Analysis of glacier flow trends of East Himalayan Glaciers using Remote Sensing Datasets

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***Abstract*- Glacier velocity is one of the most important parameter used in glacier dynamicsstudies. Various image matching techniques implemented in different domains, have been utilized to estimate the surface velocity of glaciers. Feature tracking using remote sensing is widely used method to estimate glacier velocity. In this study, an analysis is done on the annual glacier flow trends from year 2016 to 2021 on three selected glaciers of East Himalayan Region using GIV tool. The glaciers are Zemu glacier, South Lhonak glacier and East Rathong glacier. Glacier Image Velocimetry (GIV) is feature tracking based open-source tool available which can automatically detect, filter, and extract velocities from hugedatasets. To check the performance of the GIV tool, this study evaluates this toolusing all available optical satellite datasets such as Landsat and Sentinel-2. The velocity measurements from the GIV tool are validated against In-situ data from Kongsvegen glacier located in Norway where stake-wise field data is available. Velocity measurements estimated from GIV tool for all four glaciers were also validated against Stable Ground Velocity calculated by GIV tool. The annual glacier velocity values from GIV tool were found to be almost double with respectto those obtained from in-situ measurements on Kongsvegen glacier. Glacier velocity measurements from the GIV and Cosi-Corr tool (SAR dataset) were found in good agreement on Kongsvegen glacier. The stable ground velocity of all the four glaciers is found to be well within the allowed limit. From trend analysis, it was found that Zemu glacier which has surface area of 70 km^2 has increasing velocity trend and other two small glacier 8-12km^2 of area, South Lhonak and East Rathong glacier have stagnant velocity trend.**

Index Terms—Glacier velocity, Feature Tracking, Glacier image velocimetry (GIV),Sentinel-2,Remote Sensing, Stable Ground Vrlocity

I INTRODUCTION

Glaciers and glacier change are of strong global significance, and we cannot understand their mechanisms by analyzing one single glacier. Thus, in this study repeat satellite imagery is used to estimate a large number of glaciers in the western Himalayan region. This research outlined a GIV pathway for processing massive amounts of data from several sensors to generate high-quality maps of Annual Glacier Surface Velocity. GIV's goal is to deliver an easy-to-use, flexible, and strong tool for glacier velocity estimation. GIV can provide high-resolution surface-velocity maps of glaciers of all sizes. In this study, the GIV tool will be extensively validated on different types of glaciers in the Eastern Himalayas. In this report by using this new workflow of the GIV toolkit, going to check the performance of GIV by comparing with In-situ measurements and also explore Landsat & Sentinels' capability to mapthe surface speed of glaciers on the KONGSVEGEN GLACIER, ZEMU GLACIER, SOUTH LHONAK, and EAST RATHONG GLACIER. The quality of the maps produced is then assessed by comparison of the resultsgained from ITS LIVE measurements. And finally, estimates the Annual Glacier Surface Velocity of ZEMU, SOUTH LHONAK, and EAST RATHONG GLACIERS from 2016 to 2021 to find out thetrend of the surface velocity of EASTERN HIMALAYAN GLACIERS.

II LITERATURE

A review of existing scientific literature on the following subjects is presented in this chapter:

- Methods to Annual Glacier Surface Velocity estimation
- Background of Feature tracking Method
- Cross-correlation algorithms used in the feature

tracking method

- Different Tools available for estimating glacier velocity using Feature Tracking

III SYESTEM DEVELOPMENT

- Define Project Requirement: Describes the study area we have chosen to perform the velocity analysis and describes the dataset used in the analysis.

Locations of the study glaciers: Kongsvegen Glacier (Norway), Zemu Glacier (India), South Lhonak Glacier (India), and Rathong Glacier (India).

- Collect Details Of Study Glaciers:

Glacier	Lat/Long	L (km)	Country	Ht (m)
Kong svegen	78°49′ 0″N/ 12°46′36″E	27	Norway	73- 1015
Zemu	27°45′0″N/ 88°16′0″E	26	India	4266-7379
South Lhonak	27°56′50.93″S/ 88°19′53.54″W	6.1	India	5202-7409
East Rathong	27°34′10″N/ 88°6′33″E	6.6	India	4615-7103

- Optical Datasets:Optical dataset used for glacier velocity estimation

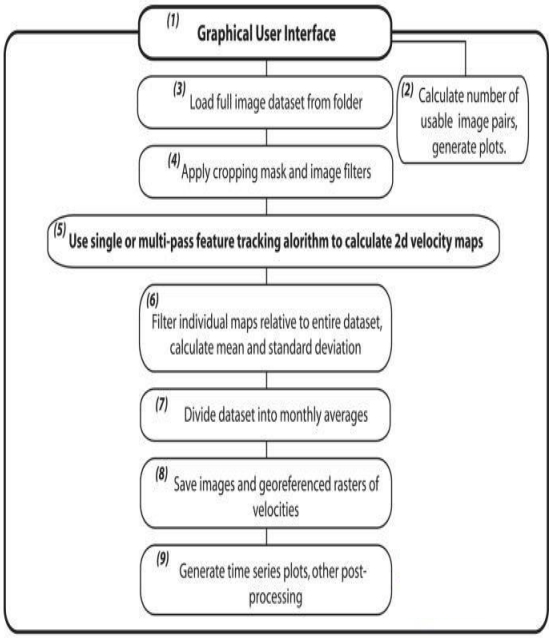
Glacier	Sensor	Year	Band No.
Kong svegen	Landsat-8 (OLI)	2016-17-2017-18	Band 8 PAN (0.5 - 0.68 µm)
	Sentinel-2 (MSI)	2015-16-2016-17	Band 8 NIR (0.85–0.87µm)
Zemu	Landsat-8 (OLI)	2016- 2021	Band 8 PAN (0.5 - 0.68 µm)
	Sentinel-2 (MSI)	2016-2021	Band 8 NIR (0.85–0.87µm)
South Lhonak	Landsat-8 (OLI)	2016 to 2021	Band 8 PAN (0.5 - 0.68 µm)
	Sentinel-2 (MSI)	2016-2021	Band 8 NIR (0.85–0.87µm)
East Rathong	Landsat-8 (OLI)	2016-2021	Band 8 PAN (0.5 - 0.68 µm)
	Sentinel-2 (MSI)	2016to 2021	Band 8 NIR (0.85–0.87µm)

- Collect In Situ Datasets: For validation GIV tool, here we used the In-situ velocity values of the Kongsvegen glacier for the year 2016-17 and 2017-18. Repeated GPS readings of stakes were gathered between 2004 and 2020 for this study's in-situ data. In August/September of each year, the stakes are assessed. In addition, measurements for the summers of 2018, 2019, and 2020 weretaken. The summer period flow speeds are calculated by comparing the position in April to theposition in August/September and calculating the difference. As not In-situ measurement is available for all other Himalayan glaciers, where another method (Stable ground Velocity) is used to validate the GIV tool for the Himalayan glacier.

IV SYSTEM PERFORMANCE

- Glacier Image Velocimetry Toolbox: Progress in remotely sensed glacier velocity estimation techniques and their evolution through time were critically examined. The challenges in the existing approaches to velocity estimation for data-scarce regions were highlighted and the opportunities to incorporate new ways to automate the glacier surface velocity estimation weresummarized.

Below are the steps involved in determination of glacier velocity



Flowchart of the Glacier Image Velocimetry toolbox design.

Model Pre Processing: Satellite imageries are first

brought into the workspace and then filtered before the feature tracking algorithm is executed. The user interface will prompt them to provide the image coordinates as minimum-maximum latitude and longitude, as well as pick the folder where the photographs will be saved. Then GIV extracts the dates and resolution from file manes and images, calculates the time difference between the images, and loads the raw imagesinto an array for processing. A photograph with an area of interest transformed to pure white is also provided by the user (RGB 255, 255, 255). The photos are then put into GIV and transformed into a binary mask with areas inside (1) and outside (2). Images' resolution and size are also calculated automatically and resampled to a similar resolution, allowing images from several satellites to be integrated into the same collection.GIV make use of following filters

- Orientation filter
- Histogram equalization
- High-pass filter

Velocity Calculation:Steps involved in velocity calculation are

- Calculate image pairs: GIV generated plots one gives total no. of image pairs and other gives temporal oversampling value.
- Frequency domain matching: Here GIV automatically calculates the window size, where GIV has a 'resolution' parameter you can set (in the 'Advanced' options tab, set to 50 meters by default). This is your 'ideal final' resolution, and GIV then back-calculates a window size from this.
- Parallel computing: Displacements are calculated in parallel on the picture pairs inside each sub-sequence. As a result, large datasets may be analyzed more quickly.

- Velocity Map Filtering And Improvement: GIV toolkit used this property to improve the last velocity maps by using the subsequent criteria and methods.
  - Georeferencing and plotting: This is the final stage, in which GIV georeferenced the velocity maps and saves them to the user's machine in Geotiff format.
- Sensitivity Analysis: In this section, to well appreciate the effect of different parameters on Annual Glacier Surface Velocity sensitivity analysis has been carried out. where four different parameters Window-size (output resolution), Pre-processing filter, Peak ratio, and Input images used in this analysis which is required to estimate Annual Glacier Surface Velocity using the GIV tool.
  - Sensitivity analysis of glacier velocity to window size:

Window-size	RMSE (m/yr)	
	Sentinel-2	Landsat-8
5x5	17.48	19.9
16x16	11.14	13.17
24x24	12.86	11.54
32x32	13.38	12.72

Summary RMSE values of all window-size used to estimate Annual Glacier Surface Velocity of Kongsvegen glacier for year 2017-18.

we can see that velocity using Sentinel-2 over-estimates in all parts of a glacier while velocity using Landsat-8 under-estimates the velocity in the ablation zone of

a glacier and over estiatems in the accumulation zone of the glacier.

Sensitivity analysis of glacier velocity to pre-processing filter: Here, Annual Glacier Surface Velocity is computed using different pre-processing filters. Velocity is claculated using CLAHE, CLAHE+High, and Orientation filter and then compared with velocity computed from the raw input image.

Filters	RMSE (m/yr)	
	Sentinel-2	Landsat-8
RAW	11.14	11.54
CLAHE	10.29	15.44
CLAHE+High	11.85	13.31
Orientation	9.69	10.15

Summary RMSE values of all pre processing filters used to estimate Annual Glacier Surface Velocity of Kongsvegen glacier for year 2017-18.

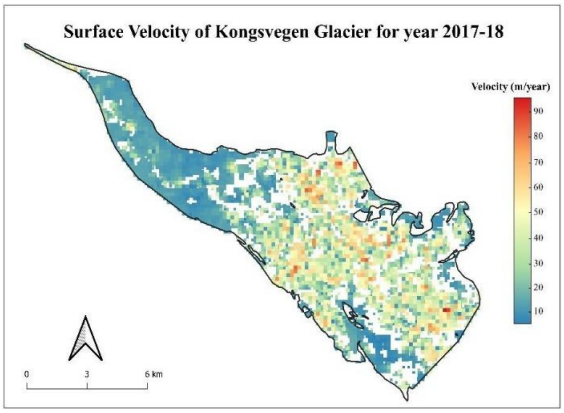
- Sensitivity analysis of glacier velocity to peak ratio: The peak ratio values are sensitive to slightly different values of noise and are extremely useful for outlier removal. Peak ratio will identify false matches in areas with multiple similar features to match (e.g., along a continuous,featureless medial moraine). $Peak\ Ratio$ =Correlation value at peak/Correlation at second highest peak.

Peak Ratio	RMSE (m/yr)	
	Sentinel-2	Landsat-8
1	4.62	3.42
1.25	3.46	2.44
1.5	2.99	2.33

1.75	2.93	2.33
2	2.87	1.26

Summary RMSE values of all Peak Ratio values used to estimate Annual Glacier Surface Velocity of Kongsvegen glacier for year 2017-18.

- Validation of GIV software using In-situ Data:



GIV tool Estimated Annual Glacier Surface Velocity of Kongsvegen glacier for year 2017-18

- Estimation of the Annual Glacier Surface Velocity of three Himalayan glaciers from 2016-2021:

Glacier	Mean Velocity
Zemu glacier	17.73
South Lhonak Glacier	11.89
East Rathong Glacier	15.42

Mean velocity of all three-glacier form year 2016 to 2021

V CONCLUSION

In this study, a feature tracking-based GIV tool for estimating glacier-wide annual Annual Glacier Surface Velocity has been successfully applied and validated for the Kongsvegen glacier (Norway) from 2017-18 during which field velocity measurements were available. After validation, the tool has been used to analyse the trends of glacier flow on three East Himalayan glaciers from year 2016 to 2021. The following section gives the major conclusions drawn from this study.

Glacier Image Velocimetry (GIV) tool was evaluated in this study on four different glaciers and validated it using two different methods, one with In-situ measurements on Kongsvegen glacier and another is stable ground measurements on Zemu, South Lhonak, and East Rathong glacier. To check the effectiveness of different parameters on glacier velocity, a sensitivity analysis is performed on various parameters utilized in the GIV tool. GIV's versatility, ease of use & capacity to quickly analyze massive datasets for computing glacier velocities are demonstrated by the findings of all four glaciers. GIV is simple to understand and use, and the results it generates are simple to replicate. GIV permits users to change image processing and feature tracking parameters depending on their professional knowledge of individual glaciers without needing to know how to code. The study's second goal is to determine the trend in glacier flow for three Himalayan glaciers from 2016 to 21. When it comes to glacier flow trends, there must be three categories: increasing, decreasing, and stagnant. We classified glaciers using a trend line. Zemu glacier has an increasing trend with an R2 of about 0.315, and South Lhonak & East Rathong glacier has a stagnant trend with R2 values of 0.07 and 0.056. And finally, the estimated glacier velocity from the GIV tool is compared with ITS LIVE measurements. A detailed comparison is made at three different cross-sections of each glacier at the upper, center, and lower zone of a glacier. From this analysis, we found that velocity in the lower zone of a glacier is lesser than in all other zones in every glacier. A rapid change in velocity values was found between the upper zone and central zone of the Zemu glacier due to the sudden change in elevation in the upper zone. Whereas in South Lhonak glacier velocity got higher at the end of the accumulation zone. Velocity measurements from Sentinel-2 data are found much more similar to ITS LIVE measurements than the Landsat-8 measurements.

- FUTURE SCOPE: This research can also be carried out to calculate glacier volume and ice thickness of this glaciers utilising glacier velocity obtained in this study. The GIV tool may be put through its paces on various levels of debris covering glaciers and glaciers in the polar zone. This will assist us in determining the tool's worldwide application potential. Currently, the GIV tool only uses an optical satellite dataset, further, there is scope to advance this tool to the SAR dataset which found to be higher accuracy velocity measurements proven in previous

various studies.

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