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Line of Sight Glacier Velocity Estimation of Transboundary Glaciers in Eastern Himalayas using High Resolution TerraSAR-X data. †

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Abstract: Glacier velocity is one of the critical parameters for understanding the current health status of a glacier. According to the momentum law, mass is inversely proportional to velocity. Higher velocity may indicate lesser mass. Fifteen transboundary glaciers from the eastern Himalayas in the vicinity of India, Nepal, Bhutan, and China are chosen for the estimation of glacier velocity. These glaciers are Changshang, Rathong, South Lhonak, South Simvo, Talung, Tongshiong, Yalung, Zemu, Glacier 2, Glacier 3, Kaer, Ktr Gr 193, Middle Lhonak, North Lhonak, and Ktr Gr 171 (Lhonak Nepal) covering total area of 440.92 km^2. A remote sensing and GIS-based approach is considered for the study. High-resolution Synthetic Aperture Radar data of TerraSAR-X was acquired from the German Aerospace Center (DLR) by European Space Agency for study area in the year 2020–2021. Satellite data are preprocessed using radiometric calibration and multi-look for speckle noise reduction. These datasets are co-registered using SRTM Digital Elevation Model. Offset Tracking is applied to estimate the glacier velocity. The maximum velocity in all glaciers ranged from 14.31-84.26ma^{-1}. The average velocity ranged from 1.78–7.09ma^{-1}. The glacier having highest average velocity is South Lhonak glacier. This glacier is melting rapidly in the last few decades. Near the snout of this glacier lies a glacial lake made up of a moraine dam. For quality assessment, latest field-based results of 2018 and observed results of 2021 were compared. It has been noticed that there is a variation of approximately 10%.

Keywords: glacier velocity; Eastern Himalaya; transboundary region; offset tracking

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1. Introduction

Glacier velocity estimation is very important because it is one of the parameters of glacier dynamics. It can help understand the health of a glacier because the momentum is directly related to the mass and the velocity is inversely related. As per the basic momentum law higher velocity could imply the decrease in mass. Though the slope parameters should be carefully considered before making any conclusion. The decrease in mass is one of the significant indicators of climate change. It is a general fact that climate change impact causes natural hazards like formation of glacial lakes which can cause Glacial Lake Outburst Floods (GLOFs). There are two approaches for the estimation of glacier velocity. One is the field-based method and other is remote sensing-based method. The field-based estimation is not possible in all the glaciers of the world. It is because most of the glaciers are inaccessible due to various reasons. For an example, in Himalayan region due to transboundary sensitivity and rugged terrain structure there are in accessibility concerns. This problem is solved though the use of satellite imagery.

In remote sensing-based method offset tracking is one of the widely used tools. Offset tracking method works well in the Himalayan region. There has been successful attempt of velocity estimation in the Chota Shigri and Bara Shigri glaciers [1]. Authors used SAR data from the sentinel 1 satellite to estimate the glacier velocity using the offset tracking method. It has also been observed recently that there is a direct relation between the mass balance and the glacier velocity [2]. Hence it is very important to estimate the glacier velocity. It is a well-known fact that in the Himalayan glaciers there is accessibility concern. In the Eastern Himalaya there are very less studies related to the glacier velocity estimation. In this study we attempt to solve this problem through the use of High-Resolution X band SAR data from the TerraSAR-X. We use the sub-pixel intensity based offset tracking to estimate the glacier velocity of 15 transboundary glaciers in Eastern Himalaya. Peak of these glaciers forms the boundary of three nations namely Nepal, India and China.

2. Materials and Methods

The study area is majorly situated in Sikkim, India. It is the landlocked transboundary border state of Nepal, China, and Bhutan. In the western part Sikkim lies Nepal and China. The bounding coordinates of the study area are 28° 06 ′41.25″ N and 26° 58 ′06.66″ N in North and South followed by 88° 53 ′41.57″ E and 88° 03 ′18.17″ E in East and West respectively. The above sea line altitude of the state ranges from 300m to 8,586 m at the Kanchenjunga peak. This peak is the 3rd highest mountain peak of the world.

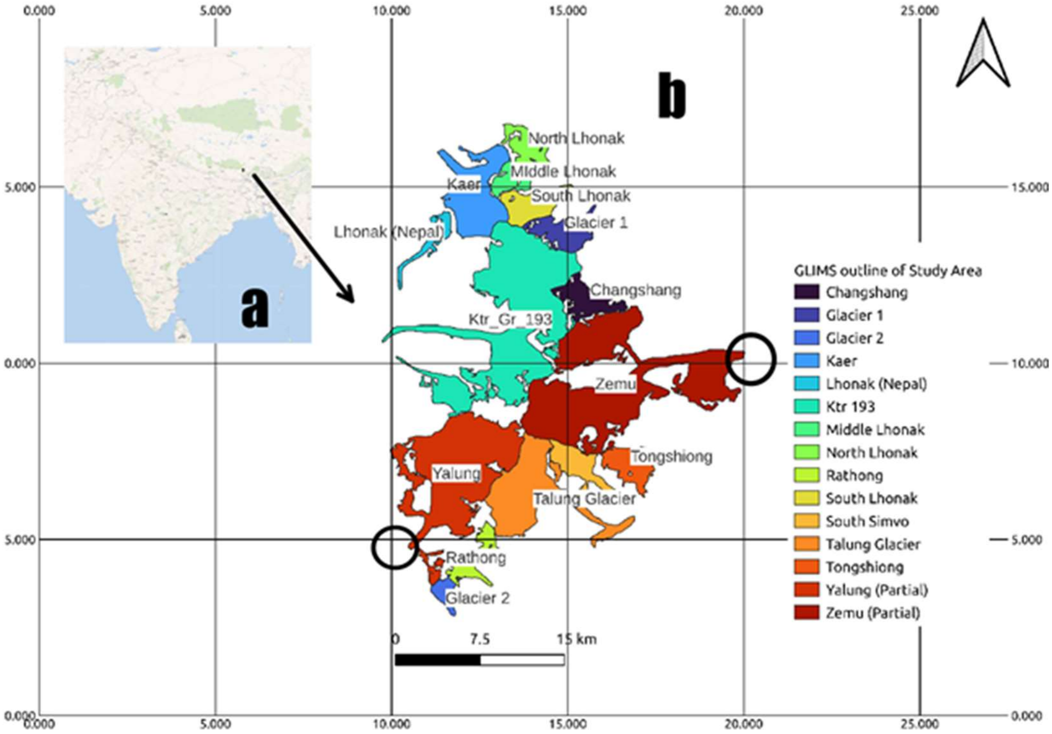

Figure 1. Study area map. (Credits: Corresponding author and GLIMS database).

The fifteen glaciers of the study area are Changshang, Rathong, South Lhonak, South Simvo, Talung, Tongshiong, Yalung, Zemu, Glacier 2, Glacier 3, Kaer, Ktr Gr 193, Middle Lhonak, North Lhonak, and Ktr gr 171 (Lhonak Nepal). These glaciers cover total area of 440.92 km^2 Ktr Gr 193 is the largest glacier in this location while glacier 3 is the smallest. East Rathong glacier is the benchmark glacier for the field studies while Zemu glacier is the origin of the Teesta River that flows till Bangladesh via the Sikkim and West Bengal. GLIMS outline is used to delineate the glacier boundary. In the whole region due to the swath limitation Zemu and Talung covers 98% of the glacier area. The terminus portion is ignored due to this reason.

3.2. Data

TerraSAR-X Stripmap products are acquired by the European Space Agency. It is a Sun-synchronous repeat orbit satellite. The range and azimuth resolution is 1.36m x 2.23m and operates on a 31mm wavelength and 9.6 GHz frequency. Chirp bandwidth is 150 MHz / 300 MHz with the nominal acquisition direction at Right side. The TerraSAR-X data is preferred because of its high resolution and the better quality.

Table 1. Time series data for the study area.

S.No	Date of Acquisition	Season	Polarisation	Range and Azimuth Resolution (m)	Pass	Incidence Angle (degree)
1	03rd Oct. 2020	Early Winter Accumulation	HH	1.36/2.23	ASCENDING	43.36 - 45.47
5	20th Sept. 2021	Autumn Ablation	HH	1.36/2.23	ASCENDING	43.36 - 45.47

3.4. Pre-Processing and Offset Tracking

The data was acquired by the European Space Agency on slant range format. For the line-of-sight velocity the slant range information is not required (Prati, 1993.) . The conversion of slant range product to the ground range product is the pre-processing required for the offset tracking. It is done after following the applying radiometric calibration and speckle noise removal.

A Radiometric Calibration is applied for the conversion because ground range products need backscatter conversion for understanding the characteristics of backscatter coefficients. Sentinels Application Platform (SNAP) uses following equation for the conversion.

$$i = \frac{DN_i}{A_i^2}$$

It is a well-known fact that SAR image contains speckle noise [4] .For the reduction of the speckled noise images are joined incoherently. This process is called multilooking. Major advantage of multilooked image is its interpretability and better visual appearance. SNAP software is used to create a warp polynomial of order 3 to map the ground range pixels to slant range pixels. Further every pixel in the ground range computes the corresponding pixel position in the slant range image using the warp polynomial. On the final step pixel value is estimated using the nearest neighbour interpolation.

Offset Tracking is used to track the offset in the slave image. A master image is the one that is being compared. A coregistration is performed to the master and slave images [5] . Offset Tracking through the SAR data is most commonly used for the estimation of Glacier Velocity. As per various authors this method is ideal for estimation of glacier velocity across the glaciers of the world. [6–8] . A 128-pixel window is chosen to track the offset in a master and slave image. Maximum velocity is set to be 0.25m/day [9]. The last step is to geocode the offset tracking results. The topographical variations in the scenes as well as the tilt of the sensor along with the distances are sensitive the distortion in SAR images. A Terrain correction is applied to rectify the distortions in the SAR images [10]

3. Results and Discussion

The glacier velocity of the 15 transboundary glaciers is estimated through the offset tracking method. The maximum average velocity is observed in the South Lhonak lake (Table 2). Minimum average velocity is observed in the Glacier 3. Near the snout of the south Lhonak lake there is a presence of a glacier lake which is expanding at the rapid rate [11,12]. As per a study by [13] it is observed that high flow results in a higher melting. The higher average velocity of South Lhonak glacier could be one of the reasons of increase in the size of the lake. The average annual velocity of the large glaciers like Ktr gr 193, Zemu, and Yalung having surface area of more than 60km^2 have relatively lower than that of South Lhonak Glacier. The maximum velocity of South Lhonak Glacier is also relatively higher than that of glaciers having similar surface area like Rathong, Middle Lhonak, South Lhonak and Lhonak (Nepal). A study has observed that maximum velocity of the glaciers in western Himalaya ranges from 50–90 m/a [14]. We observe maximum velocity of glaciers having similar surface area to be ~52–84 m/a. A study observed higher velocity trend [15] in slopy regions of the Himalaya. The velocity values in the slopy regions as per this study was greater. This study had only used time gap of 6 months. High velocity in regions having higher slope is justifiable because of gravity factor. In the line-of-sight approach the analysis is completely based on the movement of the satellite sensor. Slope factor is not considered due to this reason. There could be variations in the results based on different approaches.

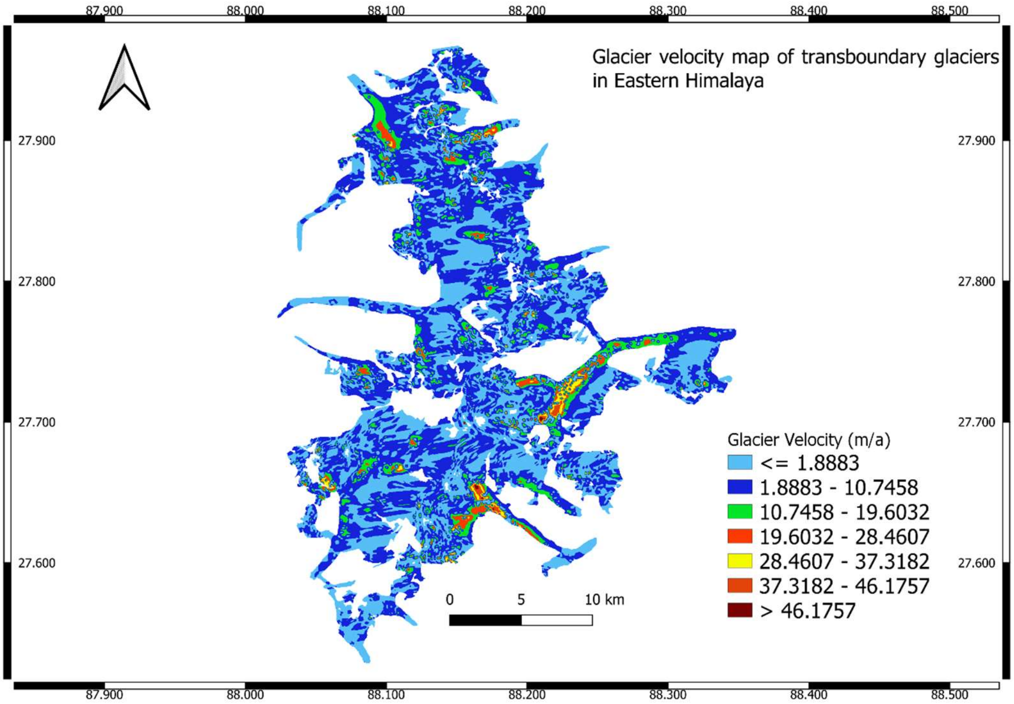

Figure 2. Glacier velocity map of transboundary glaciers in Eastern Himalaya.

Table 2. Velocity estimates of 15 glaciers in transboundary Eastern Himalaya.

Glacier Name	Mean Velocity	Maximum Velocity	Variance
Changshang	3.74	26.69	0.04
Glacier 2	3.62	25.43	0.03
Glacier 3	1.78	14.31	0.01
Kaer	5.94	33.69	0.08
Ktr gr 193	4.41	26.76	0.06
Ktr gr 171	2.77	12.40	0.01
MIddle Lhonak	4.61	43.80	0.09
North Lhonak	4.03	30.04	0.04
Rathong	3.15	26.03	0.04
South Lhonak	7.09	55.03	0.16
South Simvo	3.48	20.72	0.04

Talung Glacier	5.99	51.80	0.18
Tongshiong	2.76	34.90	0.03
Yalung	3.62	39.15	0.05
Zemu	4.85	84.26	0.12

In the study area field data of glacier velocity is available only for the benchmark outline of East Rathong Glacier. The last field-based survey was done in the ablation season of year 2018. The average velocity value of 8 different points for a year in the benchmark outline was estimated to be 5.92m/a (For ablation season). It is compared with the average velocity value of same points in the TerraSAR-X offset tracking estimates. The value is observed to be 6.61m/a. Variation of approximately 10% was observed in the field value of year 2018 (ablation season converted into yearly scale) and direct yearly estimates of 2020–2021. This is not a direct validation of the results but an estimate of variation from latest available field data.

4. Conclusion

Variation in glacier velocity could indicate significant changes in glacier health. As per the basic momentum and angular momentum law an increase in velocity is capable of decrease in the mass of a glacier. It is one of the very important parameters to estimate the present flow conditions and mass of a glacier. There are many empirical relations that can be used to estimate overall glacier mass using shallow ice approximation methods [16,17] Hence it is important to create a baseline data for future study. This study creates a baseline average velocity and maximum velocity using high resolution TerraSAR-X data. The chosen study area is the transboundary region of the eastern Himalaya. This transboundary region is the border of four nations India, Nepal, Bhutan and China. The maximum velocity in all the glaciers ranged from 14.31–84.26m/a. The average velocity ranged from 1.78–7.09m/a. The glacier having highest average glacier velocity is observed to be South Lhonak Glacier. This glacier is melting rapidly in the last few decades. At the snout of this glacier lies a glacier lake made up of moraine dam. It is the direct evidence of climate change for the regional policy formation. For the quality assessment of the results, latest field-based results of 2018 and the observed results of 2021 were compared. A variation of approximately 10% was observed.

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Conflicts of Interest: Authors declare no conflict in interest for the above research.

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