J. Mt. Sci. (2018) 15(6): 1241-1253 e-mail: jms@imde.ac.cn http://jms.imde.ac.cn
https://doi.org/10.1007/s11629-017-4474-0

Streamflow response to shrinking glaciers under changing climate in the Lidder Valley, Kashmir Himalayas

Asif Marazi http://orcid.org/0000-0002-7182-2904; e-mail: asif.geo3@gmail.com

Shakil A. Romshoo* http://orcid.org/0000-0003-0070-5564; e-mail: shakilrom@kashmiruniversity.ac.in

* *Corresponding author*

Department of Earth Sciences, University of Kashmir, Srinagar Kashmir, India

Citaion: Marazi A, Romshoo SA (2018) Streamflow response to shrinking glaciers under changing climate in the Lidder Valley, Kashmir Himalayas. Journal of Mountain Science 15(6). https://doi.org/10.1007/s11629-017-4474-0

Abstract: The study investigated the streamflow response to the shrinking cryosphere under changing climate in the Lidder valley, Upper Indus Basin (UIB), Kashmir Himalayas. We used a combination of multi-temporal satellite data and topographic maps to evaluate the changes in area, length and volume of the glaciers from 1962 to 2013. A total of 37 glaciers from the Lidder valley, with an area of 39.76 km² in 1962 were selected for research in this study. It was observed that the glaciers in the valley have lost ~28.89 ±0.1% of the area and ~19.65 ±0.069% of the volume during the last 51 years, with variable inter-decadal recession rates. Geomorphic and climatic influences on the shrinking glacier resources were studied. 30-years temperature records (1980-2010) in the study area showed a significant increasing trend in all the seasons. However, the total annual precipitation during the same period showed a non-significant decreasing trend except during the late summer months (July, August and September), when the increasing trend is significant. The depletion of glaciers has led to the significant depletion of the streamflows under the changing climate in the valley. Summer streamflows (1971-2012) have increased significantly till mid-nineties but decreased significantly thereafter, suggesting that the tipping point of streamflow peak, due to the enhanced glacier-melt contribution under increasing global temperatures, may have been already reached in the basin. The observed glacier recession and climate change patterns, if continued in future, would further deplete the streamflows with serious implications on water supplies for different uses in the region.

Received: 04 April 2017
Revised: 09 January 2018
Accepted: 25 March 2018

Keywords: Glacier Mapping; Glacier Volume; Climate Change; Streamflow; Himalayas

Introduction

The Himalayas, referred as the 'water tower of Asia' due to its vast glacier resources, provide water to the population of about a billion living in the Indus, Ganges and Brahmaputra basins. However, glaciers are sensitive to the changes in temperature and precipitation (Oerlemans 1994; Anderson and Mackintosh 2006) and are depleting at varying rates (Cogley 2016; Dobhal and Pratab 2016; Murtaza and Romshoo 2017). Himalayan glaciers, since the mid-19th century are in a continuous state of recession in response to the long term temperature changes over the region (Bahuguna et al. 2007; Bhambri et al. 2011; Salerno et al. 2016). The accelerated loss of glaciers over Himalayas and its anticipated impact on streamflows has attracted the attention of researchers over the past few decades and implications are a cause of concern for the scientific and political communities (Bolch et al. 2012; Kulkarni and Karyakarte 2013). The increasing temperatures have serious consequences on the hydrology of regions where streamflows are dominated by snow- and glacier-melt (Bajracharya et al. 2008). In the Upper Indus Basin (UIB), snow- and glacier-melt contributes more than 70% to the annual streamflows (Immerzeel et al. 2009); hence the streamflows in the glaciated basins are highly vulnerable to climate change. Recent studies have linked the significant changes in the streamflows of the Himalayan rivers to the accelerated shrinking of glaciers (Immerzeel, et al. 2010; Romshoo et al. 2015). According to the IPCC (2014), an increase of 1.8°C in Earth's average surface temperature shall shrink the Himalayan glaciers by 45% by the end of this century, and under the worst warming scenario of 3.7°C projected for 2100, the glacial reduction would be up to 68% and would seriously impact the streamflows.

In Kashmir Himalayas, the indicators of global warming are clear and loud in terms of increase in temperature, enhanced receding of snow and glacier resources, decrease in snow precipitation and depleting streamflows (Dar and Romshoo 2012; Romshoo et al. 2015). The recent studies have shown that the snow precipitation over Lidder basin has reduced in response to increasing temperature (Mishra and Rafiq 2016, Romshoo et al. 2015), which in turn has resulted in less accumulation of snow over the glaciers, thus leading to negative glacier mass balance (Murtaza and Romshoo 2017). The continued reduction in the stored frozen water in the Kashmir Himalayas will lead to various socio-economic and environmental problems in future like decline of hydropower generation, decrease in agriculture productivity, fall in winter tourism and drinking water scarcity (Dar et al. 2014; Muslim and Romshoo 2015). Even though the cryospheric resources in Kashmir Himalayas are vulnerable and the impacts on various dependent sectors are serious, the region has remained under-studied. Therefore, it is of utmost importance to map and monitor the glacier changes in the region to assess the climate-glacier relationship and the consequent impact on the streamflows in the Lidder valley, Upper Indus Basin, Kashmir Himalayas.

The present study focuses on the causal factors for the shrinking of glaciers and the consequent impacts on the streamflows. The main objectives of the study are (i) to map the glacier area and volume changes from 1962 to 2013 using multiple data sources; (ii) an analysis of the climatic data to get an insight about the influence of climatic variables on glacier recession; and (iii) streamflow data analysis corroborated with the climatic data to elucidate the complex response of streamflows to the shrinking glacier resources.

1 Study Area

Lidder valley, with the total geographical area of ~1260 km^2, lies in the south-eastern part of the Kashmir basin, North-western Himalayas and extends between 33°15′ - 34°30′ N latitudes and 75°30′ - 75°45′ E longitudes, (Figure 1). It has a craggy topography with highly varying elevation ranging from 1500-5200 m a.s.l., and hosts many glaciers including the largest glacier in the Kashmir basin, the Kolahoi (Rashid et al. 2017; Ali et al. 2017). Lidder River, which is one of the biggest tributaries of Jhelum River originating from the Kolahoi glacier (West torrent) and Sheshnag Lake (East torrent); join near Pahalgam to form Lidder River. During the winter months, a major part of the valley remains under a vast and thick snow cover (Dar et al. 2014), which sustains the mass of glaciers in the valley and preserves the perennial character of the Lidder river. The climate of the Lidder valley is sub-humid temperate and exhibits four seasons; spring, summer, autumn and winter.

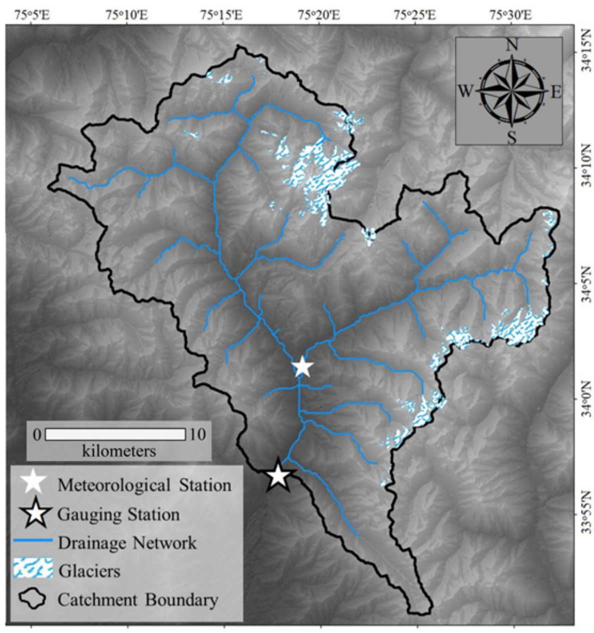

Figure 1 Location map of the study area.

It receives precipitation predominantly during the winter and spring; though winter precipitation is highly dominated by snow. The mean annual precipitation in the area is 1240 mm, recorded at the Indian Meteorological Department (IMD) station, Pahalgam. The mean annual temperature is 9.5°C, varying from monthly mean of 19°C in July to the monthly mean of -1.7°C in January.

2 Data Sources

Multi-temporal satellite data including the images from Landsat-5 Thematic mapper (1992), Landsat-7 Enhanced Thematic Mapper ETM+ (2000) and Landsat-8 Operational Land Imager OLI (2013), all having 30 m spatial resolution, were used to map the temporal changes in the glacier area in the study area. Preferably, cloud- and snow-free satellite images, acquired at the end of the ablation period, were used for mapping the glacier boundaries (Racoviteanu et al. 2009). Survey of India (SOI) topographic maps at 1:50,000 scale were used to extend the glacier investigations further back in time to 1962. Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) Digital Elevation Model (DEM v.2) was used to generate the slope, aspect and elevation details of the glaciers to aid the delineation of glacier boundaries. The characteristics of the data sets used in this research are given in Table 1.

Meteorological data (daily precipitation, T_{max} and T_{min}) of the last 30 years (1980-2010) was acquired from the Indian Meteorological Department, Pahalgam observatory and the streamflow discharge data (1971-2012) of the Batakote gauging station, near Pahalgam was obtained from the Irrigation and Flood Control Department, J&K Government for hydro-meteorological analysis. The discharge data obtained from the Batakote station generally comprises of 3-4 measurements per month and therefore, monthly average discharge values were used in this study.

3 Methodology

3.1 Glacier mapping

The climate-glacier interactions and its impact on streamflow in the study area was assessed by analyzing the temporal changes in the surface area and volume of the glaciers under the changing climate using multi-temporal multisource data sets. All the satellite images were visually interpreted onscreen using digital False Color Composition (FCCs) to delineate the glacier extent in GIS environment (Paul et al. 2009; Pandey et al. 2011). The ASTER DEM v.2 was used to generate the unique morphological details of the glaciers for better and precise delineation of the true glacier boundaries, ice divides and snout positions (Svoboda and Paul 2009). The location of lateral and terminal moraines identified on the satellite images were used for the identification of snout positions in particular and whole glacier boundaries in general (Bolch and Kamp 2006). Moreover, the stream network delineated from ASTER DEM v.2 and satellite images, corroborated with the field observations, provides a better idea about delineating the true position of glacier snouts, by considering snout as the emergence point of glacier streams. Furthermore, the length of glaciers was measured by digitizing the centre flow lines of the glaciers in GIS environment (Le Bris and Paul 2013; Pellicciotti et al. 2015).

3.2 Mapping accuracy

Glacier boundaries digitised from a time series of satellite images and Topographic maps do introduce uncertainty in the mapping accuracy. The satellite data may have different spatial resolution, varying snow cover, clouds and shadow

Table 1 Data sets used, their spatial resolution/scale and acquisition date

Sensor/Image/Maps	Resolution/Scale	Acquisition date	Source
Topographic Maps	1:50000	1962	Survey of India
Landsat TM	30m	October 15, 1992	http://earthexplorer.usgs.gov/
Landsat ETM+	30m	September 30, 2000	http://earthexplorer.usgs.gov/
Landsat OLI	30m	October 27, 2013	http://earthexplorer.usgs.gov/
ASTER GDEM v.2	30m		http://gdem.ersdac.jspacesystems.or.jp/

conditions which might introduce errors in the mapping work. Even though the satellite images of same spatial resolution (30 m) were used in the current study, the glacier area delineation and co-registration of satellite data can introduce errors in the estimation of glaciers area changes. Therefore, it is important to estimate the mapping accuracy to improve the significance of the findings. Paul et al (2013) have reported that the mapping of clean glaciers would introduce an uncertainty of ±2-3%, while under ideal conditions, the glacier mapping accuracy could be as high as half-pixel (Bolch et al. 2010). In the present study, the uncertainty (U) introduced while mapping the changes in the glacier terminus positions was estimated by the method (Eq. (1)), as suggested by Hall et al. (2003).

$$U = \sqrt{a^2 + b^2} + \sigma \quad (1)$$

Where a and b are the spatial resolution of satellite images used and σ represents the error in image registration.

The registration error was visually confirmed as 8 m for Landsat TM (1992) and 7 m for 2000 Landsat ETM+ when registering these images with the base image of Landsat OLI 2013 and similar co-registration error has been reported by Murtaza and Romshoo (2017) for the co-registration of a time series of satellite images with same spatial resolution. For computing the mapping errors between any two images, registration error was added to the uncertainty value. Thus, the uncertainty in mapping the changes in the snout position of glaciers was estimated as ±50.42 m when registering the Landsat TM image of 1992 with the base image Landsat OLI (2013), and ±49.43 m when registering the images with the Landsat ETM+ image of 2000.

The uncertainty in mapping the glacier area (U_{area}) was estimated by using the following equation (Hall et al. 2003).

$$U_{\text{area}} = 2UV \quad (2)$$

Where U is the terminus uncertainty and V is the image pixel resolution.

The uncertainty in mapping the areal extent of the glaciers was estimated to be 0.0030 km² for 1992 TM image and 0.0029 km² for 2001 ETM+ image. The accuracy of the topographic maps is considered as unknown (Hall et al. 2003), however the mapping uncertainty using topographic maps is much higher than satellite images and therefore we assumed the uncertainty error as twice of that calculated for the Landsat TM, i.e. 16 m.

3.3 Glacier volume estimation

Volume of the glaciers was estimated using slope dependent thickness approach (Haeberli and Hoelzle 1995; Frey et al. 2014). Surface slope of the glacier is the prime factor that governs the thickness of glacier ice, which means that steeper glaciers tend to have thinner ice and vice versa (Linsbauer et al. 2009). However, it also depends on various other factors such as plasticity of the glacier, basal sliding and horizontal to vertical extent ratio of the glaciers. Therefore, simplifications are added to the force equations in the slope dependent method for estimation of the glacier volume as has been discussed in details by Linsbauer et al. (2012) and Frey et al. (2014). Subsequently, the thickness d (m) of a glacier is calculated by using the following equation.

$$d = \frac{\tau}{\rho g f sin\alpha} \quad (3)$$

where ρ is the density of glacier ice (900 kg/m³), g is acceleration due to gravity (9.81 m/s²) and f is the shape factor (0.8) constant for valley glaciers. The shape factor f is basically related to the friction of a glacier body with its valley walls and is the ratio between cross-sectional area of a glacier and its perimeter (Paul and Linsbauer 2012), α is the mean slope of a glacier. The basal shear stress τ (Pa) is a function of elevation range and is calculated by the Eq. (4) (Haeberli and Hoelzle 1995), Δh is elevation range in km and the maximum value for τ is 1.5 bars for Δh equal to or larger than 1.6 km.

$$\tau = 0.005 + 1.598\Delta h - 0.435\Delta h^2 \quad (4)$$

The slope α for the year 1962 was calculated from the SOI topographic maps using elevation range ΔH and glacier length l

$$\alpha = arctan\frac{\Delta H}{l} \quad (5)$$

The glacier slope for the year 2013 was computed from the ASTER GDEM v.2. Generally

Table 2 Slope Correction factor for different Glacier sizes

Glacier Area (km²)	Slope Correction factor
> 20	-10
5 - 20	-5
< 5	-2.5

the slope calculated from the DEM in GIS environment is higher as compared to the slope calculated through arctan method, therefore a correction factor was introduced to reduce the uncertainty (Frey et al. 2014), as shown in Table 2. Furthermore, Frey et al. (2014) suggested that the estimated depth along the centre flow line could be extrapolated to the entire glacier area by multiplying a constant $\pi/4$ to the mean thickness assuming the semi-elliptic cross-sectional geometry of a glacier.

Nonetheless, it is important to mention here that the accuracy of the above method could not be estimated due to the lack of Ground Penetrating Radar (GPR) instrument that could have been used to measure the glacier depths in the field. However, Farinotti et al. (2016) compared the performance of different approaches using surface characteristics to estimate the ice thickness of glaciers and ice caps. The Glabtop model (Linsbauer et al. 2012), which uses the same principal for measuring glacier depth as slope-dependent method, has performed comparatively better than many other models that were compared in their study, with the average deviation of -16±46%, from the GPR measurements of glacier thickness.

3.4 Statistical analysis of Hydro-Meteorological Data

The time series of temperature (T_{max} and T_{min}), precipitation (1980-2010) and streamflow data (1971-2012) was analysed statistically using non-parametric Mann-Kandall test, to determine the magnitude and significance of the trends in the data (Mann 1945; Kendall 1975; Hamed 2008). Glacier melt is expected to be the dominant component in streamflow during the late summer months (July, August and September). Thus, detailed analyses of the hydro-meteorological variables recorded during the period were carried out using the standard statistical methods. The Mann-Kendall statistics S, $V(S)$ and standardized test statistics Z were calculated using the following mathematical equations:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sig(X_j - X_i),$$

$$sgn(X_j - X_i) = \begin{cases} +1 & if\ (X_j - X_i) > 0 \\ 0 & if\ (X_j - X_i) = 0 \\ -1 & if\ (X_j - X_i) < 0, \end{cases}$$

$$V(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5)\right]$$

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}} & if S > 0 \\ 0 & if S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}} & if S < 0. \end{cases} \quad (6)$$

X_i and X_j represents the time series observations in chronological order, n is the length of time series, t_p is the number of ties for p th value, and q is the number of tied values. Upward trend in the hydrologic time series is indicated by the positive Z values; negative Z values indicate a negative trend. Statistically significant trend exists in hydrological time series if $|Z| > Z_{1-\alpha/2}$ and H_0 is rejected. The critical value of $Z_{1-\alpha/2}$ is 1.96 (from the standard normal table) for the p = 0.05.

4 Results and Discussion

4.1 Glacier area changes (1962-2013)

Analysis of the multi-temporal data shows that the glacier area of the 37 glaciers in the Lidder valley has significantly reduced from 39.76 km² in 1962 to 28.27 km² in 2013, a decrease of 11.49 km² of glacier area i.e. 28.89±0.1% in 51 years at the rate of 0.57±0.002% yr⁻¹. The glacier area change was 15.14±0.15% (1962 to 1992), 8.5±0.2% (1992 to 2000) and for the period between 2000 and 2013 the glacier recession was 8.4±0.11%. The glacier extent in different years is shown in Figure 2. Several studies have reported a higher melting rate of glaciers in the Himalayan regions compared to the other parts of world, with maximum recession rate reported from the state of Jammu and Kashmir (Bolch et al. 2012; Kääb et al. 2012). Moreover, a significant recession of the total glacier

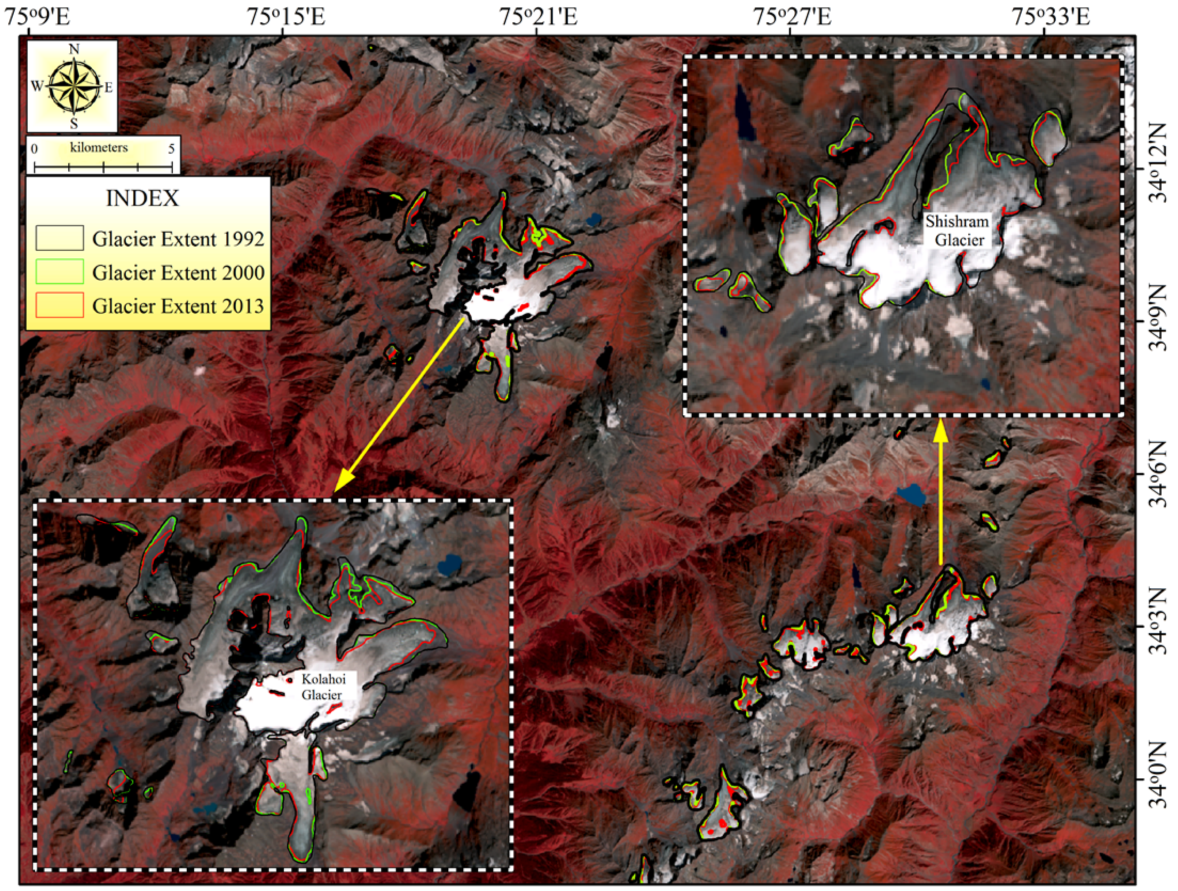

Figure 2 Glacier Extent in 1992, 2000 and 2013 in the Lidder valley; and zoomed view of Kolahoi and Shishram Glaciers

length was observed in the region since 1962. The total length of the 37 studied glaciers in 1962 was 63 km which reduced to 54.80 km in 2013 i.e. approximately a shortening of 8.20 km during the last 51 years. Furthermore, fragmentation and disappearance of small and lower elevation glaciers is a common phenomenon since 1960s in the Himalayan region (Byers 2007; Bhambri et al. 2011). Pertinently, four of the 37 investigated glaciers *G-66, G-123, G-124 and G-132,* have fragmented and one glacier (*G-75*) has vanished during the observation period, thus effectively the number of glaciers in the study area has increased. The number of glaciers and glacier area over the time is given in the Table 3.

To have a better understanding of the glacier recession observed in the area, the investigated glaciers were grouped into three categories based on their size. The changes in areal extent of the glaciers in each category are given in Table 4. Smaller glaciers (size < 1 km²) have shown the maximum recession and lost 56.81±0.13% of their area between 1962 and 2013. Contrary, the medium sized glaciers (1-5 km²) and the large glaciers (area > 5 km²) have lost 23.78±0.22% and 20.74±0.14% of their area respectively since 1962. It is pertinent to mention here that the maximum number of investigated glaciers in the study area are less than <1 km² in the size. Kumar et al.

Table 3 Number of glaciers and the total glacier area in different years in Lidder valley

Year	Sensor/Source	No. of Glaciers	Area Extent (km²)
1962	Topographic maps	37	39.76
1992	Landsat TM	40*	33.74
2000	Landsat ETM+	40	30.87
2013	Landsat OLI	41*	28.27

Note: * fragmentation of glaciers.

Table 4 Glacier area loss (%) under different size categories (1962-2013)

Glacier Size Category	Area loss (%)
Less than 1 km²	56.81
1-5 km²	23.78
Above 5 km²	20.74

(2009) reported that smaller glaciers are more vulnerable to changing climate. Furthermore, smaller glaciers have comparatively small accumulation area which in turn is reflected in their negative mass balance (Huss and Farinotti 2012). It is evident from Figure 3a that smaller glaciers have lost more area than larger glaciers in the study area and thus seem to be more sensitive to the climate change (Grudd 1990).

Various studies suggest that altitude of a glacier determines its shrinking pattern and lower altitude glaciers tend to recede more rapidly (Byers 2007; Fujita and Nuimura 2011; Wang et al. 2015). Therefore, the impact of the snout altitude on glacier recession was assessed by categorising glaciers on the basis of their snout altitude. The snout altitude of glaciers in 1962 ranged from 3430 to 4420 m a.s.l. and were categorised into two altitudinal classes, <4000 m a.s.l. and >4000 m a.s.l. Out of the 37 glaciers, 13 glaciers had snout altitudes at <4000 m a.s.l. Among these low snout altitude glaciers, 7 glaciers were small in size (area < 1 km^2), 4 glaciers were medium sized (1-5 km^2) and 2 glaciers were large sized (area > 5 km^2). The small glaciers in <4000 m a.s.l. category have lost 57.44±0.5%, medium sized glaciers lost 23.35±0.33% and the large glaciers lost 20.74±0.14% of the area from 1962 to 2013. Further, the combined area loss of glaciers with snout altitudes <4000 m a.s.l. from 1962 to 2013 was 23.94±0.1%. However, in the >4000 m a.s.l. snout altitude category, there are 24 glaciers including 22 small sized glaciers (area <1 km^2) and 2 medium sized glaciers (area 1-5 km^2). The combined recession observed for the glaciers with >4000 m a.s.l. snout altitude is 44.84±0.14%. The small-sized glaciers in the >4000 m a.s.l. have lost 56.59±0.18% and the medium-sized glaciers in the attitude category have lost 24.75±0.7% area. It is evident from the results that the size of the glaciers predominantly controls the glacier recession process irrespective of the snout or minimum altitude of glaciers (Figure 3a and 3b). Contrary, in other western Himalayan basins like Tirungkhad and Chandra basins lower altitude glaciers have receded more rapidly than the higher altitude glaciers (Mir et al. 2014; Tawde et al. 2017). This discrepancy could be explained by the fact that a large number of smaller glaciers are lying at higher altitudes in the Lidder valley, which are showing higher recession, as the small glaciers are more sensitive to climatic change (Basnett et al.

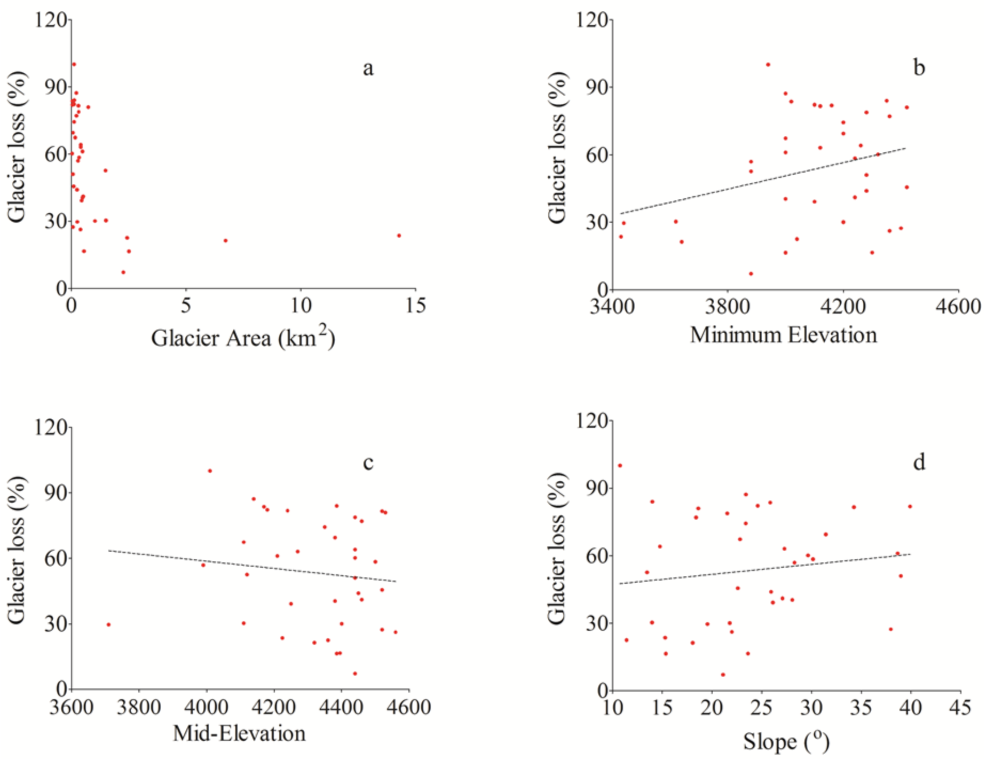

Figure 3 Scatter plots (a) Glacier area loss (%) vs Glacier Area, (b) Glacier area loss (%) vs Minimum Elevation (c) Glacier area loss (%) vs Mid-Elevation and (d) Glacier area loss (%) vs Slope (°).

2013; Colucci and Guglielmin 2015). The number of smaller glaciers at higher altitudes (>4000 m) is thrice than the number at the lower altitude (<4000 m a.s.l.). Other glacier characteristics like mid-elevation and mean slope of glaciers did not significantly affect the receding pattern of the glaciers in the study area, as is evident from Figure 3c and 3d. Thus, it is apparent that the pattern of glacier recession in the Lidder valley is more dominated by the size of glaciers than any topographic factor. Furthermore, the aspect of the investigated glaciers was used to evaluate its impact on glacier melting as the glacier aspect has been reported to affect the glacier recession (Wang et al. 2009). The dominant aspect of most of the glaciers varies between Northeast, North and Northwest. Results showed that the south facing glaciers have lost more area than the north facing glaciers as depicted in Figure 4. This observation is similar to various other studies carried out in different Himalayan glaciated basins (Deota et al. 2011; Bhambri et al. 2011).

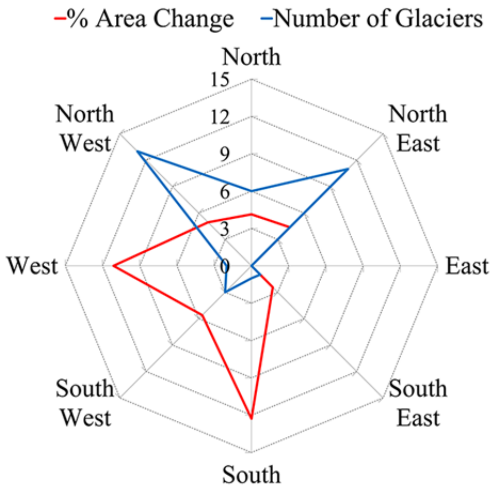

Figure 4 Number of glaciers with their dominant aspect and area loss (%) (1962-2013).

The glacier recession pattern observed in the Lidder valley was compared with the studies from adjacent regions e.g. Greater Himalayan, Zanskar and Ladakh ranges (Nathawat et al 2009; Schmidt and Nüsser 2012, 2017; Chudley et al 2017). It is evident that the glacier recession rate observed in the Lidder valley is higher than the recession rate in the adjacent Himalayan regions (Table 5) but the patterns of recession are similar (Kulkarni et al 2007). According to Schmidt and Nusser (2012), small glaciers (< 1 km^2) from Kang Yatze Massif in Trans-Himalayas have receded at higher rate (0.5% yr^{-1}) compared to the larger glaciers. However, small glaciers (< 1 km^2) in the Lidder valley have receded at much higher rate (1.1% yr^{-1}) than the glaciers of same size in Kang Yatze region. Similarly, in Garhwal Himalayas, glaciers < 1 km^2 in size have receded at 0.5% yr^{-1} during the period from 1968 to 2006 (Bhambri et al. 2011), and much lower glacier recession rate has been reported for the debris-covered glaciers (0.1% yr^{-1}) in the Khumbu Himalayas (Bolch et al. 2008).

Higher recession rate of glaciers, particularly of the small glaciers, in the Lidder valley could be partly attributed to the lower mean altitude of glaciers in the Lidder valley compared to the glaciers in its proximal regions. Moreover, the changing climatic parameters including the higher rate of increasing temperature and changing form of precipitation (snow to rain) could be the other possible reasons for higher glacier recession rates observed in the Lidder valley (Rashid et al. 2017; Romshoo et al. 2015). Furthermore, Bhat et al. (2017) have ascribed the faster melting of the

Table 5 Glacier area changes (%) and recession rate (% yr^{-1}) in different Himalayan ranges and basins

Authors	Region/Basin		Glaciers monitored	Observation period	Area change (%)	Recession rate (% yr^{-1})
Nathawat et al. (2008)	Doda Valley Zanskar		-	1962-2001	-18.0	0.46
Schmidt and Nüsser (2012)	Kang Yatze Massif		121	1969-2010	-14.3	0.3
Schmidt and Nüsser (2017)	Central Ladakh Range	Phutse Glacier	-	1969-2016	-18.9	0.4
		Nangtse Glacier	-		-13.3	0.28
		Hemis Shukpachan catchment*	-		-38	0.8
	Stok Range		-		-22.39	0.47
	Lungser Range		-		-17.7	0.37
Koul et al. (2016)	Drass Area		-	1965-2013	-16.63	0.34
Chudley et al. (2017)	Ladakh Range		657	1991-2014	-12.8	0.55
Current Study	Lidder Valley (Kashmir Basin)		37	1962-2013	-28.89	0.57

Note: *Including perennial snowpacks.

glaciers to the higher concentration of observed Black Carbon (BC) in the Kashmir Himalayas. Besides this, Ali et al. (2017) have reported that the glaciers in Kashmir basin are relatively clean glaciers or are feebly covered by debris, which could be one among the various reasons for the enhanced glacier melting observed in the Lidder valley.

4.2 Glacier volume changes (1962-2013)

Surface area is one of the indicators of the ice volume stored in a glacier, thus larger the area, more is the volume of glacier (Meier and Bahr 1996). Volumetric estimates of the investigated 37 glaciers show that the total volume has considerably reduced from 1.73 km^3 in 1962 to 1.39 km^3 in 2013, a total loss of ~0.34 km^3 (19.65±0.069%) at the rate of ~0.38 ±0.001% yr^{-1} during the past 51 years. The combined glacier volume changes in different glacier-size categories from 1962 to 2013 are given in Table 6. Estimates show that the volume of small sized glaciers (area <1 km^2) has reduced by ~56±0.13% while as the large-sized glaciers (area >5 km^2) have lost only ~10±0.07% of their volume during the last 51 years. Again, this indicates the high susceptibility of the smaller sized glaciers to the changing climate. The large glaciers have comparatively larger accumulation area and have tributary glaciers, which contribute ice mass to the main glacier, thus slowing down the overall glacier retreat (Nainwal et al. 2008).

4.3 Trends in the Climate Data

Temperature and precipitation data recorded at Pahalgam meteorological station from 1980-2012 was analyzed to investigate the trends in the climatic parameters. The records were analyzed for significance of the trends using Mann-Kendall test (Yue et al. 2002; Hamed 2008). The analyses of mean yearly temperature showed a statistically significant increasing trend at a < 0.01 and the Z statistic value was more than 2.576, which indicates the high significance of the increasing trend. Strong and statistically significant increasing trends exist in both mean annual minimum and maximum temperature records at a < 0.01 as shown in Figure 5. This indicates that a positive relationship exists between the observed glacier recession and the increasing trend of temperatures observed in the study area.

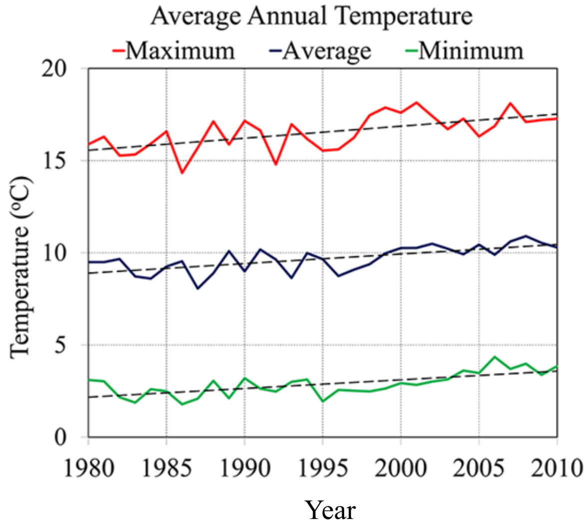

Figure 5 Inter-annual variation and trends in annual minimum, maximum and average temperature recorded at Pahalgam station (1980-2010).

Precipitation is an important climatic parameter that controls the overall health of a glacier. In Lidder valley, statistical analysis of the precipitation records (1980-2010) showed a non-significant decreasing trend (Figure 6). However, Romshoo et al. (2015) stated that there is a change in the form of precipitation in the valley from snow to rain; particularly during the winter months (DJF), which is one of the important factors that describes the negative mass balance of glaciers in the Lidder basin (Murtaza and Romshoo 2017). The decreasing winter snowfall observed in the region together with the increasing temperatures leads to the rapid disappearance of seasonal snow cover in Kashmir Himalaya (Singh and Kumar 1997; Dar et al. 2014). Consequently, the early disappearance of the winter snow could accelerate the glacier melting by exposing the glacier surface

Table 6 Glacier volume changes in different size categories from 1962 to 2013

Size Category	Ice Volume (1962)	Ice Volume (2013)	Volume Change (km^3)	Change in %
Small (< 1 km^2)	0.11	0.05	0.06	56.59
Medium (1-5 km^2)	0.45	0.29	0.16	35.34
Large (> 5 km^2)	1.17	1.05	0.11	9.82
Total	1.73	1.39	0.34	19.65

to direct sunlight for longer periods. Contrary to the total annual precipitation, the seasonal precipitation records show that the precipitation in the late summer season (July August and September) for the last 30 years has increased significantly (Figure 7). This indicates the complexity of the changing climate in the region, as one of the important meteorological parameter like precipitation is not showing uniform response to the changing climate in the region.

4.4 Trends in Hydrological Data

The time series of streamflow data of the Lidder river for the last 41 years (1971-2012) was statistically analyzed to determine and understand the changes in the streamflow regime. The glacier-melt is assumed to be the dominant component in the streamflows of Lidder river in the late summers (JAS) because most of the seasonal snow in the basin depletes significantly by the end of June (Dar et al. 2014). Consequently, the streamflow during the summers is dominated by glacier-melt and the runoff from the precipitation events. The Mann-Kendal analysis of the late summer discharge data (JAS) for the last four decades in the Lidder valley showed a non-significant decreasing trend with a significance level of 90% (Figure 8). A comprehensive analysis of the streamflow data of JAS months from 1971-2012 showed that the discharge in this season has significantly increased till mid 1990s and significantly decreased thereafter, even though the precipitation since mid-1990s for the JAS months has increased significantly (Figure 9). The decreasing streamflows observed under the increasing precipitation is primarily due to the significant depletion of the glacier cover and mass in the valley during the last 5-7 decades. Recent studies have shown that due to the accelerated melting of glaciers, glacier-fed streams observe an increase in the discharge for a certain period of time and subsequently show a decrease with the reducing ice-mass (Rees and Collins 2006; Thayyen and Gergan 2010).

The findings therefore suggest that the enhanced melting of the glaciers in the Lidder valley have significantly contributed to the increasing streamflows during the first three decades (1971-2000) of the observation period.

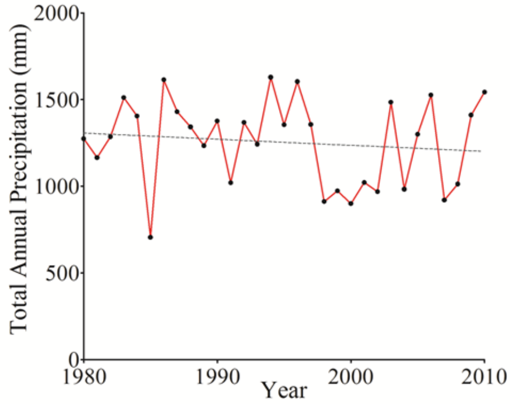

Figure 6 Inter-annual variation and trend in Total Annual Precipitation records at Pahalgam station (1980-2010). Dotted line is the linear trend.

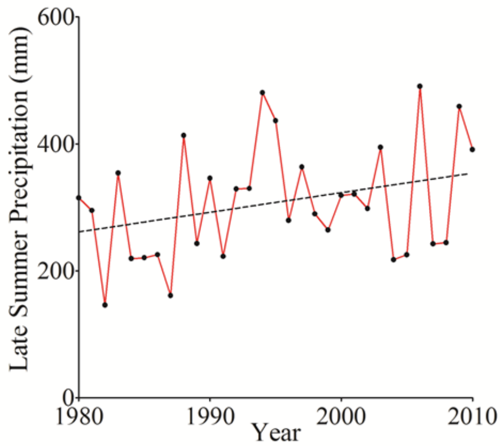

Figure 7 Trend in total Precipitation of late summer months (July, August and September) recorded at Pahalgam station from 1980-2010.

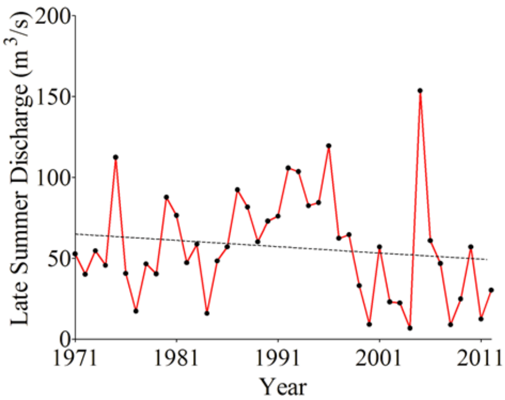

Figure 8 Inter-annual variation and trend in average summer discharge records measured at Batakote gauging station.

With the significant loss of the ice mass (19.65%), the contribution of glacier-melt to the streamflow reduced thereafter as reflected by the depleting

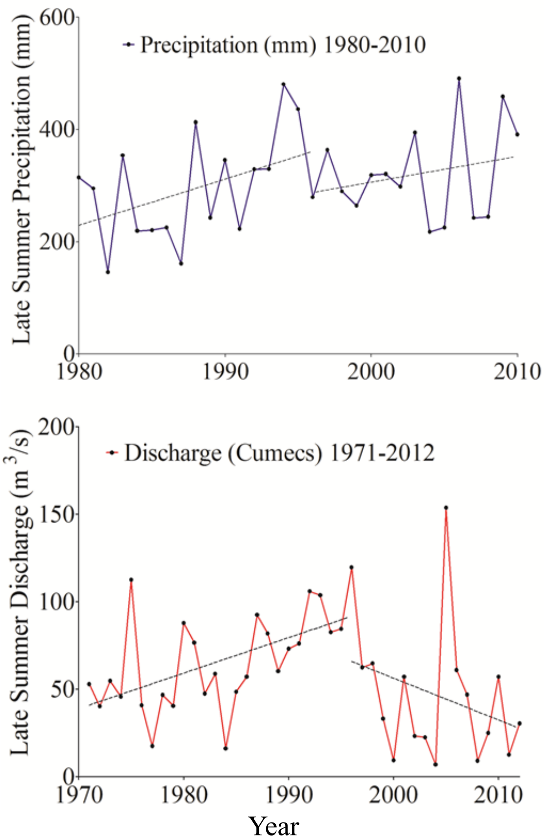

Figure 9 Contrasting trends in summer precipitation (1980-2010) and summer discharge (1971-2012).

streamflow of the Lidder river. Thus, the observed decrease in the streamflows of Lidder river is a clear indication of the response to the shrinking glaciers under changing climate change in the region. Moreover, the change-point in the discharge data was found in the mid-1990s. This suggests that the streamflows have peaked in the valley in mid-nineties due to the enhanced glacier-melt and might have reached the tipping point wherefrom the streamflows will keep decreasing with the further reduction in the contribution from the glacier-melt under changing climate.

5 Conclusions

From the statistical analyses of the times series of the climatic data, it was observed that the temperature, both T_{max} and T_{min}, has significantly increased over the area since the last 30 years. It was observed that the overall precipitation during the period 1980-2010 has not significantly changed, however a significant increasing trend was observed in the precipitation during summer season indicating the complexity of the changing climate in the area. Glaciers in the valley are in the retreating state since 1962 (a loss of 28.89±0.1% from 1962-2013), with the variable recession rates observed during different observational periods (1962-1992, 1992-2000 and 2000-2013). From 1962 to 1992, glaciers lost 15.14% ±0.15% of their area, with an annual retreating rate of 0.51±0.005% yr^{-1}. The observation period from 1992 to 2000 witnessed a glacial area loss of 8.50±0.20% at the rate of 1.1±0.02% yr^{-1} and 8.40±0.11% of glacier area loss was observed from 2000 to 2013 at the rate of 0.65±0.009% yr^{-1}. Furthermore, the volume of mapped glaciers in the Lidder valley has reduced by ~19.65±0.069% from 1962 to 2013. The shrinking of glaciers in the region is due to the increasing temperatures and the change in the form of precipitation (from snow to rain) observed in the region during winters. The streamflow shows an overall decreasing trend in the summer months; however an increasing trend was observed in the streamflow from 1971 to 1995 primarily due to the enhanced glacier-melting during the period. Conversely, a significant decreasing streamflow was observed from 1996 to 2012, despite the increasing summer precipitation, mainly due to the reduced contribution of the glacier melt to the streamflows from the depleted ice-mass in the valley i.e. ~19.65% during the last five decades. The study suggests that the observed changes in the climate, the shrinking of glaciers and the depleting streamflows, if continuing in the future, will adversely affect the availability of water in the study area, especially during the summers when it is needed the most.

Acknowledgement

The research work was conducted as part of the Department of Science and Technology (DST), Government of India sponsored national research project titled “Himalayan Cryosphere: Science and Society” The financial assistance received from the Department under the project to accomplish this research is thankfully acknowledged. The authors express gratitude to the two anonymous reviewers for their valuable comments and suggestions on the earlier versions of the manuscript that greatly improved the content and structure of this manuscript.

References

Ali I, Shukla A, Romshoo SA (2017) Assessing linkages between spatial facies changes and dimensional variations of glaciers in the upper Indus Basin, western Himalaya. Geomorphology. https://doi.org/10.1016/j.geomorph.2017.01.005

Anderson B, Mackintosh A (2006) Temperature change is the major driver of late-glacial and Holocene glacier fluctuations in New Zealand. Geology 34: 121-124. https://doi.org/10.1130/G22151.1

Bahuguna IM, Kulkarni, AV, Nayak S, et al. (2007) Himalayan glacier retreat using IRS 1C PAN stereo data. International Journal of Remote Sensing 28: 437-442. https://doi.org/10.1080/01431160500486674

Bajracharya SR, Mool PK, Shrestha BR (2008) Global climate change and melting of Himalayan glaciers. Melting glaciers and rising sea levels: Impacts and implications. pp 28-46.

Basnett S, Kulkarni AV, Bolch T (2013) The influence of debris cover and glacial lakes on the recession of glaciers in Sikkim Himalaya, India. Journal of Glaciology 59: 1035-46. https://doi.org/10.3189/2013JoG12J184

Bhambri R, Bolch T, Chaujar RK, et al. (2011) Glacier changes in the Garhwal Himalaya, India, from 1968 to 2006 based on remote sensing. Journal of Glaciology 57: 543-556. https://doi.org/10.3189/002214311796905604

Bhat MA, Romshoo SA, Beig G (2017) Aerosol black carbon at an urban site-Srinagar, Northwestern Himalaya, India: Seasonality, sources, meteorology and radiative forcing. Atmospheric Environment 165: 336-48. https://doi.org/10.1016/j.atmosenv.2017.07.004

Bolch T, Kamp U (2006) Glacier mapping in high mountains using DEMs, Landsat and ASTER data. Grazer Schriften der Geographie und Raumforschung 41: 37-48.

Bolch T, Buchroithner M, Pieczonka T, et al. (2008) Planimetric and volumetric glacier changes in the Khumbu Himal, Nepal, since 1962 using Corona, Landsat TM and ASTER data. Journal of Glaciology 54: 592-600. https://doi.org/10.3189/002214308786570782

Bolch T, Menounos B, Wheate R (2010) Landsat-based inventory of glaciers in western Canada, 1985–2005. Remote sensing of Environment 114: 127-37. https://doi.org/10.1016/j.rse.2009.08.015

Bolch T, Kulkarni A, Kääb A, et al. (2012) The state and fate of Himalayan glaciers. Science 336: 310-314. https://doi.org/10.1126/science.1215828

Byers AC (2007) An assessment of contemporary glacier fluctuations in Nepal's Khumbu Himal using repeat photography. Himalayan Journal of Sciences 4: 21-26. https://doi.org/10.3126/hjs.v4i6.979

Chudley TR, Miles ES, Willis IC (2017) Glacier characteristics and retreat between 1991 and 2014 in the Ladakh Range, Jammu and Kashmir. Remote Sensing Letters 8: 518-27. https://doi.org/10.1080/2150704X.2017.1295480

Cogley JG (2016) Glacier shrinkage across High Mountain Asia. Annals of Glaciology 57: 41-49. https://doi.org/10.3189/2016AoG71A040

Colucci RR, Guglielmin M (2015) Precipitation–temperature changes and evolution of a small glacier in the southeastern European Alps during the last 90 years. International Journal of Climatology 35: 2783-2797. https://doi.org/10.1002/joc.4172

Dar RA, Romshoo SA (2012) Estimating daily streamflow in the glacierized mountainous Kashmir Himalayan basin. Journal of Research and Development 12: 113-130.

Dar RA, Rashid I, Romshoo SA, et al. (2014) Sustainability of winter tourism in a changing climate over Kashmir Himalaya. Environmental Monitoring Assessment 186: 2549-2562. https://doi.org/10.1007/s10661-013-3559-7

Deota BS, Trivedi YN, Kulkarni AV, et al. (2011) RS and GIS in mapping of geomorphic records and understanding the local controls of glacial retreat from the Baspa Valley, Himachal Pradesh, India. Current Science (Bangalore) 100: 1555-1563.

Dobhal DP, Pratap B (2015) Variable response of glaciers to climate change in Uttarakhand Himalaya, India. In: Dynamics of Climate Change and Water Resources of Northwestern Himalaya. Springer International Publishing. pp 141-150. https://doi.org/10.1007/978-3-319-13743-8_12

Farinotti D, Brinkerhoff D, Clarke GKC et al. (2017) How accurate are estimates of glacier ice thickness? Results from ITMIX, the Ice Thickness Models Intercomparison Experiment. The Cryosphere 11: 949-970. https://doi.org/10.5194/tc-11-949-2017

Fujita K, Nuimura T (2011) Spatially heterogeneous wastage of Himalayan glaciers. Proceedings of the National Academy of Sciences 108: 14011-14014. https://doi.org/10.1073/pnas.1106242108

Frey H, Machguth H, Huss M, et al. (2014) Estimating the volume of glaciers in the Himalayan–Karakoram region using different methods. The Cryosphere 8: 2313-2333. https://doi.org/10.5194/tc-8-2313-2014

Grudd H (1990) Small glaciers as sensitive indicators of climatic fluctuations. Geografiska Annaler A 72: 119-123. https://doi.org/10.1080/04353676.1990.11880305

Haeberli W, Hölzle M (1995) Application of inventory data for estimating characteristics of and regional climate-change effects on mountain glaciers: a pilot study with the European Alps. Annals of Glaciology 21: 206-212. https://doi.org/10.3189/S0260305500015834

Hall DK, Bayr KJ, Schöner W, et al. (2003) Consideration of the errors inherent in mapping historical glacier positions in Austria from the ground and space (1893–2001). Remote Sensing of Environment 86: 566-577. https://doi.org/10.1016/S0034-4257(03)00134-2

Hamed KH (2008) Trend detection in hydrologic data: the Mann–Kendall trend test under the scaling hypothesis. Journal of Hydrology 349: 350-363. https://doi.org/10.1016/j.jhydrol.2007.11.009

Huss M, Farinotti D (2012) Distributed ice thickness and volume of all glaciers around the globe. Journal Geophysical Research: Earth Surface 117(F4). https://doi.org/10.1029/2012JF002523

Immerzeel WW, Droogers P, De Jong SM, et al. (2009) Large-scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing. Remote Sensing of Environment 113: 40-49. https://doi.org/10.1016/j.rse.2008.08.010

Immerzeel WW, Van Beek LP, Bierkens MF (2010) Climate change will affect the Asian water towers. Science 328: 1382-1385. https://doi.org/10.1126/science.1183188

Intergovernmental Panel on Climate Change (2014) Climate Change 2014-Impacts, Adaptation and Vulnerability: Regional Aspects. Cambridge University Press.

Kääb A, Berthier E, Nuth C, et al. (2012) Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas. Nature 488: 495-498. https://doi.org/10.1038/nature11324

Kendall M (1975) Multivariate analysis. Charles Griffin.

Kulkarni AV, Karyakarte Y (2013) Observed Changes in the Himalayan glaciers. Current Science 106: 237-244.

Kumar R, Areendran G, Rao P (2009) Witnessing change: glaciers in the Indian Himalayas. Pilani, WWF-India and Birla Institute of Technology 2.

Linsbauer A, Paul F, Hoelzle M, et al. (2009) The Swiss Alps without glaciers–a GIS-based modelling approach for reconstruction of glacier beds. Proceedings of Geomorphometry 243-247.

Linsbauer A, Paul F, Haeberli W (2012) Modeling glacier thickness distribution and bed topography over entire mountain ranges with GlabTop: application of a fast and robust approach. Journal of Geophysical Research: Earth Surface 117(F3). https://doi.org/10.1029/2011JF002313

Le Bris R, Paul F (2013) An automatic method to create flow lines for determination of glacier length: a pilot study with Alaskan glaciers. Computers and Geosciences 52: 234-245. https://doi.org/10.1016/j.cageo.2012.10.014

Mann HB (1945) Nonparametric tests against trend. Econometrica: Journal of the Econometric Society 13: 245-259. https://doi.org/10.2307/1907187

Meier MF, Bahr DB (1996) Counting glaciers: use of scaling methods to estimate the number and size distribution of the glaciers of the world. In: Glaciers, Ice Sheets and Volcanoes: a tribute to Mark F. Meier. CRREL Special Report 96: 89-94.

Mir RA, Jain SK, Saraf AK, et al. (2014) Glacier changes using satellite data and effect of climate in Tirungkhad basin located in western Himalaya. Geocarto International 29: 293-313. https://doi.org/10.1080/10106049.2012.760655

Mishra AK, Rafiq M (2017) Analyzing snowfall variability over two locations in Kashmir, India in the context of warming climate. Dynamics of Atmospheres and Oceans 79: 1-9. https://doi.org/10.1016/j.dynatmoce.2017.05.002

Murtaza KO, Romshoo SA (2017) Recent glacier changes in the Kashmir Alpine Himalayas, India. Geocarto International 32: 188-205. https://doi.org/10.1080/10106049.2015.1132482

Muslim M, Romshoo SA, Rather AQ (2015) Paddy crop yield estimation in Kashmir Himalayan rice bowl using remote sensing and simulation model. Environmental Monitoring and Assessment 187: 316. https://doi.org/10.1007/s10661-015-4564-9

Nainwal HC, Negi BDS, Chaudhary M, et al. (2008) Temporal changes in rate of recession: Evidences from Satopanth and Bhagirath Kharak glaciers, Uttarakhand, using Total Station Survey. Current Science 94: 653-660.

Nathawat MS, Pandey AC, Rai PK, et al. (2008) Spatio-temporal dynamics of glaciers in Doda valley, Zanskar Range, Jammu & Kashmir, India. In Proceedings of the International Workshop on Snow, Ice, Glacier and Avalanches, IIT Bombay Vol. 256264.

Oerlemans J (1994) Quantifying global warming from the retreat of glaciers. Science-AAAS-Weekly Paper Edition-including Guide to Scientific Information 264: 243-244. https://doi.org/10.1126/science.264.5156.243

Paul F, Kääb A, Rott H, et al. (2009) GlobGlacier: a new ESA project to map the world's glaciers and ice caps from space. EARSeL eProceedings 8: 11-25.

Paul F, Linsbauer A (2012) Modeling of glacier bed topography from glacier outlines, central branch lines, and a DEM. International Journal of Geographical Information Science 26: 1173-1190. https://doi.org/10.1080/13658816.2011.627859

Paul F, Barrand NE, Baumann S, et al. (2013) On the accuracy of glacier outlines derived from remote-sensing data. Annals of Glaciology 54: 171-182. https://doi.org/10.3189/2013AoG63A296

Pandey AC, Ghosh S, Nathawat MS (2011) Evaluating patterns of temporal glacier changes in Greater Himalayan Range, Jammu and Kashmir, India. Geocarto International 26: 321-338. https://doi.org/10.1080/10106049.2011.554611

Pellicciotti F, Stephan C, Miles E, et al. (2015) Mass-balance changes of the debris-covered glaciers in the Langtang Himal, Nepal, from 1974 to 1999. Journal of Glaciology 61: 373-386. https://doi.org/10.3189/2015JoG13J237

Racoviteanu AE, Paul F, Raup B, et al (2009) Challenges and recommendations in mapping of glacier parameters from space: results of the 2008 Global Land Ice Measurements from Space (GLIMS) workshop, Boulder, Colorado, USA. Annals of Glaciology 50: 53-69. https://doi.org/10.3189/172756410790595804

Rashid I, Romshoo SA, Abdullah T (2017) The recent deglaciation of Kolahoi valley in Kashmir Himalaya, India in response to the changing climate. Journal of Asian Earth Sciences 138: 38-50. https://doi.org/10.1016/j.jseaes.2017.02.002

Rashid I, Romshoo SA, Chaturvedi RK, et al. (2015) Projected climate change impacts on vegetation distribution over Kashmir Himalayas. Climatic Change 132: 601-613. https://doi.org/10.1007/s10584-015-1456-5

Rees HG, Collins DN (2006) Regional differences in response of flow in glacier-fed Himalayan rivers to climatic warming. Hydrological Processes 20(10): 2157-69. https://doi.org/10.1002/hyp.6209

Romshoo SA, Dar RA, Rashid I, et al. (2015) Implications of shrinking cryosphere under changing climate on the streamflows in the Lidder catchment in the Upper Indus Basin, India. Arctic Antarctic and Alpine Research 47: 627-644. https://doi.org/10.1657/AAAR0014-088

Salerno F, Thakuri S, Guyennon N, et al. (2016) Glacier melting and precipitation trends detected by surface area changes in Himalayan ponds. The Cryosphere 10: 1433-1448. https://doi.org/10.5194/tc-10-1433-2016

Schmidt S, Nüsser M (2012) Changes of high altitude glaciers from 1969 to 2010 in the Trans-Himalayan Kang Yatze Massif, Ladakh, northwest India Arctic, Antarctic, and Alpine Research 44: 107-121. https://doi.org/10.1657/1938-4246-44.1.107

Schmidt S, Nüsser M (2017) Changes of High Altitude Glaciers in the Trans-Himalaya of Ladakh over the Past Five Decades (1969–2016). Geosciences 7: 27. https://doi.org/10.3390/geosciences7020027

Singh P, Kumar N (1997) Impact assessment of climate change on the hydrological response of a snow and glacier melt runoff dominated Himalayan river. Journal of Hydrology 193: 316-350. https://doi.org/10.1016/S0022-1694(96)03142-3

Svoboda F, Paul F (2009) A new glacier inventory on southern Baffin Island, Canada, from ASTER data: I. Applied methods, challenges and solutions. Annals of Glaciology 50(53): 11-21. https://doi.org/10.3189/172756410790595912

Tawde SA, Kulkarni AV, Bala G (2017) An estimate of glacier mass balance for the Chandra basin, western Himalaya, for the period 1984–2012. Annals of Glaciology 58: 1-11. https://doi.org/10.1017/aog.2017.18

Thayyen RJ, Gergan JT (2010) Role of glaciers in watershed hydrology: a preliminary study of a Himalayan catchment. The Cryosphere 4: 115-128. https://doi.org/10.5194/tc-4-115-2010

Wang Y, Hou S, Liu Y (2009) Glacier changes in the Karlik Shan, eastern Tien Shan, during 1971/72–2001/02. Annals of Glaciology 50: 39-45. https://doi.org/10.3189/172756410790595877

Wang P, Li Z, Luo S, et al. (2015) Five decades of changes in the glaciers on the Friendship Peak in the Altai Mountains, China: Changes in area and ice surface elevation. Cold Regions Science and Technology 116: 24-31. https://doi.org/10.1016/j.coldregions.2015.04.002

Yue S, Pilon P, Cavadias G (2002) Power of the Mann–Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. Journal of Hydrology 259: 254-271. https://doi.org/10.1016/S0022-1694(01)00594-7