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Preliminary Study on Estimation of Volume of Eastern Himalayan Glaciers Using Remote Sensing Methods

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Abstract: The volume of glaciers in Sikkim with specific reference to East Rathong glacier is estimated. The variability in the results from different methods of volume estimation is also studied. Volume of East Rathong glacier is estimated using on-field and off-field methods. Then volume of other 424 glaciers is estimated using off-field methods. Using the glacier outline from Randolph Glacier Inventory 5.0, a total of 424 Sikkim glaciers are analysed in this study. The area estimated is 509 km^2. Total volume of glaciers estimated using volume-area scaling method is 35 km^3. Estimates of the total volume and average thickness of these glaciers using slope-dependent method in 2008 are 51 km^3 and 100 m respectively. Estimates of the total volume (average thickness) of these glaciers using ice-flow velocity method in 2010 and 2014 are 48 km^3 (95 m) and 47 km^3 (93 m) respectively. The glaciers of Sikkim Himalaya seem to show annual mass balance of –0.44±0.2 m w.e. using ice-flow velocity method during the period of 2010-2014.

Slope of Sikkim glaciers is calculated from Cartosat-1 DEM 2008. Cartosat-1 DEM is validated with Global Positioning System (GPS) points. The volume of the ablation (Ab) zone of East Rathong glacier using GPS data is found to be 0.054 km^3. Its volume calculated using slope-dependent method is ~0.037 km^3 and using ice-flow velocity method is ~0.038 km^3. Volumes estimated for East Rathong glacier using field and off-field methods are comparable. The negative mass balance of Sikkim glaciers could be attributed to an increase in air temperature (0.23 °C/decade) at higher altitude (~5500 m a.s.l.) and reduction of precipitation as reported in Agrawal et al. (2014).

Keywords: Glaciers; Volume; Remote sensing.

Introduction

Knowledge of ice volume of glaciers is essential for study of many glaciological and hydrological processes like mass balance, glacier retreat and run-off etc. Global warming is going to affect water availability of regions dependent on glacier run-off. It has been observed that the Sikkim region is experiencing warming and change in water availability. Increased melting of glaciers will lead to problems in maintaining sustainable water supplies for regions dependent on Sikkim Himalayan glaciers. It is important to assess volumes of glaciers to plan for climate change adaptation and take necessary steps to stop the further degradation of the environment of eastern Himalayas.

Field studies of volumes and mass balances of glaciers of the Himalayas of Sikkim are few because of difficult terrain and access, thus making remote sensing methods important. Racoviteanu et al. (2015) reported glacier area loss in Sikkim during 1962-2000 as 88.9±5 km^2, i.e. 13% or 0.36±0.17% per year, which is lower than other glacierized areas world-wide (0.7% per year).

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They also reported from 2000 Landsat/ASTER analyses that the mean glacier size in Sikkim is 3 km^2; the mean slope is 23°; the median elevation is 5569 m a.s.l.; and the debris fraction is 23%. Frey et al. (2014) estimated mean ice thickness of Eastern Himalayan glaciers as 50.2 m (H & H slope dependent method), 54.6 m (GlabTop 2), 49.2 m (HF method) and 70.6 m (Bahr et al., 1997 scaling method). For Eastern Himalaya, no ice-thickness measurements are available. Mass balance of –0.16 m w.e. a^{-1} for Changme Khangpu glacier for Sikkim was reported based on glaciological measurements (Bolch et al., 2012). Mean recession rate of 26 Sikkim glaciers was reported for the period 1976-2005 as –12.2 m a^{-1} as seen by in situ measurements (Bolch et al., 2012).

There are a greater number of research publications on changes in mass balance from western Himalaya, but eastern Himalaya have not been explored that rigorously. In this paper, study has been carried out on Sikkim glaciers and their volumes have been estimated using remote sensing methods. Different methods are used and results compared and their suitability assessed for carrying out volume estimation of glaciers. Measuring the ice-thickness distribution of a glacier and finding an estimate of its total volume by means of borehole measurements and radio-echo soundings are expensive and difficult because of topographical constraints. Due to this, off-field methods are increasingly being used for volume estimation of glaciers. Farinotti et al. (2009) estimated ice-thickness distribution of alpine glaciers from surface topography using principles of mass conservation and ice-flow dynamics naming their method as Ice-Thickness-Estimation Method (ITEM). They calculated ice-flux using field values of mass balance and thickness change; ice-flux was subsequently used to estimate ice thickness by Glen's flow law.

Linsbauer et al. (2012) estimated ice thickness using surface slope data and assumption of perfect plastic flow with a constant basal shear stress; they termed their method as Glacier bed Topography (GlabTop). ITEM is not used in this paper as mass balance distribution data are not available over Sikkim glaciers. In this paper ice thickness is estimated by slope-dependent method (similar to GlabTop) and ice surface velocity method. Ice-surface velocity method is based on application of Glen's flow law to ice-surface velocity data calculated from satellite pictures (Gantayat et al., 2014). In this study, volumes of 424 Sikkim Himalayan glaciers are estimated using glacier outlines from Randolph Glacier Inventory (RGI) 5.0, Landsat 8 images of 2009, 2010, 2013 and 2014 and Cartosat-1 DEM 2008.

Study Area

In this study the focus is on Sikkim Himalaya. The state of Sikkim is surrounded by Nepal in the west, Bhutan in the east, China (Tibet) in the north and northeast (Chumbi valley) and Darjeeling district of West Bengal in the south. There are four basins in Sikkim. East Rathong basin has 36 glaciers. Talung basin has 61 glaciers. Changme-Khangpu basin is the smallest basin of Sikkim and has 102 glaciers. Zemu basin is the largest basin of all and has 250 glaciers divided into two sectors, Zema Chhu and Hema Chhu (Sangewar and Shukla, 2009). The state of Sikkim is situated between 27°00′46″ and 28°07′48″ N and 88°00′58″ and 88°55′25″ E. It has mountainous topography ranging from 300 to 8598 m a.s.l.. The highest concentration of glaciers is between 5000 and 6000 m a.s.l.. It receives an annual precipitation of 2000–4000 mm in which the Asian monsoon contributes more than 80% during the summer months (Basnett et al., 2013). The study area, with the glaciers whose volumes are estimated, is shown in Figure 1.

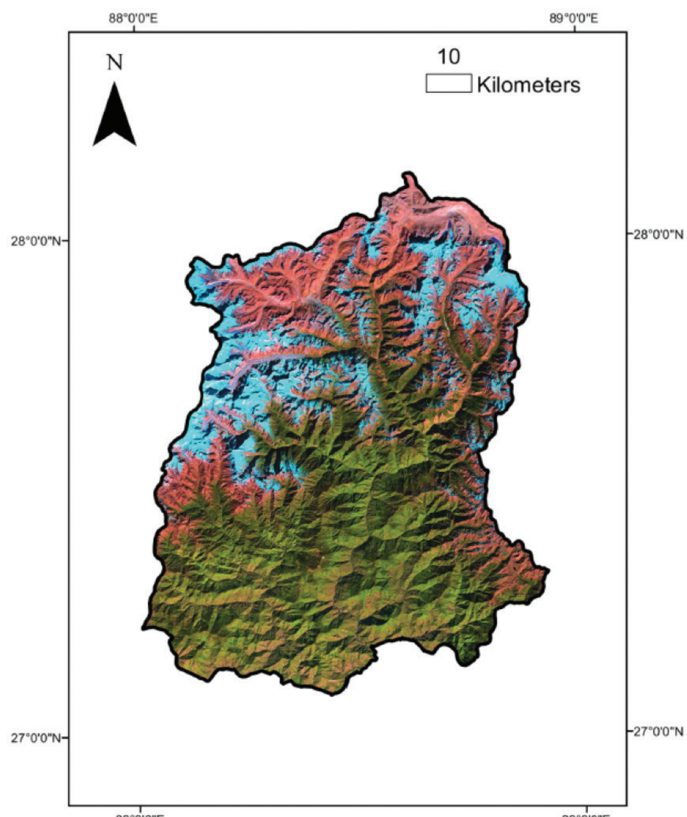

Figure 1: FCC of Sikkim (Landsat image: 27 August 2011).

Data Sets

Ground Data

Global Positioning System (GPS) Points

GPS points were collected during GPS survey conducted in 2009. 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 (Agrawal and Tayal, 2013). GPS readings were taken on the surface of the glacier and on the glacier-free bed around the glacier. A total number of 1334 points were collected for generation of the DEM.

Differential Global Positioning System (DGPS) Points

Twelve stakes are placed vertically across the centre of the Ab zone of the East Rathong Glacier. First stake is placed at the top of the Ab zone and twelfth stake is placed at the bottom near the snout of the Ab zone. Coordinates of stakes obtained using DGPS Trimble Geomatics during August-2011 and July 2012, are used in this study. These coordinates are used to calculate the velocity at these twelve points of the Ab zone of the glacier.

DGPS Trimble Geomatics is a high-performance DGPS with the integrated Space Based Augmentation System (SBAS), internal antenna, and EVEREST multipath rejection technology. It uses both EVEREST and H-star technology to provide sub-foot (30 cm) accuracy, either in real time or post-processing.

Satellite Data

Cartosat-1

Department of Space (DOS), Government of India, launched the Cartosat-1 satellite on 5th May ’05. The satellite provides high resolution near-instantaneous stereo data. It has a spatial resolution of 2.5 m and radiometric resolution of 10 bit quantization. The satellite carries two PAN sensors with fore-aft stereo capability. The high resolution stereo data can be used to generate high-quality DEM. CartosatDem of year 2006-2008 for Sikkim glaciers, used in this study, is downloaded from http://bhuvan3.nrsc.gov.in/bhuvan/bhuvannew/bhuvan2d.php.

Landsat

Landsat program provides the longest temporal coverage of multispectral satellite data.

Cloud-free and seasonal snow-free Landsat 2, 5, 7 and 8 images are downloaded from Earth explorer (http://earthexplorer.usgs.gov/).

Randolph Glacier Inventory 5.0

The Randolph Glacier Inventory (RGI) is a complete collection of digital outlines of glaciers. It does not include the ice sheets (Pfefer et al., 2014). The glacier outlines are delineated on latest landsat images (Arendt et al., 2015). In this paper RGI 5.0, downloaded from http://www.glims.org/RGI/index.html, are used.

Data sets used in the study are summarized in Table 1.

Methodology

Validation of Cartosat-1 DEM

For the points for which GPS coordinates are available, elevation values are also extracted from Cartosat-1 DEM. The elevation values extracted from Cartosat-1 DEM over East Rathong glacier show very high correlation with the elevation values from the GPS points collected on the glacier in 2009 (Figure 2), thus showing suitability of Cartosat-1 DEM for glacier studies.

Table 1: Details of the data sets used in the current study

Date	*Sensor*	*Mission*	*Path/Row*	*Pixel Res (m)*
30.11.1976	MSS	Landsat 2	149/41	60
26.12.2000	ETM+	Landsat 7	139/41	30
19.11 2009	TM	Landsat 5	139/41	30
23.09.2011	TM	Landsat 5	139/41	30
20.11.2013	OLI	Landsat 8 (band 8)	139/41	15
28.03.2014	OLI	Landsat 8 (band 8)	139/41	15
2006-2008	PAN	Cartosat-1 DEM		2.5
April 2009	GPS Survey	Trimble GeoXT		
August 2011, July 2012	DGPS Survey	Trimble Geomatics		
July 2015	RGI 5.0			

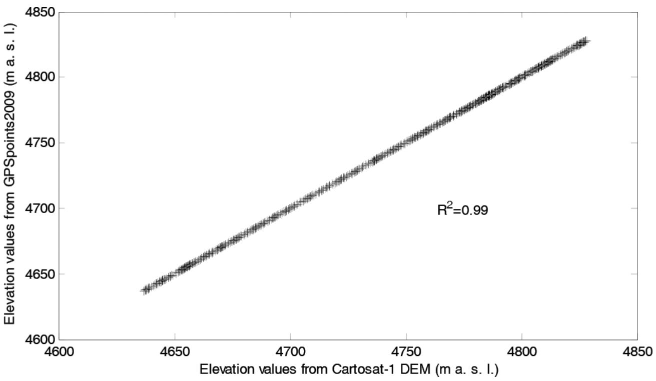

Figure 2: Elevation values of GPS, carried out in 2009 on East Rathong glacier, showing high correlation with elevation values obtained from Cartosat-1 DEM for the same region.

Volume Estimation of Sikkim Glaciers Using Remote Sensing

Volume of a glacier is one of the most important glaciological parameters. Methods based on volume-area scaling, slope and ice-flow velocity are used in this study for volume estimation of Sikkim Himalayan glaciers. Volume-area scaling is the most widely applied approach for assessing global inventories, e.g. Radic et al. (2008), Radic and Hock (2010) etc. Ice-flow velocity method was used for volume computation of Gangotri glacier by Gantayat et al. (2014). Slope dependent method was used by Frey et al. (2014) for volume computation of Himalayan glaciers.

Slope-dependent Method

Shapefiles of glaciers are extracted from RGI. Area and volume of 424 Sikkim glaciers are estimated. Following Cooper et al. (2007), slope-dependent method is used. Equation (1) is used to estimate ice-thickness distribution of the glacier:

$$\tau = f\rho g H \sin\alpha \text{ (Cooper et al., 2007)} \qquad (1)$$

where τ is the basal shear stress, ρ is the density of ice, g is the acceleration due to gravity, f is the shape factor, H is the ice thickness and α is the surface slope. Basal shear stress varies from 0.5 to 1.5 bar. Here value of τ used is 1.5 bar, value of g is ~9.81 m/s^2, and density of ice is taken as 900 kg/m^3 (Cooper et al., 2007; Oerlemans, 2001; Linsbauer et al., 2012). Here an average value of f = 0.8 is used for the entire glacier (Haeberli and Hoelzele, 1995; Linsbauer et al., 2012). Surface slope α is estimated from Cartosat-1 DEM elevation contours at 100 m intervals in order to get an average value of the surface slope over a reference distance which is about an order of magnitude larger than the local ice thickness (Linsbauer et al., 2012). Lower values of slopes give very high thickness estimates. Hence to avoid very large thickness values in very flat zones thresholding of the lower limit of the slope has been done; similar to Huss and Farinotti (2012), a value of 6° is assumed as the lower limit of the slope.

Triangulated Irregular Network (TIN) for the polygons of the glaciers is created from the raster, ‘thickness of the glacier’. Volume of every glacier is computed using function ‘polygon volume’ under ‘functional surface tool’ in Arc-GIS. The volume is computed above the reference plane.

The ground penetrating radar measurements were seen by Linsbauer et al. (2012) to be within 30% uncertainty range of ice-thickness calculated with GlabTop, i.e. slope-dependent method.

GlabTop method used by Linsbauer et al. (2012) finds thicknesses at points on central flowline. They found ice thickness distribution by inverse distance weighted interpolation using thickness values at base points. But in this study thickness is computed at every pixel of satellite image using equation (1), and volume of the glacier is computed by adding all pixel volumes.

Volume Estimation from Ice-flow Velocity Method

Volumes of the glaciers are estimated using ice-flow velocity method as well. The ice surface velocity is used to compute ice-thickness using the equation:

$$H = \sqrt[4]{\frac{1.5U}{Af^3(\rho g \sin\alpha)^3}} \text{ (Gantayat et al., 2014)} \quad (2)$$

Here U is the surface velocity of the glacier, A is the creep parameter (3.24×10^{-24} Pa^{-3}s^{-1}) for temperate glaciers (Cuffey and Paterson, 2010), and rest of the parameters ρ (density of ice), g (acceleration due to gravity), f (shape factor) and α (surface slope) have the same values as given in preceding section. The glacier ice is assumed to follow Glen’s flow rule with exponent n = 3.

Thickness raster prepared using equation (2) is used to prepare the TIN for the glaciers. Again ‘polygon volume’ function is used to compute the volume of the glacier.

Volume-area Scaling Method

Following Bahr et al. (1997), volume of the glaciers are estimated from volume-area scaling method.

Volume of a glacier can be computed using volume-area scaling relationship $V = cS^\gamma$ where γ is the scaling exponent derived from physical principles and has a value of 1.375 for valley glaciers; scaling parameter c is calculated by constrained regression from data of surface area and volume of glaciers of a region (Bahr et al., 2015). Bahr et al. (2015) expressed reservations about using scaling law for computing volume of an individual glacier. The method is suitable for estimating value of an ensemble of glaciers of a region. The value of scaling parameter *c* used in this paper is 0.034 $km^{3-2\gamma}$, which is worldwide mean of the scaling parameter (Bahr et al., 2015).

Meier et al. (2007) estimated that errors in volume estimation for individual glaciers can exceed 50% by volume-area scaling, but these uncertainties reduce to 25% for an ensemble of glaciers of a region. Scaling method provides an order-of-magnitude estimate of the volume of a glacier complex (Bahr et al., 2015). In this work, no regression analysis has been performed on a sample of glaciers from the region due to lack of field data, still the scaling method has been used with the help of universal scaling exponent γ equal to 1.375 and the world-wide mean value of *c* equal to 0.034 $km^{3-2\gamma}$.

Volume of Ablation Zone of East Rathong Glacier Using Field Measurements and Remote Sensing Methods

From the field expedition it is known that the altitude of snout is 4637 m, and its base is at 4630 m. The DEM for Ab zone (Figure 3) of the East Rathong glacier is prepared by transferring the GPS survey data, on the GIS platform. The ablation zone volume for this DEM above the reference plane 4630 m a.s.l. is estimated.

The length of the Ab zone is found to be 1.6 km. Width of the Ab zone at the top and bottom are found to be ~320 m and 45 m respectively. Slope profile is constructed for the 1.6 km length of exposed ground downstream of present glacier snout; it is used as the stratum for the location of glacier to develop the DEM of no glacier valley. GPS points are picked for this 1.6 km long stretch. A trapezium shaped shapefile is made with bases b_1 and b_2 equal to 320 m and 45 m. This shapefile and elevation values from the GPS points are subjected to Inverse Distance Weighted (IDW) interpolation to create the DEM for the region. There are several interpolation methods to create continuous data from the digitized contours like kriging, inverse distance weighted interpolation, splines (TOPOGRID) and TIN. The methods have their advantages and disadvantages (Lu and Wong, 2008). But here IDW is used for DEM creation.

Volume of the Ab zone is the volume of ice between the DEM of glacier surface and the DEM of no glacier valley. On the basis of the laws of similar triangles it is assumed that the volume estimated for the Ab zone of the glacier includes the volume of a part of bed-rock with slope similar to that of the trapezium built downstream of the glacier. Hence, the volume of the trapezium is subtracted from the volume of the Ab zone of the glacier. This corrected the total ice content for the Ab zone of East Rathong glacier.

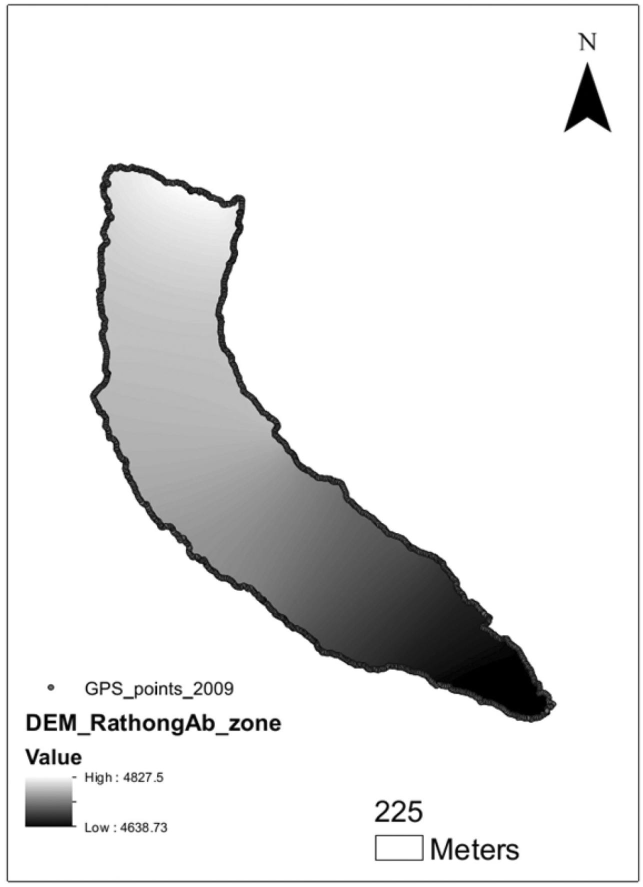

Figure 3: DEM generated, at resolution 2.5 m, for the glacier from GPS points collected in 2009.

Volume of Ab zone is also calculated using slope dependent method. Slope for the Ab zone is taken from Cartosat-1 DEM. The accuracy analysis of the DEM generated using GPS points is carried out. Elevation values of 120 uniformly distributed points are picked from the DEM. Elevation values of these points are correlated with the elevation values of Cartosat-1 DEM.

Volume of the Ab zone of the glacier is computed using ice-flow velocity method as well. Velocity of the Ab zone of the glacier at central flow-line is computed using DGPS points for year 2011-2012 (Figure 4). Velocity at every point of the Ab zone of the glacier is estimated by subjecting the central flowline velocity to IDW interpolation method. The velocity estimated is used to compute thickness of the glaciers using the ice-flow velocity method of computing thicknesses.

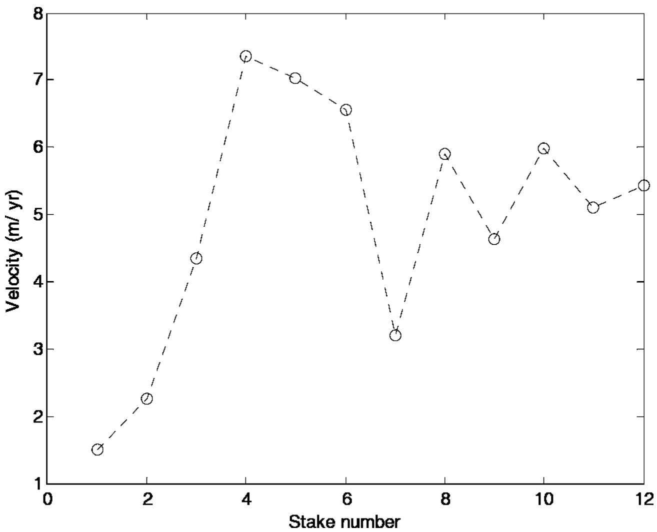

Figure 4: Velocity, computed using DGPS points of 2011 and 2012, of Ab zone of East Rathong glacier.

Uncertainty Analysis

The uncertainties in area, thickness, volume and mass balance are estimated as follows:

Uncertainty in Area

Perimeter of the glacier is estimated on ArcGIS platform. The perimeter is multiplied by half of the resolution of the pixel of the data set used for area estimation. This gives estimate of error in area, i.e. *dS*. This value is divided by the actual estimated area to obtain *dS/S*, which is ~5% in our case.

Uncertainty in Thickness Estimates

Uncertainty in Thickness Estimated Using Slope-dependent Method

Thickness of the glaciers is estimated using the equation:

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

The uncertainty in depth can be given as:

$$\frac{dH}{H} = \frac{d\tau}{\tau} + \frac{df}{f} + \frac{d\rho}{\rho} + \frac{dg}{g} + \frac{d\sin\alpha}{\sin\alpha} \quad (4)$$

Typical uncertainty of input parameters is (τ: 30%, α: 10%, *f*: 12.5%) (Linsbauer et al., 2012). Uncertainty in ρ is taken as 10%. Uncertainty in *g* is taken as zero. Summing all these uncertainties gives maximum uncertainty in thickness as 62%. If uncertainties in these parameters are treated as independent, probable uncertainty in thickness, i.e. 34% is computed by square-root of the sum of squares of individual uncertainties.

Uncertainty in Thickness Estimated Using Ice-flow Velocity Method

Thickness of the glaciers is estimated using the equation (2). The uncertainty in depth is estimated as.

$$\frac{dH}{H} = \frac{1}{4}\left(\frac{dU}{U} + \frac{dA}{A} + \frac{3df}{f} + \frac{3d\rho}{\rho} + \frac{3dg}{g} + \frac{3d\sin\alpha}{\sin\alpha}\right) \quad (5)$$

Uncertainty in the velocity estimated using satellite data is about ~5%. From Gantayat et al. (2014), *dA*/*A* has been taken as 0.26. Rest of the terms are same as described in preceding section. Maximum uncertainty in thickness calculation using equation (5) is estimated to be 35%.

Uncertainty in volume: The volume of a glacier is the multiplication of its average thickness by its area. The uncertainty in volume is therefore sum of uncertainties in area and thickness, i.e. 40%.

Uncertainty in mass balance: When volume of glacier is found using ice flow velocity method, uncertainty in mass balance can be approximated as sum of uncertainties of thickness and density (Agrawal et al., 2017), i.e. 45%.

Results

Validation of Cartosat-1 DEM

GPS points, 1334 in number, when compared with the Cartosat-1 DEM show RMS error 6.1 m with mean bias of –1.1 m. In Mukherjee et al. (2013), GPS points when compared with the Cartosat-1 DEM show RMS error 3.64 m with mean bias of –0.42 m. Evans et al. (2008) also concluded that Cartosat-1 data can be used to produce high quality DEMs; they found that Cartosat-1 absolute DEMs had vertical accuracies almost same as those derived from SRTM 30 m data.

Area, Thickness, Volume and Mass Balance of Glaciers Using Remote Sensing

RGI outlines and Cartosat-1 DEM gave the area and volume of 424 glaciers of Sikkim. The total area of the glaciers is found to be 509±25 km^2. Volume of Sikkim glaciers estimated using volume-area scaling relationship is 35 km^3.

Total volume of the glaciers is found to be 51±20 km^3 in 2008 using slope-dependent method. Total volume of the glaciers is found to be 48 km^3 in 2010 and 47 km^3 in 2014 using ice-flow velocity method. Thus the glaciers of the region are seen to show annual mass balance of –0.44±0.2 m w. e. using ice-flow velocity method for the period 2010-2014.

Kääb et al. (2012) reported mass balance of eastern Himalayan glaciers to be –0.38 m w.e./yr. This is close to the mass balance value estimated using ice-flow velocity method.

Volume of Ablation Zone of East Rathong Glacier Using Field Measurements and Remote Sensing Methods

The volume for the DEM made above the reference plane, for the Ab zone of East Rathong glacier using GPS data on the GIS platform, is found to be 0.055 km^3. DEM of no glacier valley corrected the total ice content to 0.054 km^3.

Volume of Ab zone, calculated using slope-dependent method where slope is derived from Cartosat-1 DEM (Figure 5), is found to be ~0.037 km^3.

Volume of Ab zone, calculated using ice-flow velocity method is found to be ~0.038 km^3. The volume of the Ab zone of the glacier computed using slope-method and ice-flow velocity method is 29% less than the volume computed using the field method.

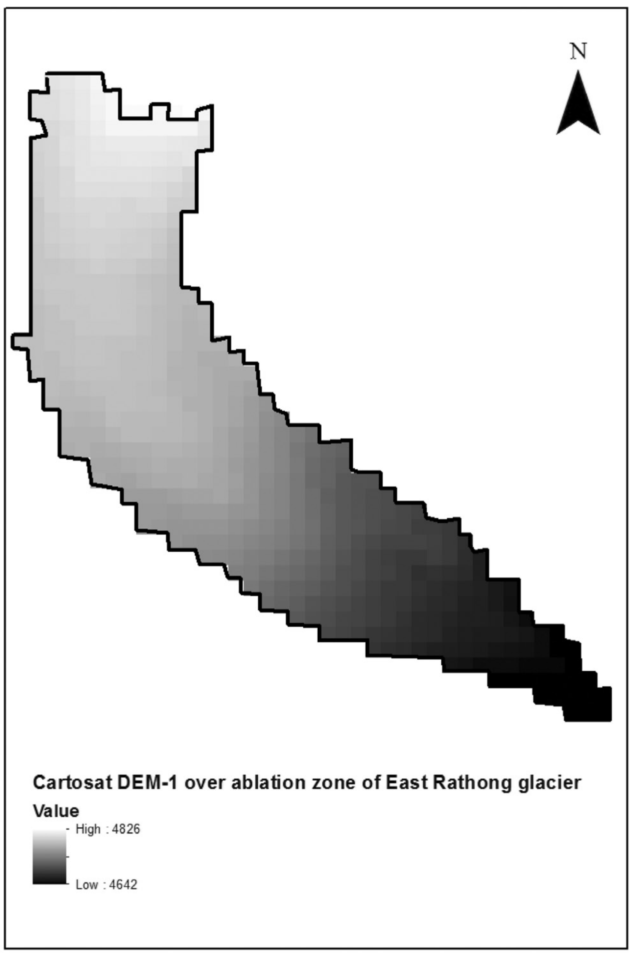

Figure 5: Cartosat DEM-1 over ablation zone of East Rathong glacier.

Accuracy analysis of the DEM generated using GPS points is carried out. Correlation between elevation values of 120 uniformly distributed points picked from the DEM generated for the glacier and elevation values from Cartosat-1 DEM is found to be very high (0.92, Figure 6). When compared with the Cartosat-1 DEM, RMS error computed for the DEM is 11.85 m with a mean bias of –2.43 m.

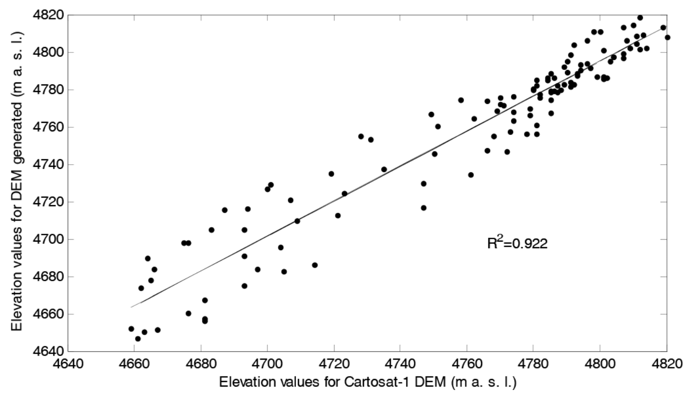

Figure 6: Elevation values of the DEM generated for the glacier and elevation values from Cartosat-1 DEM showing high correlation between them.

Discussion

A difference of 29% in the volume of Ab zone of East Rathong glacier estimated using field method and off-field methods is seen; it shows that ice-flow velocity and slope-dependent methods can be used for the assessment of volume of glaciers. Volumes estimated using these three different methods are found to be comparable.

Volume and area of 424 eastern Himalayan glaciers are estimated. Volumes estimated using slope dependent method and ice-flow velocity method are comparable. Uncertainties in the glacier's thickness and volume estimates computed using ice-flow velocity are c. 35% and 40%, respectively. The uncertainty in MB computed is 45%.

In this study, a mass balance of –0.44±0.2 m w. e. a^{-1} for the time period 2010-2014 is estimated. This is close to the value given by Kaab et al. (2012) which is –0.38±0.09 m w.e. a^{-1}, for the time period 2003-08. The negative mass balance could be attributed to an increase in air temperature (0.23 °C/decade) at higher altitude (~5500 m a.s.l.) and reduction of precipitation as reported in Agrawal et al. (2014). Shrestha et al. (1999) reported warming trends ranging from 0.06 to 0.12°C/yr in most of the Himalayan region from the analyses of maximum temperature data of 49 stations in Nepal for the period 1971-1994. Also Kulkarni et al.

(2011) reported that the climate change is responsible for the glacial retreat and negative mass balance in the Indian Himalaya.

Conclusions

The conclusions made from this study are as follows:

- The volume of the Ab zone of East Rathong glacier using Global Positioning System (GPS) data is found to be 0.054 km^3. Volume of Ab zone of the glacier calculated using slope-dependent and ice-flow velocity methods are ~0.037 $km^3$and ~0.038 km^3 respectively. Volumes estimated for Ab zone of East Rathong glacier using field and off-field methods are comparable.
- The total area of 424 Sikkim glaciers is estimated to be 509 km^2.
- Total volume (average thickness) of the Sikkim glaciers is found to be 48 km^3 (95 m) in 2010 and 47 km^3 (93 m) in 2014 using ice-flow velocity method. Total volume (average thickness) of the glaciers is found to be 51 km^3 (100 m) in 2008 using slope-dependent method. Volume of Sikkim glaciers estimated using volume-area scaling relationship is 35 km^3.
- Sikkim glaciers seem to show annual mass balance of –0.44±0.2 m w. e. using ice-flow velocity method during the period 2010-2014.

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