

Comparative Assessment of Volume Change in Kolahoi and Chhota Shigri Glaciers, Western Himalayas, Using Empirical Techniques

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Abstract: Volume change in glaciers across the world is an established fact; however, response of Himalayan glaciers to climate change is not well understood. Looking at the importance of volumetric information of glaciers, glaciologists use different methods of volume estimation e.g., geophysical methods including GPR surveys, seismic profiling and tomography; glaciological methods by installing stakes and empirically established scaling methods. However, considering the difficulty in field measurements associated with Himalayan glaciers, indirect assessment techniques are being used widely. The objective of this study was to compare the response of two most studied western Himalayan glaciers i.e. Kolahoi glacier and Chhota Shigri glacier over the last three to four decades using empirical relationships of glacier volume estimation. The factors such as glacier length, area and slope were extracted from satellite data and digital elevation models. Glacier area change for Kolahoi glacier and Chhota Shigri glacier was mapped from 1980 to 2015 using Landsat images. The analysis of data showed that the areal extent of glaciers has receded from 1980 to 2015.

Three scaling laws applied in this study yield different volume estimates for the glaciers from two adjoining sub-basins of the Indus basin, western Himalaya. The glaciers reported in this study show –10% (Kolahoi glacier) and –2.6% (Chhota Shigri glacier) change in their length and –13.5% (Kolahoi glacier) and –2.1% changes in the areal surface during the study period of 35 years. Cumulative change in volume estimated using different methods was found to be comparable i.e., –18% for Kolahoi and –3% for Chhota Shigri glacier, during the study period. However, progressive change in volume of two glaciers shows slight difference—Kolahoi glacier is declining rapidly as compared to Chhota Shigri glacier. Incorporation of field measurements into satellite data analysis, and their comparison strengthens the estimates of pattern in ice volume variability. The study tried to identify parallels and differences in the melt response of two most studied glaciers in Indus basin, based on available satellite images.

Keywords: Volume change; Glaciological methods; Kolahoi glacier; Chhota Shigri glacier; Climate change.

Introduction

Glaciers around the world are experiencing massive ablation due to global warming (Wang et al., 2014). Glacier studies around the world indicate that most mountain glaciers lost mass during the last three decades

(Kaser et al., 2006). Advent of remote sensing techniques and advancement therein revolutionized regional scale studies in earth sciences in general (Hulley et al., 2012; Svoboda and Paul, 2009; Wang et al., 2015; Fisher et al., 2012; Sexton et al., 2013) and glaciological studies in particular (Kachosue et al., 2013; Bolch et al., 2010;

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Bhardwaj et al., 2015; Erdenetuya et al., 2006; Berthier et al., 2004). Easy availability of various types of satellite data e.g. Landsat, ASTER, Sentinel, MODIS, Google Earth (Luetscher et al., 2011; Yamagishi et al., 2010; Lisle, 2006; Patterson, 2007) etc. has brought an unprecedented increase in the indirect assessment of various glaciological parameters in recent times.

For a better understanding of the glacier dynamics, ice thickness is a key indicator which can be measured using techniques such as seismic sounding, ice penetrating radar or by drilling (Cooper et al., 2012). The Himalayas also known as the third pole due to largest glacier coverage outside the polar regions are still comparatively lesser understood because of remoteness, ruggedness, the complicated geopolitics of the region, and associated difficult physical access to these glaciers (Bolch et al., 2012). The rugged terrain in the Himalayas hampers extensive logistic arrangements for carrying out field-based glacier volume estimation studies. Some researchers have attempted glacier volume studies either directly in the field using geophysical sounding (Monnier et al., 2011; Irvine-Fynn et al., 2006; Singh et al., 2010; Shean and Marchant, 2010; Del Rio et al., 2012; Nijampurkar et al., 1993; Singh et al., 2013; Kumar, 1999) or glaciological methods (Wagnon et al., 2007; Azam et al., 2012; Dobhal et al., 1995; Nijampurkar and Rao, 1992). But these methods cannot be applied in regional scale glacier volume estimation for each and every glacier.

Remote sensing techniques and satellite data helps in areal parameterization of glacier surfaces not only at the regional scale but global scale too, and using area as an input, various approaches to estimate glacier volumes have been used successfully e.g. volume–area (V–A) relations (Chen and Ohmura, 1990; Bahr, 1997; Agarwal and Tayal, 2013; Frey et al., 2014) and slope-dependent ice thickness estimations (Haeberli and Hoelzle, 1995). Ice thickness models have been used recently to model ice thickness (Farinotti et al., 2009a; Linsbauer et al., 2009; Huss and Farinotti, 2012; Li et al., 2012; Clarke et al., 2013; McNabb et al., 2012; van Pelt et al., 2013). A vast number of literature is available related to volume estimation using various approaches (Adhikari and Marshall, 2012; Singh et al., 1997; Farinotti et al., 2009b; Surazakov and Aizen, 2006; Keutterling and Thomas, 2006; Kumar et al., 2008; Chen and Ohmura, 1990; Jost et al., 2012; Gärtner-Roer et al., 2014; Chen and Ohmura, 1990; Mohd Soheb, 2016). The Randolph Glacier Inventory (RGI) providing a globally complete data set of glacier coverage is available in the public

domain and can be used for assessing glacier volumes without relying on data extrapolation.

Cogley (2016), Marzeion et al. (2012), Grinsted (2013) and Radić et al. (2014) are some important large scale glacier volume studies using empirically established laws meant for volume estimations. The volume estimations carried out for the Hindu Kush-Himalayan (HKH) region indicate substantial differences. However, inconsistencies in delineations of areas and differing regional set-up hamper a comparative analysis and these are some of the limitations of volume approximation exercise using established scaling laws. Apart from that area-volume scaling biases issue for large ice masses, and incomplete inventory data also pose a limitation of scaling laws which offer explanations for the difference in ice volumes by different scholars (Grinsted, 2013). Depending on the chosen glacier inventory, Bolch et al. (2012), Ohmura et al. (2009) and Cogley (2011) estimated ice volumes in the Himalayas and reported the pros and cons of these methods. Also, researchers modifying and evolving new empirical methods are engaged intensively in refining and strengthening these techniques (Huss, 2013; Adhikari and Marshall, 2012; Radić et al., 2007; Berthier et al., 2006; Nye, 2015).

Extraction of glacier parameters such as glacier length, area, mean elevation, slope, aspect, vertical thinning, etc. from space-borne satellite data and digital elevation models is one of the most plausible options in regional scale studies (Lopez et al., 2010; Paul et al., 2007; Machguth and Huss, 2014; Winsvold et al., 2014). Though, satellite data and DEMs of very high spatial resolutions are available now-a-days, those with very high resolution are very cost expensive and that too, for working at regional scale lead to huge budgetary consumption and hence limit their regional to global scale use in inventory endeavours because of financial and logistic constraints. However, freely available SRTM, ASTER DEMs and Landsat multisensor data are also suitable for such inventory and glacier volumetric studies (Frey and Paul, 2012; Surazakov and Aizen, 2006; Berthier et al., 2006; Frey et al., 2012).

Here, we present volume estimation of two glaciers from India in western Himalayas i.e. Kolahoi from Jhelum valley in Jammu & Kashmir and Chhota Shigri from Chenab valley in Himachal Pradesh. Field-based mass balance studies for Kolahoi glacier continues since 2009 and for Chhota Shigri glacier since 2003. Several workers like Dobhal et al. (1995) and Azam et al. (2014, 2016) have reported volume estimates of the Chhota Shigri glacier using field-based methods, and Murtaza and Romshoo (2016) have presented volume estimates

of Kolahoi glacier using Area-Thickness method. This study applies to empirically established physics based methods for volume estimation up to 2015, incorporates field observations in improving the assessment of glacier extents, and identifies commonalities and differences in melt response of these two glaciers over different time periods. This study thus signifies the micro-climatic variation in rates of mass loss of glaciers in two different sub-basins of Indus basin.

Study Area

Kolahoi glacier and Chhota Shigri glacier are two glaciers of Pir Panjal range in western Himalayas (Figure 1). Kolahoi glacier is the largest glacier in the West Liddar valley in Anantnag, whose meltwater is a major contributor to the river Jhelum. Kolahoi glacier in the Liddar valley has the sub-Mediterranean type of climate and receives its 80% of annual rainfall in winter and spring season (Kanth et al., 2011). Chhota Shigri glacier is influenced by two atmospheric circulation systems: the Indian monsoon during summer (July–September) and the northern hemisphere mid-latitude

westerlies during winter (January–April) (Bookhagen and Burbank, 2006; Singh et al., 1997; Gardelle et al., 2011). Chhota Shigri glacier is situated in the Chandra River valley which is comparatively drier than the southern slopes of the Pir Panjal range because this part falls in the rain shadow region with the main ridge mostly oriented to W-E. This presents hindrance to part of the monsoon flux to reach the valley (Bookhagen and Burbank, 2006). In the upper accumulation zone, relative humidity reaches >65% and gets occasional snow and drizzle. The annual precipitation on the glacier is in the range of 150-200 cm of snow (Nijampurkar and Rao, 1992). Cold dry season from October to April is the chief characteristic climatic feature of the lower valley. Despite being in the same basin i.e. Indus basin, both the glaciers show some differences in geometrical, altitudinal and climatic characteristics. Latitudinal extent of Kolahoi is $34^{\circ} 9' 29''$ N to $34^{\circ} 10' 57''$ N and that for Chhota Shigri is $32^{\circ} 11' 54''$ N– $32^{\circ} 17' 12''$ N. Kolahoi glacier's orientation is northwest in accumulation and North in ablation zones and Chhota Shigri is oriented northeast in its accumulation zone and North in ablation zones as Kolahoi. In terms of size, Chhota Shigri is

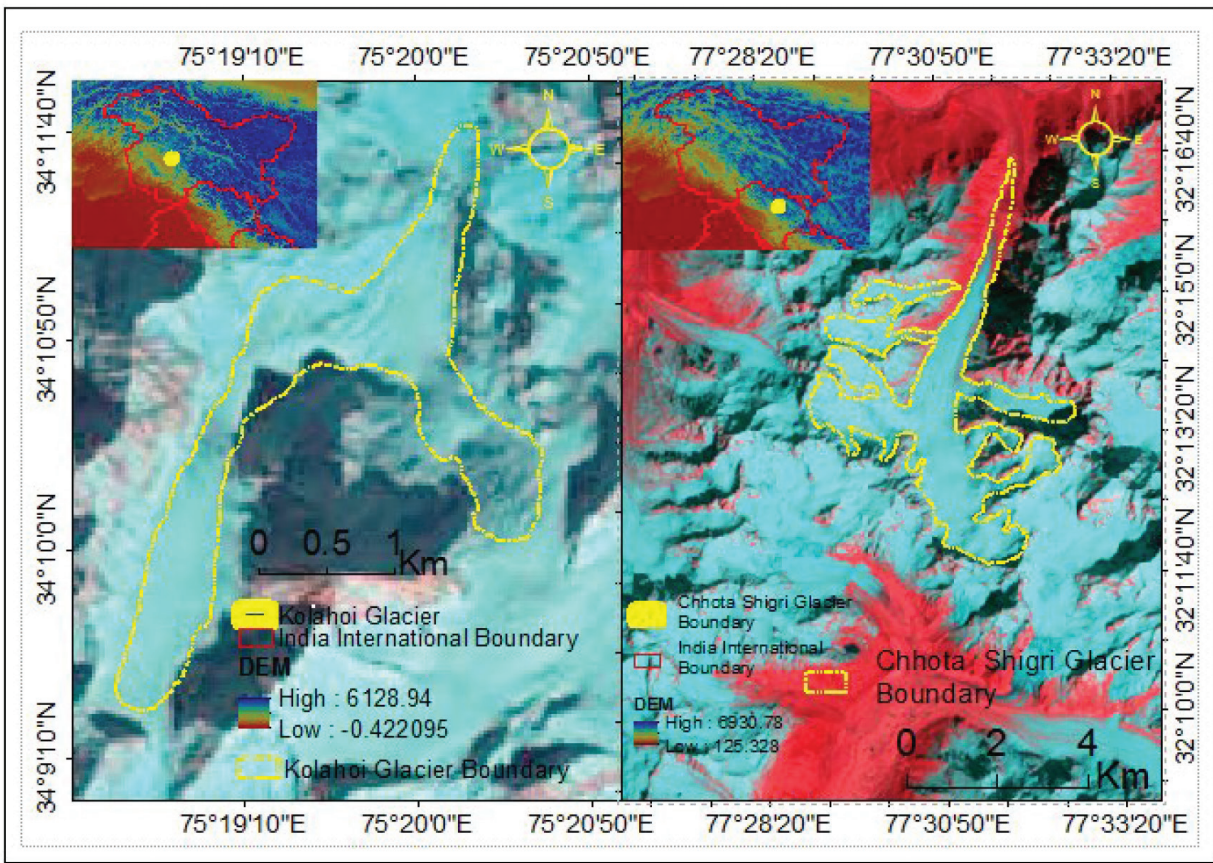


Figure 1: Map of study area.

bigger than Kolahoi. Bolch et al. (2012) reported that overall debris cover percentage in the Karakoram Himalayas is about 10%, which could be validated through our field observations for these two glaciers.

Data and Methodology

Three empirically established methods: two area–volume relations and one slope-dependent have been used for ice volume approximation for the two glaciers of western Himalayan region in this study. The empirical relationships and scaling laws are applied to geospatial data extracted from digital elevation models (DEMs): one from ASTER DEM and the other SRTM DEM; and the areal parameter of the glacier surface calculated from Landsat multisensor images for the time periods starting from 1980 to 2015, details for which are listed in Table 1. We used SRTM and ASTER digital elevation models (DEMs) to calculate mean slope of both the glaciers to estimate changes in glacier volume over the period 2000–2010 using Nye’s (1952) glacier flow mechanics method. We also analyzed Landsat multisensor, multispectral images to quantify the rate of glacier recession.

The glacier outlines used for the calculations have been compiled by remote sensing, based on Landsat satellite scenes acquired between 1980 and 2015. Boundaries of both the glaciers were delineated from Landsat scenes using visual interpretations and overlaying high-resolution imagery from Google Earth, which made the outlines accurate than RGI 5.0. Centreline estimation used here has been performed on multisensor Landsat satellite data overlaid over SRTM DEM version 4.0 of 30 m spatial resolution. The values for mean slope as well as minimum and maximum elevation were attained using DEMs. Details of satellite data and DEMs used are provided in Table 1.

Area Change Assessment

Decadal area changes of both the glaciers were carried out using the Landsat satellite images. The recessional changes over the 1980–2015 were observed for Chhota Shigri and Kolahoi glaciers.

Calculation of Accumulation Area Ratio

“The accumulation area ratio (AAR) is a ratio between accumulation area and the total area of a glacier” (Georges, 2004). Change in Accumulation Area Ratio (AAR) has a significant implication on the retreat or advance of any glacier and hence on glacier health. AAR of the Kolahoi glaciers was extracted based on the snow line using satellite images for the year 1980, 1990, 2000, 2010 and 2015 and that for the Chhota Shigri glacier has been used from the published and unpublished sources.

Methods to Calculate Glacier Thickness and Volume

Three approaches were applied to calculate the ice volume in this study.

Glacier Flow Mechanics Method/Slope-dependent Thickness Estimation Method

Nye’s (1952) theory was taken by Paterson (2000) to build upon the flow mechanics of an infinitely wide glacier, suggested a relation of ice thickness to the ice surface slope.

$$h = \tau / \rho \times g \times \sin(\alpha) \quad (1)$$

where τ is the average basal shear stress, ρ the ice density, g the gravitational acceleration, and α the mean surface slope along the central flowline.

Values of τ used in the literature vary from 50 kPa to 150 kPa (Hooke, 2005; Cooper et al., 2012). Here, we have used 100 kPa as the ideal value of τ (basal shear

Table 1: Satellite data and DEM specifications

<i>Kolahoi</i>		<i>Chhota Shigri</i>		<i>Spatial Resolution</i>
<i>Date</i>	<i>Path/Row</i>	<i>Date</i>	<i>Path/Row</i>	
06-10-1980	160/36	16-09-1980	158/38	60
07-08-1990	149/36	06-08-1989	147/38	30
15-10-2000	148/36	24-09-2001	147/38	30
17-10-2010	149/36	03-10-2010	147/38	30
08-10-2015	148/37	15-09-2015	147/38	30
11-02-2000		SRTM DEM		30
17-10-2011		ASTER DEM		30

stress). The value of g used in this study is 9.8 m/s^2 . Since this is a slope dependent method, the slope was derived using SRTM DEM for 2000 and ASTER DEM for 2011. The volume estimation method developed by Nye (1952) and applied by many workers (Raper and Braithwaite, 2009a; Kamb and Echelmeyer, 1986; James and Carrivick, 2016; Farinotti et al., 2009a; Raper and Braithwaite, 2009b; Bahr et al., 1998; Azam et al., 2012) is slope dependent, which is calculated using DEM in most of the studies (Hoelzle et al., 2007; Li et al., 2012; Agarwal and Tayal, 2013).

Area-related Thickness Estimations

An empirical relation between mean thickness and area of the glacier has been given by Chaohai and Sharma (1988), Singh et al. (2015), Bolch et al. (2011a), Schauwecker et al. (2015) and Bolch et al. (2011b).

$$H = -11.32 + 53.21 F^{0.3} \quad (2)$$

where H is the mean glacier thickness (m) and F is the glacier area (sq. km).

Volume-Area Scaling

For estimating the ice volume of any glacier, Volume–Area scaling has been the most widely used approach. Ice volume is calculated as a function of surface area, as large glaciers tend to be thicker. This method is simple to use and swiftly provides glacier volumes when provided with scaling parameters along with area. In general form, Volume–Area scaling relation is expressed as:

$$V = cA^\gamma$$

where V is glacier volume, A the glacier area, and c and γ two scaling parameters.

In our study, we used sets of scaling parameters from Chen and Ohmura (1990) who proposed values for c and γ to be 0.2055 and 1.36 respectively by regression analysis of data measured from 63 European glaciers because use of these scaling parameters provide volume of these glaciers close to that calculated from the field studies. These laws have been successfully used for

tracing glacier volume changes in the Himalayas and has come up with comparable results (Frey et al., 2013; Bahr et al., 2015).

Results

Area obtained for both the glaciers using Landsat data shows cumulative change of -13.5% for Kolahoi Glacier and -2.12% for Chhota Shigri glacier, since 1980. This indicates that Kolahoi glacier is losing its area faster than the Chhota Shigri. Progressive change in the surface area of the Kolahoi glacier was -5.86% during 1980-1990 and -0.10% from 1990-2000, but has lost close to 7.4% since 2000. Similarly, area change of Chhota Shigri glacier was computed as 0.7% before 2001, but 1.26% since 2001. Decadal rate of change in surface area of two glaciers is different, and the trend of change is also different. While Chhota Shigri glacier shows variation in area loss trends as compared to trends before 2000, surface area of Kolahoi glacier was almost stagnant during 1990-2000, but has lost almost 0.2 km^2 since then, equivalent to 7.4% of its area (Table 2; Figure 2).

Length of both the glaciers is decreasing with a cumulative change of -10.22% in the length of Kolahoi and -2.6% in Chhota Shigri glacier. Based on centreline measurements with the help of GIS tools, the annual rate of retreat of Kolahoi and Chhota Shigri glacier is about 15.6 and 7 metres per year respectively. However, this rate of retreat has not been uniform for all the decadal time intervals. For example, Kolahoi glacier shows a retreat of 114 m in the pre-2000 period, which increased by almost three times during the post-2000 period, showing a total retreat of 550 metres in 35 years time. Similar to the trend in area change, Chhota Shigri glacier shows a retreat of 250 m in 35 years, with a near uniformity in retreat rate in pre- and post 2000 periods (Figure 3).

An AAR of more than 50% generally represents a good glacier health (Mernild et al., 2013). Accumulation Area Ratio (AAR) was derived from satellite images and

Table 2: Decadal change in area and length of the glaciers

Year	Decadal area change (in %)		Decadal length change (in %)	
	Kolahoi	Chhota Shigri	Kolahoi	Chhota Shigri
1980-90	-5.8	-0.32	-1.0	-0.95
1990-2000	-0.1	-0.39	-1.1	-0.28
2000-2010	-6.9	-0.94	-5.4	-0.92
2010-2015	-1.1	-0.48	-3.0	-0.47

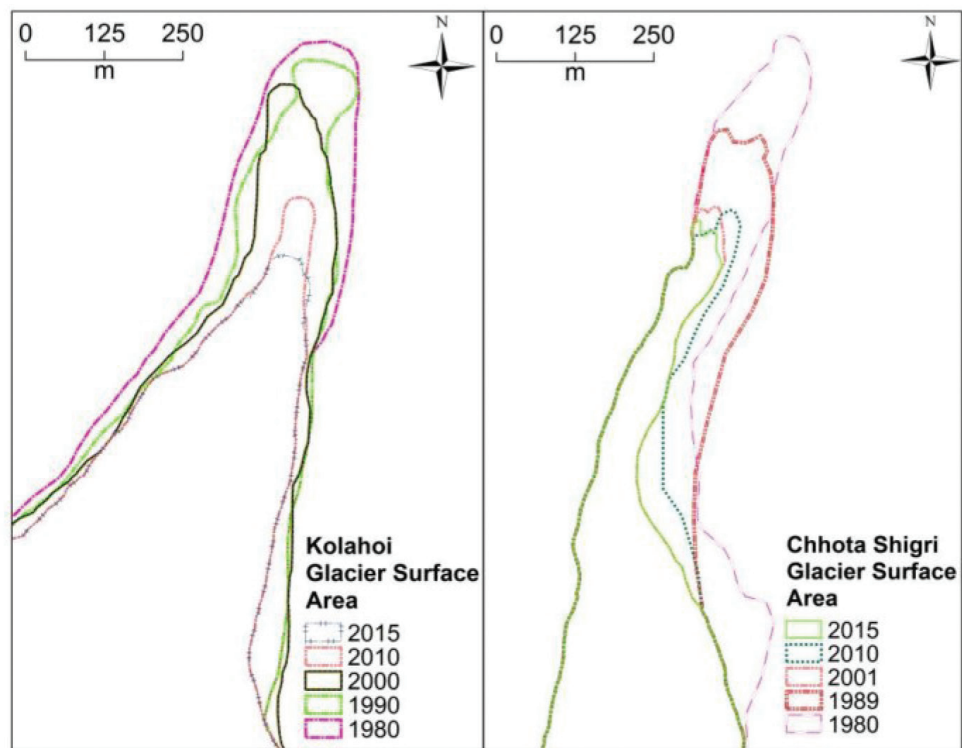


Figure 2: Frontline changes of both the glaciers.

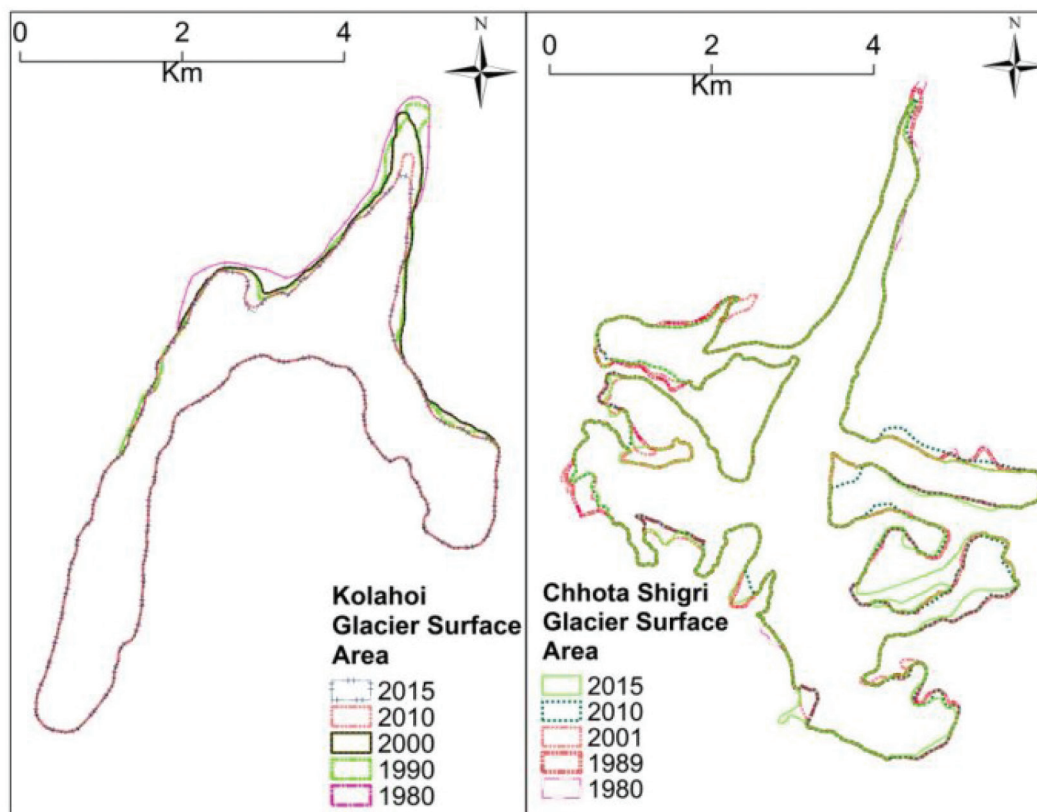


Figure 3: Area change of Kolahoi and Chhota Shigri glaciers.

compared with ELA estimates from field observations. ELA for Kolahoi glacier is almost stagnant lying within a specific zone above 4100 masl, indicating AAR values ranging between 45–40% throughout the study period. In fact, increase in AAR is also observed over some decades which may be due to decrease in total area of the glacier than the actual downward shifting of ELA. On the contrary, most recent observations of ELA for Chhota Shigri glacier (since 2009) indicate a positive trend and expansion of AAR mainly due to increase in area of Accumulation Zone (Azam et al., 2016).

Volume Change of the Kolahoi Glacier and Chhota Shigri Glacier

Glacier Flow Mechanics Method

Using Glacier Flow Mechanics method, the volume was found to be 0.14 km³ and 0.65 km³ in 2000 and 0.12 km³ and 0.60 km³ in 2010, for Kolahoi and Chhota Shigri glaciers respectively. This indicates a decline of 11.26% and 7.48% in the volume of two glaciers respectively, during the decade.

Thickness-Area Scaling (T-A) Method

Using Thickness-Area scaling method, volume of Kolahoi glacier was estimated to be 0.19 km³ in 1980 and 1.45 km³ for Chhota Shigri glacier indicating a large difference in ice content of two glaciers. Progressively, Kolahoi glacier lost –7.85%, –0.13% during 1980 to 1990, 1990 to 2000 and almost –10.7% since 2000. Simultaneously, Chhota Shigri glacier lost 0.4%, 0.5% during 1980 to 1990 and 1990 to 2000, but has lost almost 1.8% since 2000. Cumulative volume change for the two glaciers has been estimated to be –17.8% for Kolahoi and –2.8% for Chhota Shigri glacier during the study period of 35 years (Table 3; Figure 4).

Volume-Area Scaling (V-A) Method

Using Volume-Area scaling method, volume of Kolahoi glacier was estimated to be 0.96 km³ in 1980 and 7.23 km³ for Chhota Shigri glacier, which are highly inflated as compared to estimates using T-A method. Cumulative decrease in the volume of Kolahoi and Chhota Shigri glacier was found to be 17.19% and 2.87% respectively, during the study period of 35 years. Progressively, Kolahoi glacier lost 7.88% and 0.14% during 1980 to 1990 and 1990 to 2000, and 10.7% since 2000, and Chhota Shigri glacier lost 0.43% and 0.52% during 1980 to 1990 and 1990 to 2000, and 1.93% since 2000 (Table 3; Figure 5).

Discussion

Glaciers in the Himalayas are changing both vertically and horizontally. Change in any of the glacier-dimensions leads to variation in volume of the glaciers. Most of the glaciers in the Himalayas are losing mass with some exceptions which are surging (Bolch et al., 2012; Cogley, 2011; Gardelle et al., 2013; Grinsted, 2013). Both the studied glaciers—Kolahoi and Chhota Shigri glacier—representing Jhelum and Chenab basins of Indus river system, retreated at the rate 15.6 m/yr and 7 m/yr and lost 13.5% and 2.1% of their surface area respectively, during the span of 35 years. This rate of retreat was found to be comparable with studies on other glaciers in Himalayas—Samudratapu glacier (18.45 m/yr 1963–2004; Shukla et al. (2009)), Dokriani glacier (16.6 m/yr 1962–1995; Dobhal et al. (2004)), East Rathong Glacier (15.1 m/yr 1962–2011; Agarwal and Tayal (2013)). However, this rate of retreat was not uniform for both the glaciers and over the decades,

Table 3: Volume of the glaciers using various methods

<i>Glacier</i>	<i>Year</i>	<i>Glacier-Flow Mechanics Method (km³)</i>	<i>Volume Area Scaling Method (km³)</i>	<i>Area Thickness Method (km³)</i>
Kolahoi	1980		0.959	0.197
	1990		0.883	0.181
	2000	0.142	0.882	0.181
	2010	0.126	0.800	0.164
	2015		0.787	0.161
Chhota Shigri	1980		7.232	1.445
	1990		7.200	1.438
	2000	0.655	7.162	1.431
	2010	0.606	7.070	1.413
	2015		7.024	1.404

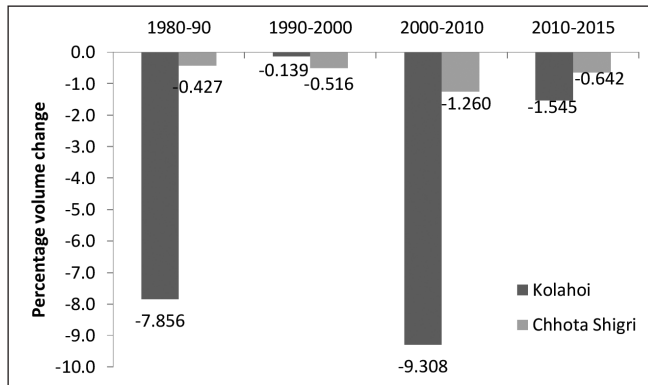


Figure 4: Decadal change in volume using thickness-area method.

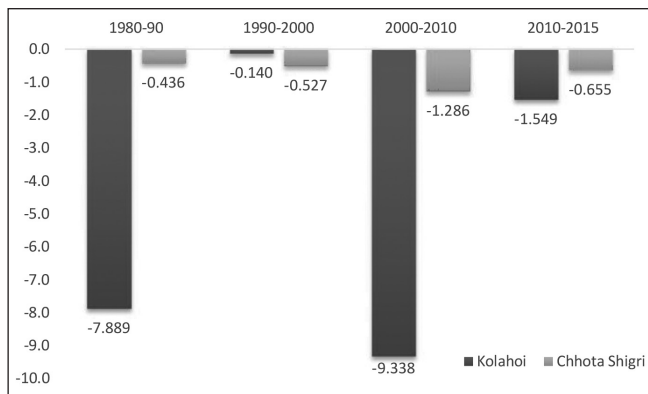


Figure 5: Decadal change in volume using volume area scaling method.

indicating high variation in individual response of glaciers to their micro-climatic settings.

Glacier surface area reported by inventory based on toposheets of 1970s (GSI, 2009) and surface area of 1980 based on satellite data, show significant difference for Kolahoi glacier, especially due to correction incorporated into the glacier image based on field observations i.e. 11.5 km² (GSI, 2009) 13.57 km² (Murtaza and Romshoo, 2016) in contrast to 3.1 km² being used in this study. Correspondingly, volume estimates for Kolahoi glacier also differ 0.58 km³ (GSI, 2009), 1.894 km³ (Murtaza and Romshoo, 2016) and ~0.2 km³ as per this study, for 1980.

A comparative assessment of volume change patterns between Kolahoi and Chhota Shigri glaciers indicate remarkably different trends. Deglaciation being reflected in percentage loss in area of volume of Kolahoi glacier is faster than the Chhota Shigri, Kolahoi being a smaller glacier than Chhota Shigri. Kolahoi was almost stagnant during 1990-2000, but has lost almost 8% of its area

in last 15 years. On the contrary, Chhota Shigri glacier shows a consistency in its declining trend, being nearly stable during decades before 2000 but shows almost a doubling of rate of areal loss since 2000 as compared to earlier decade. Corresponding to the trends in length and area change, volume change also follows a similar trend.

V-A method gives highly inflated volume estimates as compared to T-A method for both the glaciers, but cumulative volume decrease for the two glaciers was estimated to be same using both V-A and T-A methods i.e. 18% for Kolahoi and 3% for Chhota Shigri glacier during the study period of 35 years. Furthermore, both the glaciers indicate a strong temporal variability in deglaciation and increase in ice loss during recent time period. Stagnancy in ice volume change was observed for Kolahoi glacier during 1990-2000, which has altered into a time period of rapid loss being witnessed currently. On the contrary, volume loss estimates using empirical relationships show that Chhota Shigri glacier is loosing ice but the rate of loss is nearly uniform though with higher ice loss trend recently. This is supported from lowering ELA in last decade (Azam et al., 2016).

As Nye (1952) method is slope dependent, which is calculated using DEM in most of the studies, availability and accuracy of DEMs influence the volume estimates. Freely available DEMs like SRTM: 11 Feb 2000 (Farr et al., 2007) and ASTER GDEM: 17 Oct 2011 (Tachikawa et al., 2011) are available for recent periods only, so an earlier assessment using Nye (1952) is not possible. There are reported glitches in the empirically established methods of volume estimation. For example, for the entire Himalaya, Bolch et al. (2012) report that empirical estimates produce highly uncertain results and the values range from about 2300 km³ (estimated using method that takes the slope-dependent ice thickness into account) to ~3600 to ~6500 km³ calculated using volume-area scaling method. Scaling factors used in scaling equations rely on several iterations of running of the same method for different data sets and, hence, are advised to be used with caution. In this study also, volumetric estimation using different empirically established equations produced different results. Sensitivity analysis of area vs volume loss conducted for the two glaciers indicate that accuracy in area estimation of glaciers is very important, which is highly limited due to quality of images available for time period earlier than 2000.

Conclusions

Most of the glaciers in the Himalayas have retreated with accelerated rate of mass-loss during last few decades (Bolch et al., 2012). The present study, aimed at calculating glacier volume change using indirect assessment techniques, indicates that glaciers in Jhelum and Chenab basin have also followed the established trend of cumulative ice loss since 1980. However, the rate of change in ice volume of glaciers has not been uniform, and shows variation on a decadal time scale. This further strengthens the fact that individual glaciers have different response to climatic parameters which may be due to difference in their location, size, debris cover, micro-climatic parameters etc. Time periods of high ice loss have intermittent periods of lower rate of ice loss. Decades with no loss or slight mass gains can also be observed, but on a cumulative scale, glaciers are losing ice.

Different empirical relationships of volume estimation have severe limitations and give varying estimates, but the pattern of change is almost consistent across different methods. Variation in assessment of length and area of glaciers has direct bearing on volume estimates using empirical techniques, which need to be improved through more field based observations and measurements, as well as refinement in remote-sensing techniques. This study also underlines the significance of comparative assessment to strengthen the understanding on varying melt response of glaciers in Himalayas.

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