31
2	53I07002	4.6	2.02	2.58	4.3 $\pm$ 0.46	3.8 $\pm$ 0.40	0.3 $\pm$ 0.24	0.5 $\pm$ 0.25
3	53I07003	2.2	1.71	0.49	2.1 $\pm$ 0.19	1.9 $\pm$ 0.14	0.1 $\pm$ 0.07	0.2 $\pm$ 0.18
4	53I07004	4.6	4.46	0.14	4.2 $\pm$ 0.31	3.8 $\pm$ 0.28	0.4 $\pm$ 0.18	0.4 $\pm$ 0.30
5	53I07005	1.7	1.86	−0.16	1.3 $\pm$ 0.13	1.2 $\pm$.10	0.4 $\pm$ 0.12	0.1 $\pm$ 0.14
6	53I11013	3.2	3.39	−0.19	3.2 $\pm$ 0.17	3.2 $\pm$ 0.17	0	0
7	53I11014	1.5	1.54	−0.04	1 $\pm$ 0.13	0.8 $\pm$ 0.09	0.5 $\pm$ 0.07	0.2 $\pm$ 0.1
8	53I12001	5.9	5.81	0.09	5.7 $\pm$ 0.43	4.6 $\pm$ 0.34	0.2 $\pm$ 0.02	1 $\pm$ 0.25
9	53I12002	38.4	36.72	1.68	34 $\pm$ 2.02	32.4 $\pm$ 1.70	4.4 $\pm$ 1.64	1.5 $\pm$ 0.79
10	53I12003	2.7	2.66	0.04	2.3 $\pm$ 0.23	2.2 $\pm$ 0.19	0.4 $\pm$ 0.14	0.1 $\pm$ 0.14
11	53I11009	7.1	7.11	−0.01	5.5 $\pm$ 0.32	4.4 $\pm$ 0.30	1.6 $\pm$ 0.26	1.1 $\pm$ 0.33
12	53I11010	6.9	6.92	−0.02	6 $\pm$ 0.45	5.5 $\pm$ 0.41	0.9 $\pm$ 0.39	0.5 $\pm$ 0.35
13	53I11011	8.7	8.6	0.1	4.9 $\pm$ 0.45	4.3 $\pm$ 0.44	3.8 $\pm$ 0.27	0.7 $\pm$ 0.32
14	53I07006	35.2	33.13	2.07	31.5 $\pm$ 1.71	29.4 $\pm$ 1.30	3.7 $\pm$ 1.69	1.8 $\pm$ 0.48
15	53I07007	11.6	10.08	1.52	10.4 $\pm$ 0.56	9.7 $\pm$ 0.47	1.2 $\pm$ 0.35	0.7 $\pm$ 0.21
16	53I07008	5.5	4.76	0.74	4.4 $\pm$ 0.3	3.7 $\pm$ 0.27	1.1 $\pm$ 0.29	0.7 $\pm$ 0.23
17	53I07009	3.9	3.72	0.18	2 $\pm$ 0.25	1.7 $\pm$ 0.17	1.9 $\pm$ 0.31	0.3 $\pm$ 0.09
18	53I07010	8	4.94	3.06	7.3 $\pm$ 0.82	6 $\pm$ 0.66	0.7 $\pm$ 0.58	1.3 $\pm$ 0.26
19	53I07011	10.8	10.2	0.6	6.2 $\pm$ 0.49	5.1 $\pm$ 0.35	4.6 $\pm$ 0.42	1.1 $\pm$ 0.29
Total		173	157.83	15.17	145.2 $\pm$ 10.08	131.7 $\pm$ 8.37	27.83 $\pm$ 7.72	13.23 $\pm$ 5.20

after 1995 [1, 3, 30, 50]. In addition, higher loss in area was observed for smaller size glaciers and at lower altitudes since 1962 (Fig. 3). This suggests that the small size

glaciers are more sensitive to climate change, compared to the larger glaciers. Similar observations have been reported earlier in the other parts of Himalaya [1, 9, 21].

Fig. 5 Mass balance measurements for Gara, Gor-Garang, Shaune Garang and Naradu glaciers (Data is from Geological Survey of India, 1992 and present study). The trend in mass balance is observed to be declining since 1975

Fig. 6 The cumulative mass loss for Shaune Garang, Gor-Garang, Gara and Naradu glaciers from 1975. Observations suggest that all the four glaciers are losing mass continuously since 1975

3.3 Mass balance observations

For the years 2001 and 2002, the estimates of mass balance are obtained from Kulkarni et al. 2004 [29] and for the remaining seven years, Landsat 5 TM multi-temporal images (given in Supplementary Table 1) was used for mass balance estimation. Equilibrium Line Altitudes are derived using hypsography obtained from Cartosat DEM (v3.0) and multi-temporal satellite imagery (Supplementary Table 3). The uncertainty in SLA for each year was estimated using area weighted method and is given in the Supplementary Table 4. AAR and uncertainties in AAR is estimated (Supplementary

Tables 5, 6 and 7) and then mass balance was calculated (Supplementary Table 8). The uncertainties in mass balance were estimated by propagating the uncertainties in ELA and regression method to annual mass balances through AAR (Supplementary Tables 9, 10). The observations suggest the glaciers have experienced negative mass balance in the observation period, with a mean mass loss varying between -0.08 ± 0.04 m.w.e to -0.9 ± 0.48 m.w.e. (Supplementary Table 10). The mass loss for 19 glaciers was observed to be 3.6 megaton (3.6×10^6 m³), for a period of nine years between 1998 and 2014 (Supplementary Table 11). To understand the mass balance changes in long term,

Fig. 7 The meteorological data is obtained from Rakcham observatory, located at 3050 m.a.s.l. The anomaly of mean annual temperature suggests a rise of 1.65 °C from 1984 to 2013, whereas, a

significant decrease (102 mm) is observed in Rainfall and snow water equivalent between 1984 and 2015

analysis was carried out for four glaciers namely Gara, Gor-Garang, Shaune Garang and Naradu glaciers. These glaciers were chosen for the long term mass balance study because of the availability of in situ (from GSI) and satellite measurements. The mean and cumulative mass balance of the four glaciers was plotted and is given as Figs. 5 and 6, which suggests that these glaciers have experienced negative mass balance since 1975 and losing mass continuously.

3.4 Climate data analysis

The temperature and precipitation (rainfall and snowfall) data of Rackham observatory (3050 m) was analyzed for a period of 29 years, between 1984 and 2013. The anomalies and trends of the precipitation (mm), annual mean temperature (T_A), minimum and maximum temperatures of summer $-S_{max}$, S_{min} (June to October) and winter $-W_{max}$, W_{min} (November to May) are shown in the Figs. 7 and 8. A rise of 0.33 °C (S_{max}), 1.23 °C (S_{min}), 2.07 °C (W_{max}) and 1.9 °C (W_{min}) was observed between 1984 and 2013. The annual mean temperature (°C), minimum temperature in summer and minimum and maximum temperature in winter showed increasing trend, whereas the total rainfall showed a decreasing trend between 1984 and 2013. To test the significance of the long term trends in temperature and precipitation, Mann–Kendall test is performed [48, 49].

This suggests that the null hypothesis was accepted for precipitation (mm) and maximum temperature of summer (°C). Whereas, the null hypothesis is not accepted for annual temperature (°C), minimum temperature of summer, minimum and maximum temperatures of winter (°C) (Table 2).

4 Conclusion

The spatio-temporal changes of glaciers in Baspa basin were studied by combining both remote sensing and field data. The study suggests that the glaciers are retreating and losing mass in long term. The study observed an area loss of 0.45 % year⁻¹ between 1962 and 1998, and 0.6 % year⁻¹ after 1998. The investigation also suggests that the area loss was found to be higher for small glaciers. Such loss in glacier area at an average rate of 0.4 % year⁻¹, and accelerated area loss after 1995 has been previously reported in different parts of the Himalayan region [1, 3, 5, 9, 28, 33, 34, 50–53]. Also, negative mass balance was observed for a period of 9 years between 1998 and 2014. Further, the analysis of climatic data showed that the glaciers have experienced hotter summers and warmer winters. Considering the mean depth of these glaciers (~30 m) [43], such accelerated loss in glacial area with continuous mass loss may create water scarcity in Baspa

Fig. 8 Anomalies of minimum and maximum temperatures in **a** summer and **b** winter. A rise of 0.33 °C ($S_{\max}$), 1.23 °C ($S_{\min}$), 2.07 °C ($W_{\max}$) and 1.90 °C ($W_{\min}$) was observed between 1984 and 2013. Among these, the rise in maximum temperature in winter is higher

Table 2 Results of Mann–Kendall test for temperature and precipitation data

Total precipitation (mm)		Annual mean temperature (°C)		Summer minimum temperature (°C)		Summer maximum temperature (°C)		Winter minimum temperature (°C)		Winter maximum temperature (°C)	
Mann–Kendall statistic (S)	3	Mann–Kendall statistic (S)	168	Mann–Kendall statistic (S)	138	Mann–Kendall statistic (S)	40	Mann–Kendall statistic (S)	142	Mann–Kendall statistic (S)	114
Variance (S)	3142	Variance (S)	3142	Variance (S)	3142	Variance (S)	3142	Variance (S)	3142	Variance (S)	3142
ZS	0.04	ZS	2.98	ZS	2.44	ZS	0.70	ZS	2.52	ZS	2.02
Zcrit.,05	1.96	Zcrit.,05	1.96	Zcrit.,05	1.96	Zcrit.,05	1.96	Zcrit.,05	1.96	Zcrit.,05	1.96
Increasing trend/not significant		Sig. increasing		Sig. increasing		Increasing trend/not significant		Sig. increasing		Sig. increasing	

The annual mean temperature (°C), minimum temperature in summer and minimum and maximum temperature in winter showed a significant increase, whereas the total rainfall showed a significant decrease between 1984 and 2013

basin. Therefore, further investigation on mass budget of glaciers in Baspa basin at a high resolution is necessary, to assess the hydropower potential and water scarcity in near future.

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