Assessment of Volume Change in East Rathong Glacier, Eastern Himalaya

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Abstract

An estimate of change in volume of East Rathong glacier in Eastern Himalayas has been made, vis-a-vis changes in its surface area over the period 1962-2011. The change in the area and volume of the glacier has been estimated using remote sensing (CORONA and Landsat images) and GIS techniques, field methods and certain empirical relationships and scaling laws. Bruckl's thickness-area relationship and volume-area scaling methods are used to estimate the volume and change in the volume of the glacier from 1962 to 2011. Nye's glacier flow mechanics equation gave the volume of the glacier for 2002. The volume of the glacier in the year 2002 calculated (using the value of τ = 150 kPa), has been found to be almost equal to the volume of glacier estimated using other methods for 2002. From 1962 to 2011, surface area of East Rathong glacier decreased by 15 % whereas the estimated total volume loss is ~20%.Total retreat of the glacier during 1962-2011 is 740 m. AAR has been observed to show an almost constant value ~0.6 throughout the study period. Though AAR is nearly constant, the decrease in surface area, the rate of retreat and the rate of % volume loss, all have been observed to be consistently positive. This shows that for a three-zone glacier like East Rathong, AAR is not a very good measure of the glacier health. Hence, while assessing the health of a glacier, it is important to look into parameters like surface area, length and the thickness parameters along with AAR.

1. Introduction

The Himalaya, being the highest mountain chain on earth, has one of the highest concentrations of glaciers outside the Polar regions. Remote sensing analysis of glaciers has become a very valuable tool for documenting their fast response to changing climate (Bamber and Kwok, 2003, Kuhn, 2007, Pellikka, 2007 and Solomon et al., 2007). Since the launch of LANDSAT in 1972, easily available free data has led to a number of glacier studies using the technique of remote sensing (Kulkarni, 1991, Kulkarni and Buch, 1993, Kulkarni, 1994, Philip and Ravindran, 1998, Sidjak and Wheate, 1999, Heiskanen et al., 2002, Braun et al., 2007 and Hendriks and Pellika, 2008). Changes in glacier area and terminus positions have been used widely as indicators of a glacier's response to climate change (Barry, 2006 and Oerlemans, 2007). Himalayan glaciers are characterized as one in general retreat based on termini fluctuations for glaciers in the Himalaya and Trans-Himalaya examined for the period AD 1850 to 1960 (Mayweski et al., 1980). Since then several studies have reported the rate of retreat of glaciers in western Himalaya with base reference of Survey of India toposheets of 1960s (Kulkarni et al., 2007, Shukla et al., 2009 and Scherler et al., 2011). In remote, rugged areas such as the Himalaya, it is difficult to apply the glaciological method for mass balance measurement due to complicated logistics and political or cultural conflicts (Racoviteanu et al., 2008). A number of indirect assessment techniques have been developed for the analysis of such glaciers. A remote sensing based method on Accumulation Area Ratio (AAR) and equilibrium-line altitude (ELA) is useful for glaciers for which no field data are available (Kulkarni, 1992, Dyurgerov, 1996 and Heiskanen et al., 2002). Glacier area calculated from remote sensing outlines may be used as input for volume-area scaling techniques (Bahr, 1997 and Bahr et al., 1997). Also, glacier outlines and its combination with DEM is useful for calculating glacier length fluctuations (Hoelzle et al., 2003). Based on these indirect assessment techniques, changes in mass balance and change in volume have been analysed on various glacier groups, across global cryosphere (Luthke et al., 2008, Ramillien et al., 2006 and Berthier et al., 2007). Mass balance was found to be slightly below zero around 1970 and has been growing more negative since then (Kaser et al., 2006). Overall mass balance for the 915 km2 of glaciers surveyed in western Himalaya was found to be −0.7 to −0.85 m/a water equivalent, corresponding to a total mass loss of 3.9 km3 of water in 5 year duration from 1999 to 2004 (Berthier et al., 2007). The technique has established good correlation between observed and calculated mass balance values for other glaciers also (Hock et al., 2007). However, AAR-Mass Balance technique is especially suitable for glaciers with distinct winter accumulation and summer ablation season (Dyurgerov, 1996). Glaciers in Himalaya show a gradual transition from winter accumulation type to summer accumulation type from the western to eastern Himalaya, with glaciers in central Himalaya showing the influence of both the summer monsoon as well as winter westerlies (Figure 1).

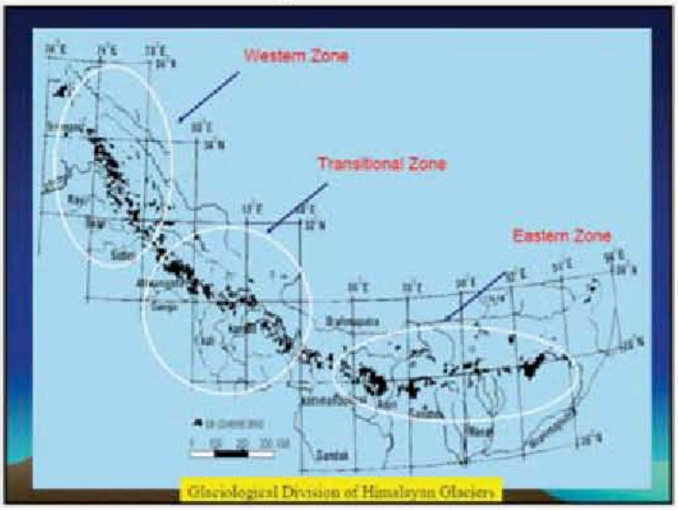

Figure 1: Figure showing glaciological division of Himalayan glaciers

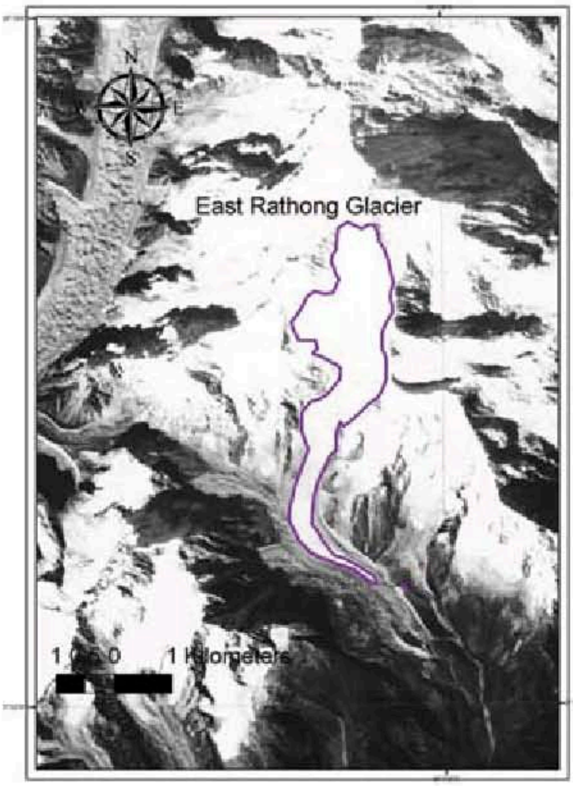

Figure 2: Demarcation of East Rathong glacier on CORONA aerial photograph

There are greater numbers of research publications on changes in mass balance from western Himalaya, but eastern Himalaya have not been explored that rigorously. Hence, the present study has been carried out on an Eastern Himalayan glacier and change in the area and volume of the glacier has been estimated using remote sensing and GIS techniques, field methods and certain empirical relationships and scaling laws.

1.1 Study Area and Data Used

East Rathong watershed (specific area under present study) is located in West Sikkim District of Sikkim state in India between latitudes 27°33′01″N and 27°36′01″N, and longitudes 88°04′42″E and 88°08′30″E. The watershed consist of 36 glaciers and is dominated by the East Rathong glacier, located between latitudes 27°33′36″N and 27°36′40″N, and longitudes 88°06′03″E and 88°07′38″E (Sangewar and Shukla, 2009). East Rathong is a south-east facing, debris-free and summer-nourished glacier. The demarcation of the glacier has been shown in CORONA aerial photograph in Figure 2.

1.2 Glacier Profile

The profile of East Rathong glacier (Figure 3) has been developed using the Survey of India toposheet (78A/2), 1966. According to the contour distribution patterns, validated through field expedition, the glacier has been divided into three distinct zones. Besides accumulation (slope = -0.45) and ablation zone (slope = -0.13), a transition zone (or ice fall) is distinctly present (slope = -0.55) connecting the accumulation and ablation zones. The transition zone covers an elevational range of >1000m in the total altitudinal range of 2000 m for East Rathong glacier. Corona imagery, cloud free Landsat images and SRTM DEM are taken (Table 1).

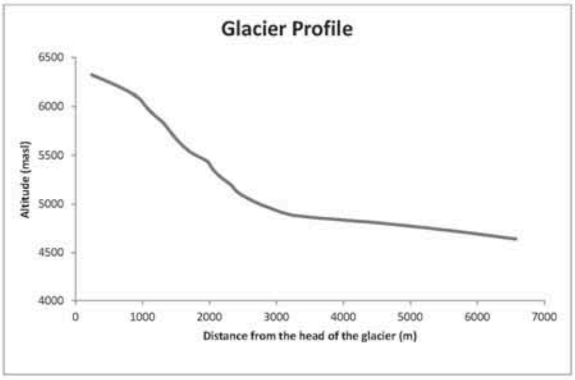

Figure 3: Profile of East Rathong glacier based on 1966 toposheet, showing three parts of the glacier (accumulation zone, transition zone and ablation zone)

Table 1: Details of the satellite data analysed in the current study

Date	Sensor	Mission	Path/ Row	Pixel Res (m)
25.10.1962	Corona	DS009048070DA243		7.62
30.11.1976	MSS	Landsat 2	149/41	60
10.11.1989	TM	Landsat 4	139/41	30
26.12.2000	ETM+	Landsat 7	139/41	30
29.10.2002	ETM+	Landsat 7	139/41	30
February 2002	C-band	SRTM	139/41	90
19.11 2009	TM	Landsat 5	139/41	30
27.8.2011	TM	Landsat 5	139/41	30
April 2009	GPS Survey	Trimble GeoXT		

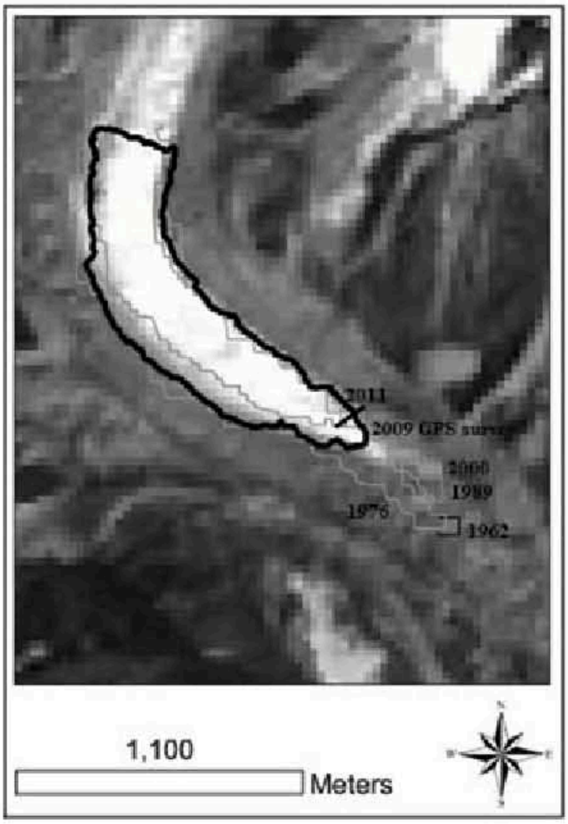

Figure 4: Retreat of East Rathong glacier from 1962 to 2011. Position of snout for years 1962, 1976, 1989, 2000, 2009 and 2011 showed over 2009 Landsat image in grey scale

GPS survey conducted in 2009 is used to demarcate the upper boundary of ablation zone as well as extent of the ablation zone of the glacier (Figure 4). The Trimble GeoExplorer 2008 GeoXT handheld GPS is used. The GeoXT handheld uses both EVEREST and H-STAR technology to provide sub foot (30 cm) accuracy, either in real time or post-processing. The GPS was carried under the area feature mode throughout the margins of ablation zone of the glacier. Also, GPS readings taken on the surface of the glacier are used to develop DEM for the ablation zone of the glacier.

2. Methodology

For the purpose of assessing progressive change, intervening time period between satellite images since 1962 has been numbered as T1 (1962-1976), T2 (1976-1989), T3 (1989-2000) and T4 (2000-2011).

2.1 Estimation of the Glacierised Area

Using methodology by Dutta et al., 2012, all the images are georeferenced taking 2009 Landsat image as the master image. All the images are carefully co-registered as the datasets are of different resolutions. To keep uniformity in the datasets, the images are registered and resampled to 30 m pixel size. Following Paul, 2000, Corona imagery of 1962 and Landsat satellite image of 1976 are subjected to unsupervised classification. The clusters observed in the signature output are further merged into two classes (supervised classification), glacierised and deglacierized areas, and the glacierised area is estimated. The classes are made by comparing the original image with the image obtained from unsupervised classification. To estimate the glacierised area of the glacier from TM/ ETM+ images, 2nd and 5th bands of the satellite images are processed. Their DN values are converted into radiance and then reflectance images. NDSI is calculated for the image obtained. From visual inspection, threshold chosen is 0.5 (NDSI>0.5 = snow/ ice), to estimate total area of the glacier.

2.2 Calculation of AAR (Accumulation Area Ratio)

2.2.1 Accumulation area

Position of snowline has been demarcated visually which is used as the lower boundary of the accumulation area. The snow covered area above this interpreted snowline is taken as the accumulation area (Heiskanen et al., 2002 and Scherler et al., 2011). Average maximum elevation (6800 m) of the watershed is taken as the upper boundary of accumulation zone.

2.2.2 Transition zone and ablation zone

The lower boundary of the accumulation zone marked the upper boundary of transition zone. The lower boundary of the transition zone (4820 m) is demarcated by the 2009 GPS survey, which has marked the upper boundary of ablation zone. The sudden steep slope observed in 1966 toposheet, from 4960 m to 5840 m, also validates the lower and the upper boundaries of the transition zone. Area from the upper boundary of ablation zone, till the snout of the glacier has been characterized as the ablation zone. Cumulative area of these three zones, the ablation, transition and accumulation, has been taken as the total glacier area.

2.3 Calculation of Glacier Thickness

It is easier to measure the length and area of a glacier than the assessment of glacier thickness as the former can be estimated using only 2D data, while for the estimation of the latter 3D data is required. A number of indirect techniques have been proposed to derive the glacier thickness, three among which have been used in present study.

2.3.1 Glacier flow mechanics method

Nye's (1952) theory for the flow of mechanics of an infinitely wide glacier has been extensively used to estimate ice-volume of a glacier (Cooper et al. 2007; Driedger and Kennard, 1986 and Li et al., 2012). Ice-volumes estimated using this method (equation 1) are considered accurate upto ±20% (Driedger and Kennard, 1986). According to the theory:

$$h = \frac{\tau}{\rho g \sin \alpha}$$

Equation 1

where, h is thickness of ice at a particular slope, ρ is density of ice (assumed to be 900 kg m-2, g is gravity (9.81 ms-2), α represents slope and τ is basal shear stress. Basal shear stress lies between 50 kPa to 150 kPa (Hooke, 2005 and Cooper et al., 2007). It is impossible to calculate the correct basal stress acting between a particular glacier and its bed. Hence, the ideal value is taken as 100 kPa. The value of α is computed using SRTM DEM. Height corresponding to each α is obtained (Cooper et al., 2007). Average height of the glacier thus obtained is multiplied with the area (glacier area in 2002 ~ 4sq. km) to get glacier volume.

2.3.2 Thickness-area relation method

Bruckl (1970) gave an empirical relation between mean-thickness (<h> in meters) and area (S in sq. km) of the glacier. The empirical relation has been used by Muller et al. (1976) to estimate the volume of Swiss glaciers.

$$< h >= 5.2 + 15.4 \times \sqrt{S}$$

Equation 2

2.3.3 Volume-area and volume-length scaling method

The volume V of a glacier has also been related with its surface area as $V = c_o S^{c_1}$ (Chen and Ohmura, 1990), with c_o and c_1 being the empirical constants which are deduced from the measures of V and S (Chen and Ohmura, 1990). Based on regression analysis of available data for European glaciers, Chen and Ohmura, 1990 proposed standard values of c_o and c_1 to be 28.5 and 1.375, respectively. The same values of c_o and c_1 have been used in this study. Volume of a glacier has also been related to its length $V = c_2 l^q$. The value of scaling exponent $q = 2.2$ and c_2 is the constant of proportionality (Bahr et al., 1997 and Radic et al., 2008). The value of c_2 could not be found in the literature (Radic et al., 2008).

3. Results

3.1 Changes in Length and Surface Area of East Rathong Glacier

From 1962 to 2011, the glacier terminus has retreated by 740 m (Figure 4), with an annual rate of 15.1 m yr-1. For different time periods starting 1976, the rate of retreat varied from 16-21 m yr-1, but considering the resolution difference for different datasets used for analysis, this difference can be considered minimal. The area of ablation zone, transition zone, accumulation area, total area of the glacier, length and AAR (Accumulation Area Ratio) of the glacier for years 1962, 1976, 1989, 2000, 2002, 2009 and 2011 are given in table 2. The total surface area of the glacier is observed to be 4.63 km^2 in 1962 and 3.94 km^2 in 2011. The glacier has vacated an area of 0.688 km^2 , equivalent to 15% of the glaciated area in last 49 years. Also, AAR shows consistency in the range between 0.59-0.61 throughout the study period, indicating an almost equilibrium existing between the glacier and its environment.

3.2 Variations in Glacier Volume

3.2.1 Glacier flow mechanics method

Using, Nye's (1965) method at τ = 150 kPa and τ = 100 kPa was found the average thickness and volume of the glacier to be 48 m and 0.192 km^3 and 30 m and 0.12 km^3 respectively for the year 2002.

3.2.2 Bruckl's method (Thickness-area relationship)

This method gives the average thickness (m) of the glacier as 38.34, 38.16, 37.66, 36.56, 36, 35.94 and 35.78 and volume (km^3) to be 0.178, 0.169, 0.167, 0.152, 0.144, 0.143 and 0.141 for years 1962, 1976, 1989, 2000, 2002, 2009 and 2011 respectively. Thus, the volume loss suffered by the glacier from 1962-2011 is 20.55%, and the net change in mass-balance is -2.56 m.w.e.

Table 2: Areas of ablation zone, transition zone, accumulation zone, total area, length of East Rathong glacier and AAR as per the analysis of Corona image 1962 and Landsat images of years 1976, 1989, 1990, 2000, 2002, 2009 and 2011

Year	**Ablation Area (km^2)**	**Transition Zone (km^2)**	**Accumulation Area (km^2)**	**Total glacier Area (km^2)**	**Length (m)**	**AAR**
1962	0.545	1.305	2.78	4.63	7040	0.600
1976	0.514	1.159	2.801	4.474	6992	0.626
1989	0.527	1.311	2.605	4.443	6721	0.586
2000	0.491	1.169	2.48	4.14	6486	0.599
2002	0.444	1.085	2.471	4.00	6480	0.618
2009	0.429	1.125	2.431	3.985	6335	0.61
2011	0.406	1.124	2.41	3.942	6300	0.612

Table 3: Volume of the glacier estimated using different methodologies for years 1962, 1976, 1989, 2000, 2002, 2009 and 2011

Year	**Area**	**Volume**		
	km^2	km^3		
		Volume-area scaling Method	**Glacier Flow Mechanics method**	**Thickness-area relationship Method**
1962	4.63	0.235		0.178
1976	4.581	0.224		0.169
1989	4.443	0.222		0.167
2000	4.14	0.201		0.152
2002	4.00	0.192	0.192	0.144
2009	3.985	0.191		0.143
2011	3.942	0.188		0.141
Net Volume Loss (%)		19.84		20.32

3.2.3 Volume-area and volume-length scaling method

The relationship and values of constants derived by Chen and Ohmura, 1990 are used for the estimation of volume of the glacier. It has been found that the volume (km^3) of glacier in 1962, 1976, 1989, 2000, 2002, 2009 and 2011 is 0.235, 0.224, 0.222, 0.201, 0.192, 0.191 and 0.188. Thus, the percentage volume loss of East Rathong glacier according to volume-area scaling method from 1962-2011 is still 20%. The volume of the glacier could not be estimated using volume-length scaling method as the value of c_2 could not be found in the literature. But the method has been used to estimate the % volume loss from 1962-2011. The % volume loss has been found to be 23.6 %. Volume of the glacier estimated using different methods for years 1962, 1976, 1989, 2000, 2002, 2009 and 2011 have been mentioned in Table 3.

4. Discussion

A glacier shows changes in its length in response to variations in the rate of nourishment and wastage (Nye, 1963). East Rathong glacier has retreated at an average of 15.1m yr-1 for last five decades, which is comparable to rate of retreat for other glaciers in Himalaya- Gangotri glacier (19.9± 0.3m yr-1, 1965-2006); (Bhambri et al., 2012), Samudratapu glacier (18.45 m yr-1, 1963-2004); (Shukla et al., 2009), Dokriani glacier (16.6 m yr-1, 1962-1995); (Dobhal et al., 2004). Also, this retreat has been uniform for different time zones except for T1, ranging from 16-21 m yr-1 (Figure 5). Similarly, there is a continuous loss in glacierised area of east Rathong glacier, equivalent to 0.688 sq. km in five decades, but it doesn't show any trends which may link these losses to climate change phenomenon.

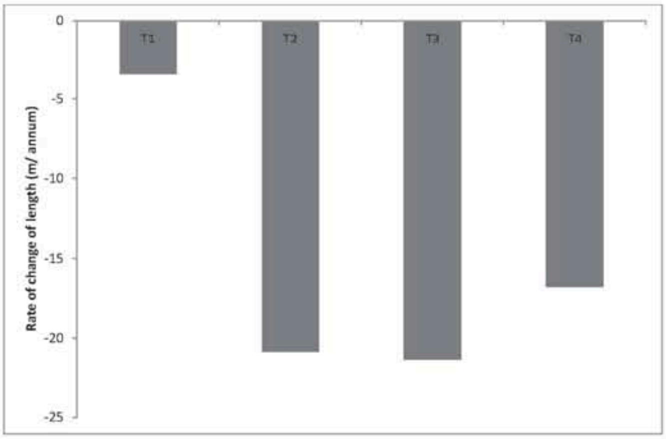

Figure 5: Rate of change of length of the glacier observed during time periods T1, T2, T3 and T4

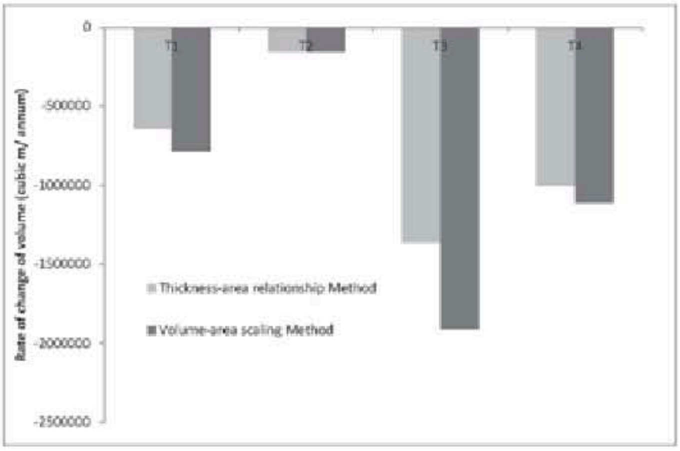

Figure 6: Rate of change of volume of the glacier observed during time periods T1, T2, T3 and T4

The glacier has lost 15% of the glacierised area from 1962-2011, which is again comparable to the area loss suffered by other glaciers in Himalaya-Gangotri glacier (5.67%, 1965-2006); (Haq et al., 2011), Samudratapu glacier (12.45%, 1963-2004); (Shukla et al., 2009), Dokriani glacier (10.25% loss in frontal area, 1962-1995); (Dobhal et al., 2004). The volume loss calculated using various methods based on glacierised area and length for different time periods as input shows that the total volume loss is higher than the total retreat and area loss. Also, the rate of change of volume does not show any particular pattern (Figure 6), which may link it to the climate change. However, considering the cumulative loss of 20-23% in ice content in 49 years, the glacier is certainly following the downward trajectory of depletion. Moreover, the pattern of loss has been continuous for different time zones, though following different rates. In-situ verification of satellite observations was performed to assess the position of glacier terminus. The field verification of the position of snout as well as GPS survey conducted in 2009 and 2010, identified two ice blocks downstream of present snout, completely detached from main glacier system. These dead ice blocks give an impression of continuity of glacier length through Landsat imagery of 2009. This observation has been used to correct the length and the area of the glacier estimated from 2009 Landsat imagery. Though it has not been possible to establish the date of detachment of these blocks, their position with respect to downward limit of snout position, indicates their origin to be recent. Furthermore, high rate of volume loss along with nearly constant AAR, suggests that rate of ablation is much higher than the rate of accumulation, for

East Rathong glacier. Considering the slow rate of snow-ice transformation and feeding to the glacier volume, results reflect that ablation zone melting dynamics is getting prominence recently, than usual straight line retreat in volume loss of the glacier.

5. Conclusion

Rate of retreat and area loss of East Rathong glacier in eastern Himalaya is seen to be comparable to the glaciers in other parts of Himalaya. However, ablation zone melting dynamics seem to be more prominent for East Rathong glacier, being reflected through detachment of ice blocks and changes in the thickness of the glacier, leading to significant amount of loss in ice content of the glacier. Rate of retreat and AAR are considered to be important parameters for studies on the glaciers in western Himalayas, but they do not indicate significant inferences for the east Rathong glacier in eastern Himalayas, as observed with constant retreat and AAR during past five decades, for east Rathong glacier. Hence, mass balance measurement through field based glaciological method is necessary to develop a complete understanding about the melt response of the glacier system to weather parameters.

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