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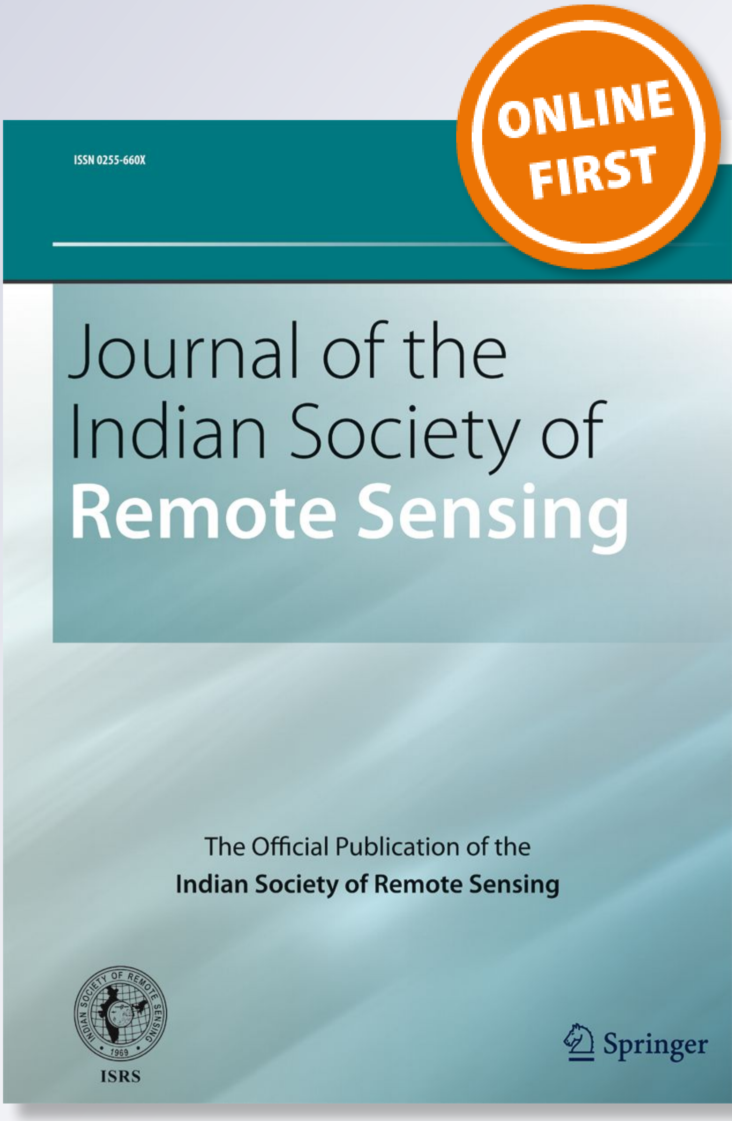

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RESEARCH ARTICLE

Mass Balance Estimation of Dokriani Glacier in Central Indian Himalaya Using Remote Sensing Data

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Abstract

Dokriani Glacier is regarded as one of the important glaciers of Bhagirathi River basin, which fed river Ganges. The length of the glacier is about 4.6 km, and snout elevation is about 4028 m m.s.l. The mass balance of this glacier was calculated using field-based measurements for few years during 1994 to 2000. However, due to remote and poor accessibility, the field-based measurements could not continue; thus, remote sensing-based methods become useful tool to estimate the long-term mass balance of the glacier. In this study, glacier mass balance has been determined using accumulation area ratio (AAR) method. Remote sensing data sets, e.g. Landsat TM, ETM + and OLI, have been used to estimate AAR for different years from 1994 to 2014. An attempt has also been made to develop a mathematical relationship between remote sensing-derived AAR and field-observed mass balance data of the glacier. Further, this relationship has been used to estimate mass balance of the glacier for different years using remote sensing-derived AAR. Estimated mass balance was validated from ground-observed mass balance for few years. The field-observed and remote sensing-derived mass balance data are compared and showed high correlation. It has been observed that AAR for the Dokriani Glacier varies from 0.64 to 0.71. Mass balance of the glacier was observed between − 15.54 cm and − 50.95 cm during the study period. The study highlights the application of remote sensing in mass balance study of the glaciers and impact of climate change in glaciers of Central Indian Himalaya.

Keywords AAR · Mass balance · Dokriani Glacier

Introduction

Out of total global water, only 2.5% is available as fresh water and about 73.1% of the fresh water is stored on glaciers in the form of snow and ice (Gleick 1996). The melt water of Himalayan glacier is serving more than 500 million people for industrial, domestic and agriculture purposes through major rivers like Ganga, Brahmaputra and Indus. Since glacier mass balance study is an important parameter to assess future availability of water, it is important in world's perspective (Bamber and Kwok 2004; Negi et al. 2012). Mass balance is defined as the total loss or gain of glacier mass at the end of a hydrological year (Kulkarni et al. 2004). It depends on various factors like size, altitude and shape of the glacier as well as climate of the region. The mass balance is generally estimated by measuring the total accumulation of seasonal snow and ablation of snow and ice. The equilibrium line, which is the boundary between accumulation and ablation area at the end of melting season (Rabatel et al. 2005), is also being calculated. Remote sensing methods have shown potential to study glaciers in the past. It helps in covering a large area of an inaccessible region. Number of glaciers has been studied in the past using remote sensing (Hall et al. 1992; Braithwaite 1984; Braither et al. 2007; Etzelmuller et al. 1996; Sapiano et al. 1998, Jaenicke et al. 2006; Kulkarni et al. 2007; Racoviteanu et al. 2008, etc.). As per the literature, the mass balance studies were started around 1945 at Sweden by the glaciological method based on the use of stakes, snow pits and probing (Holmlund et al. 2005). The conventional measuring techniques are difficult as these are time-consuming, labour extensive and weather dependent,

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since glaciers are located in the remote areas (Dyurgerov. 2002), especially in the Himalayan region. Due to these limitations, mass balance estimation by glaciological method was used for very few glaciers, e.g. Chhota Shigri (Dobhal et al. 1995; Wagnonet al. 2007; Puri and Thakur 2015), Dokriani Glacier (Dobhal et al. 2008), Shaune Garang and Gor Garang Glaciers (Singh and Sagewar 1989) in Himalayan ranges.

It is important to study and analyse Himalayan glaciers periodically to understand or predict future behaviour as they are lifeline of large population in North India. Recent studies over Himalayan region investigated that most of the glaciers are retreating and having negative mass balance (Raina 2009). In the present study, mass balance is estimated for the Dokriani Glacier, which is located in central Indian Himalaya and is one of the important glaciers of Bhagirathi River basin. AAR method has been extensively used for the mass balance estimation. AAR of Dokriani Glacier has been estimated using field observations between the years 1994 and 2000 using glaciological method by Dobhal et al. (2008).

However, continuous data for the glacier till recent years are not available due to limitations in regular field observations (Berthier et al. 2007). Remote sensing technique provides an effective and alternate way to study the glaciers situated in such inaccessible regions (Rabatel et al. 2005; Bamber and Rivera. 2007; Kulkarni et al. 2004). In the present paper, an attempt has been made to estimate mass balance of the Dokriani Glacier using remotely sensed Landsat TM, ETM + and OLI images. As glaciers vary with altitude, size, shape, etc., and behave differently in different conditions, one mathematical equation used to calculate mass balance may not be appropriate for other glaciers. In this study, a regression equation has been also developed using AAR and mass balance from field data (1994–2000). AAR has been calculated using procured Landsat images during the end of melting seasons during the period 1994–2015 to estimate the mass balance. The results of this study are promising and provide information of the mass balance of the Dokriani Glacier for more than a decade. Furthermore, generated mathematical model provides a direct relationship between AAR and mass balance to estimate the mass balance of the glacier using only remotely sensed data.

Study Area and Data

Dokriani Glacier is a valley glacier and located in the central Indian Himalaya (Fig. 1). This glacier is bounded between 30°49′ to 30°52′N and 78°47′ to 78°51′E in Bhagirathi river basin. The length of the glacier is about 4.6 km, and altitude varies from 4000 m to 6000 m. The catchment area of glacier is about 15.1 sq km, and ice-covered valley glacier area is about 5 sq km. It flows in the northwest direction.

The glacier is formed by two cirques, starting at the northern slope of Draupadi-Ka-Danda (5600 m) and Jaonli peak (6000 m). The thickness of glacial ice varies from 120 m in accumulation zone and 25 m near the snout (Dobhal et al. 2008). Rainfall during June to September due to monsoon and snowfall during winter due to western disturbances are the main constituents of the total precipitation. Totally, six images of Landsat data were selected for the study from 1994 to 2014 and given in Table 1. The data of August/September months with minimal cloud cover were used in the study for better results. Equilibrium line altitude (ELA) is determined in all the images using ASTER digital elevation model (DEM), which is then used to determine AAR.

Methodology

The method of estimating mass balance is given in the flow chart shown in Fig. 2. Landsat data (TM, ETM, OLI), which were acquired as discussed earlier, have been used. As snow line can be estimated using visual interpretation as well as through supervised classification technique in the remote sensing data sets, an attempt has been made to compare results of both the techniques. In visual interpretation, a number of band combinations were used and it has been observed that snow can be visually identified using short-wave infrared (red), near infrared (green) and red band (blue) combination more appropriately. These band combinations distinguish snow, cloud and ice easily as cloud appears white, snow appears bright cyan, and ice appears dark cyan as shown in Fig. 3.

Supervised classification technique was also used to extract the snow line on the glacier. Glacier area was classified into three classes, i.e. snow, ice and ice-mixed debris (IMD). Samples of classes were selected after studying the spectral reflectance curves of pixels and comparing them with spectral signatures of snow, ice and ice-mixed debris. Figure 3 shows one of the classified images in which cyan colour signifies snow, grey colour signifies ice, and red colour signifies IMD. Results of both the techniques were comparable. Classification of the image assists in identification of the snow line and further in demarcation of equilibrium line. This step of identification of snow line in combination with DEM assists in estimating equilibrium line altitude and further accumulation area and AAR of the glacier. Table 2 shows the field-observed data of mass balance and AAR (Dobhal et al. 2008). On the basis of these available data (Table 2), a mathematical relationship was developed between AAR

Table 1 Details of satellite data acquired for the study

Date	Sensor	Satellite	Spatial resolution (m)	Radiometric resolution	Source
22/8/1994	TM	Landsat 5	30	8 bits	USGS
21/8/1997	TM	Landsat 5	30	8 bits	USGS
5/8/2000	ETM	Landsat 7	30	8 bits	USGS
9/9/2001	ETM	Landsat 7	30	8 bits	USGS
22/8/2009	TM	Landsat 5	30	8 bits	USGS
21/9/2014	OLI	Landsat 8	30	16 bits	USGS

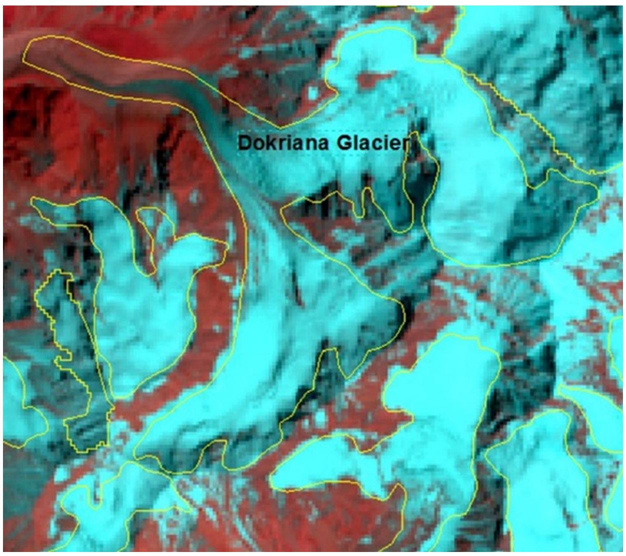

Fig. 1 Dokriani Glacier demarcated on Landsat

and mass balance, as shown in Fig. 4. The linear relationship is given by the equation $y = 596.92x - 437.25$, with $r^2 = 0.92$, where y represents mass balance and x represents AAR.

According to this equation, AAR value for zero mass balance for Dokriani Glacier is much higher (0.73) than generalized AAR (zero mass balance) value for Himalayan region (0.44) given by Kulkarani (1992).

The mathematical model thus developed has been used to estimate mass balance during different years of the period 1994–2015.

Results and Discussion

The regression equation was developed and validated the AAR and mass balance of the Dokriani Glacier. The model-estimated mass balance has high correlation ($r^2 = 0.92$) with field observations and is significant. Results show negative mass balance during study period which indicates continuous mass loss of the Dokriani Glacier. The glacier is losing ice mass with an average of 33.34 cm during a hydrological year. AAR value ranges from 0.647 to 0.707, which shows large accumulation area of the glacier and only one-third part of the glacier is under ablation zone. These values are in conformity with the available field data. Even having the high AAR value, Dokriani Glacier is continuously retreating and is having negative mass balance. Similar behaviour might be shown by other central Himalayan glaciers. The negative mass balance estimated was validated with the field-based available mass balance for few years. Mass balance was also calculated from AAR estimated using visual classification technique and varied from − 15.485 cm (for the year 2001) to − 50.959 cm (for the year 2014). Mass balance calculated with AAR derived from supervised classification varied from − 30.35 cm (for the year 2001) to − 52.6 cm (for the year 2014) (Table 3). It has also been observed that during 1994–2000 mass balance was non-uniform. It was most negative for the year 2000 indicating high melting or lower snow fall for that particular year.

The mass balance was less negative for the year 2001 indicating lower melting for that particular year. Higher negative mass balance was observed for the years 2009 and 2014 compared to 2001. Comparison between mass balance values and comparison between AAR values estimated using visual interpretation and supervised classification are shown in Figs. 5 and 6. These results are comparable and show high correlation. Direct relationship between AAR and mass balance was established, and the relationship was validated. The equation can estimate the mass balance of the Dokriani Glacier using only remote sensing data.

Conclusion

Equilibrium line at the end of ablation period is directly related to the glacier mass balance. Prediction of equilibrium line altitude is important for estimation of mass balance of a glacier. Moreover, EL altitude can be used to estimate AAR value of a glacier and shifting of ELA towards higher altitude with respect to past ELA suggests negative mass balance of the glacier. Mass balance and AAR relation varies from glacier to glacier and can be established with the help of field observations. As Himalayan glaciers are less explored due to various reasons like

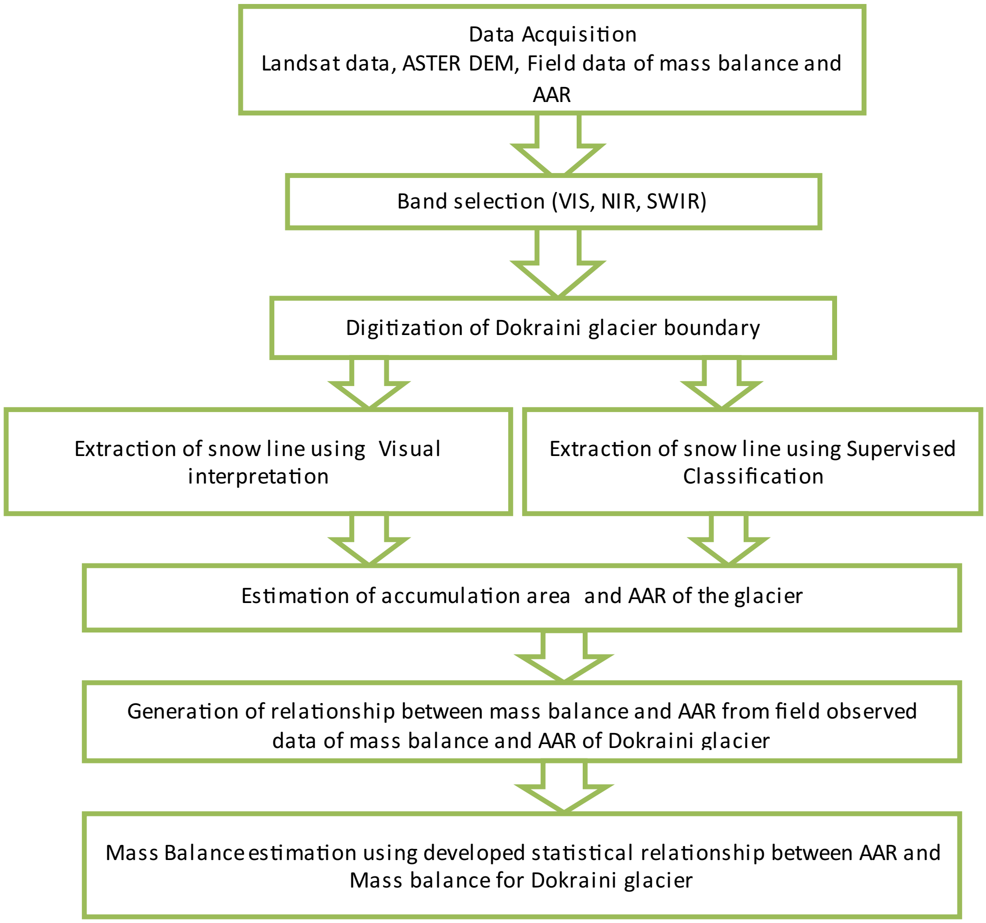

Fig. 2 Flow chart showing methodology of estimating mass balance using remote sensing data

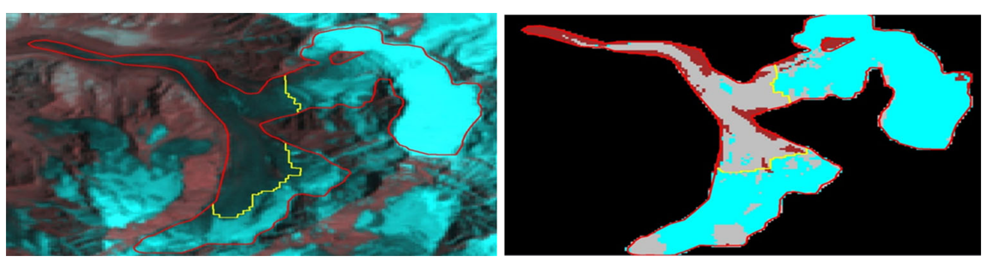

Fig. 3 Equilibrium line extraction using visual interpretation and supervised classification

Table 2 Field-observed data of AAR and MB

Year	AAR (*X*)	Mass balance (*Y*-cm)
1993	0.7	− 22
1994	0.69	− 23
1995	0.68	− 31
1998	0.67	− 34
1999	0.66	− 46
2000	0.67	− 38

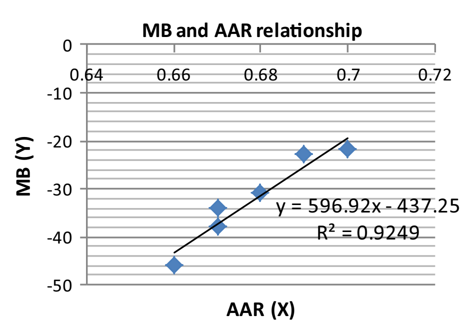

Fig. 4 Mass balance and AAR relationship

Table 3 Mass balance values using AAR by visual interpretation and supervised classification

Year	AAR (visual)	MB (cm)	AAR (SC)	MB (cm)	Variation in MB (%)
1994	0.677	− 32.889	0.65	− 48.96	0.7
1997	0.685	− 28.431	0.684	− 29.05	1.0
2000	0.662	− 41.889	0.644	− 52.69	0.8
2001	0.707	− 15.485	0.727	− 30.35	0.5
2009	0.682	− 30.35	0.676	− 33.65	0.9
2014	0.647	− 50.959	0.657	− 45.11	1.1

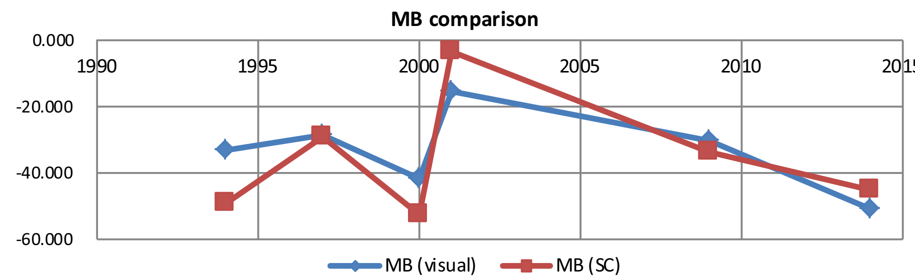

Fig. 5 Comparison between mass balance values using supervised classification and visual interpretation

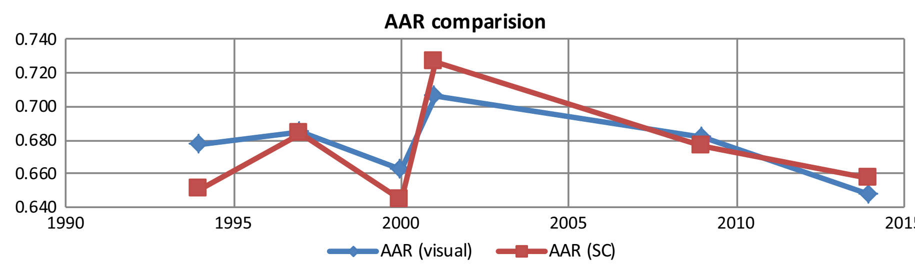

Fig. 6 Comparison between AAR values using supervised classification and visual interpretation

harsh climatic conditions and inaccessibility, field data of only few glaciers are available. These conditions provide opportunity to estimate mass balance using remote sensing techniques. Regression model generated for the estimation of mass balance for a particular glacier may give inaccurate results for other glaciers, as glaciers vary with altitude, size, shape, etc. In the present study, a mathematical equation was generated for Dokriani Glacier for the estimation of mass balance. AAR values for the Dokriani Glacier ranges from 0.647 to 0.707. AAR values for Dokriani Glacier were observed higher than the generalized AAR value (0.44) for central and western Himalayan glaciers. Mass balance of the Dokriani Glacier was observed negative for all the years during study period and varied from − 15.5 cm to − 50.9 cm. A comparative study has also been done to determine AAR by visual interpretation and supervised classification techniques. It has been observed that visual interpretation results are closer to field-observed data as compared to supervised classification. Proposed regression equation ($y = 596.92x - 437.25$) for the estimation of mass balance of Dokriani Glacier has good agreement with observed mass balance for the glacier. The study may be useful for various glaciological, climatological and hydrological applications in Dokriani Glacier. This generated mathematical relationship may be further improved.

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