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Estimation of Glacier Retreat/Advance for the Baspa Bamak Glacier Using Remotely Sensed Data

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Abstract

This study aims to estimate the retreat or advance of the Baspa Bamak glacier in the Baspa basin, Himachal Pradesh, by utilizing remotely sensed data. The dynamic nature of the glacier snout, which changes its position over time, necessitates the generation of a time series of snout positions using satellite imagery for different periods. The selected images must be cloud-free and correspond to the end of the ablation season to ensure the snout is fully exposed. Landsat images, known for their high spatial and radiometric resolution, have been chosen for mapping and extracting the glacier snout. Eight Landsat images were downloaded in L1T data type and GeoTiff format from the USGS Earth Explorer website for this study.

Introduction

Glaciers are sensitive indicators of climate change, and their retreat or advance provides critical insights into the global climate system (Oerlemans, 2001). The Baspa Bamak glacier, located in the Baspa basin of Himachal Pradesh, India, has experienced significant changes over the past few decades. This study utilizes remote sensing data to monitor these changes, focusing on the glacier snout's position over time. Remote sensing has proven to be a valuable tool in glacier monitoring due to its ability to cover large and inaccessible areas with high temporal frequency (Paul et al., 2013).

Importance of Glacier Monitoring

Glacier monitoring is essential for several reasons. First, glaciers serve as vital freshwater reservoirs, especially in regions like the Himalayas, where they contribute significantly to river systems. Second, understanding glacier dynamics helps in predicting potential natural hazards, such as glacial lake outburst floods (GLOFs), which can have devastating impacts on downstream communities. Finally, glacier retreat is a critical indicator of climate change, providing tangible evidence of warming trends and their impacts on natural systems.

Study Area: The Baspa Bamak Glacier

The Baspa Basin, located in the Kinnaur district of Himachal Pradesh, is characterized by rugged terrain and significant glacial coverage. The Baspa Bamak glacier is one of the prominent glaciers in this basin. The region experiences a typical Himalayan climate with cold winters and moderate summers, which influences the glacier's seasonal ablation and accumulation patterns. Understanding the behavior of the Baspa Bamak glacier is crucial for water resource management and climate impact studies in the region.

Baspa glacier is compound valley type alpine glacier which extends over *31⁰11'26''-31⁰15'04''* N latitude and *78⁰41'11''-78⁰50'26''* E longitude. River Baspa originates from this glacier, and this is the largest glacier of Baspa basin. The maximum length of the glacier along its centreline is 18.4 km from snout to upper accumulation zone. The glacier has various erosional and depositional glacier morphological features like moraines, crevasses, glacier till, cirques, glacier tables, moulins etc. The glacier is oriented roughly N-S in its ablation area and has a variety of orientations in the accumulation area. The glacier has approximately 33 km^2 aerial extent with elevation ranges from 4302m to 6054m asl having mean elevation of 5150m asl whereas the accumulation area has a mean elevation of 5563m (year 2015).

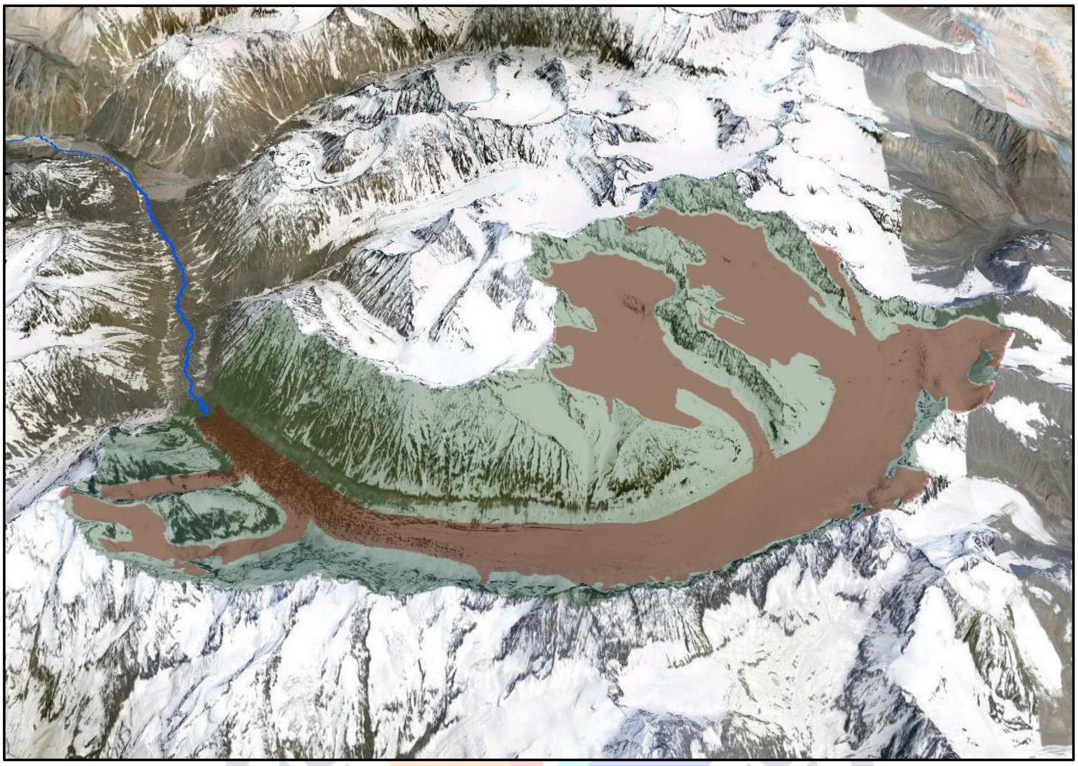


Figure 1: Baspa Bamak glacier (GLIMS ID. G078779E31218N) and its watershed (Base map: Google Earth).

Materials and Methodology

Data Collection

The selection of appropriate satellite imagery is a crucial step in studying glacier dynamics. For this study, eight cloud-free Landsat images were selected, ensuring that the acquisition dates corresponded to the end of the ablation season. This timing is essential as it guarantees that the glacier snout is fully exposed, making it easier to delineate and analyze. The images, known for their high spatial and radiometric resolution, were downloaded from the USGS Earth Explorer website in L1T data type and GeoTiff format (Kulkarni et al., 2007).

Table 1: List of Satellite images used for snout demarcation and their specifications.

	Satellite Image	WRS Path/Row (Lat./ Long.)	Sensor Identifier	Date Acquired	Image Quality	Scene Cloud Cover
1	LT51460381994273ISP00	146/ 038	5_TM	30/09/1994	9	01.00
2	LT51460381997265ISP00	146/38	5_TM	22/09/1997	9	03.57
3	LE71460382001252SGS00	146/38	7_ETM	09/09/201	9	5.32
4	LE71460382003274ASN01	146/38	7_ETM	01/10/2003	9	08.34

5	LE71460382008256ASN00	146/38	7_ETM	12/09/2008	9	02.12
6	LE71460382011264PFS00	146/38	7_ETM	21/09/2011	9	01.34
7	LC81460382014264LGN00	146/38	OLI_TIRS	21/09/2014	9	03.78
8	LC81460382015251LGN00	146/038	OLI_TIRS	08/09/2015	9	6.05

Image Pre-processing

Image pre-processing is essential to enhance the quality and usability of the satellite images for detailed analysis. This study involved several pre-processing steps. Firstly, ortho-rectification was performed to geocode the images in WGS84, UTM Zone 44, ensuring that the spatial positioning of the images was accurate. Radiometric calibration followed, converting the digital number (DN) values of the images to reflectance. This step is crucial for correcting any sensor-related distortions and ensuring that the images accurately represent the Earth's surface reflectance (Chander, Markham, & Helder, 2009).

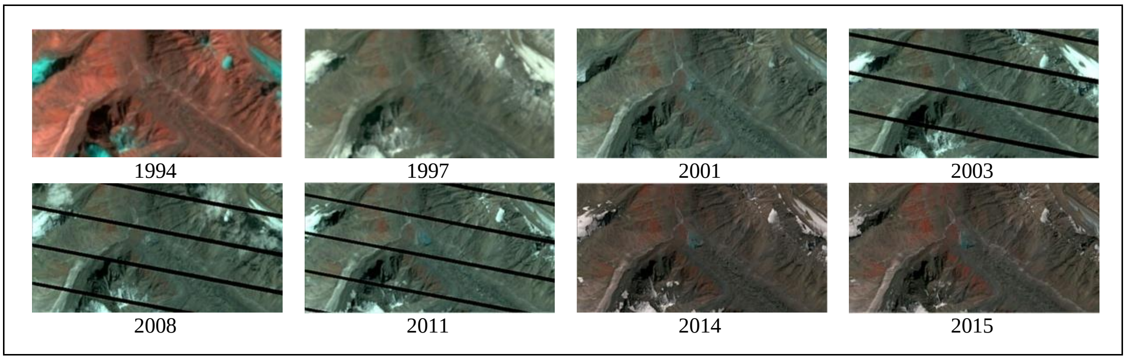
Additionally, pan sharpening was applied to enhance the spatial resolution of the images. For Landsat 8 and 7 images, pan sharpening was done using their respective panchromatic bands, which have higher spatial resolution compared to the multispectral bands. For older images where a panchromatic band was not available, the pan band from Landsat 7 was used. This process helps in obtaining more detailed and sharper images, which are vital for accurate delineation of glacier boundaries.

Delineation of Glacier Boundary

Delineating the glacier boundary involves a combination of techniques to ensure accuracy. The glacier watershed boundaries and ice divides were initially demarcated by overlaying the satellite images on the Aster GDEM digital elevation model. This provided a three-dimensional perspective of the glacier terrain, essential for identifying natural divides and flow patterns. The glacier boundary was then extracted using a semi-automatic approach that included visual interpretation and the application of band ratio techniques, such as the Normalized Difference Principal Component Snow Index (NDPCSI). These methods help distinguish between snow, ice, and other land cover types, ensuring precise glacier boundary delineation (Hall et al., 2003).

Identification of Snout Position

Identifying the snout position of a glacier on satellite images requires careful analysis of various visual clues. The snout positions were identified using features such as the black tone resulting from the shadow of the ice wall, the origin of streams from the glacier, and the red tone of vegetation near terminal moraines. Additionally, moraine-dammed lakes and other morphological features provided further clues to accurately locate the snout (Gaddam, Kulkarni, & Kumar Gupta, 2016). Once identified, the glacier outlines were manually interpreted, and the areas were calculated.



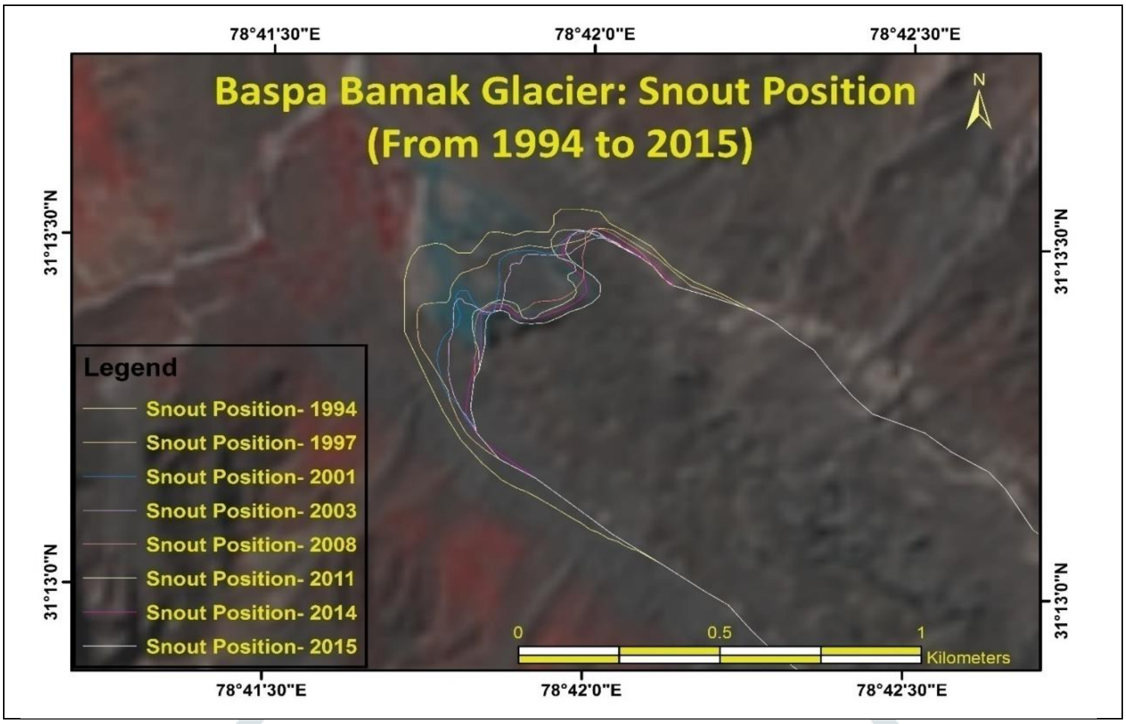


Figure 2: Baspa Bamak glacier's snout positions from 1994 to 2015 derived from different high resolution Landsat satellite data overlaid on Landsat 8 OLI (2015) pan sharpening imagery.

Data Processing and Analysis

The pre-processed satellite data were used to generate a digital database and map the glacial extents. The primary software tool utilized for this purpose was ArcMap (V. 10), which facilitated the integration, analysis, and visualization of spatial data. ArcMap's robust tools for geospatial analysis and its ability to handle large datasets made it an ideal choice for this study. The software was used to overlay the processed satellite images with the digital elevation model, enabling precise mapping of the glacier's extent and the calculation of retreat rates.

The integration of these various methodological steps ensured that the analysis was both comprehensive and accurate. By combining satellite imagery, digital elevation models, and advanced image processing techniques, the study was able to generate detailed and reliable data on the retreat of the Baspa Bamak glacier.

Results and Discussion

Glacier Retreat Analysis

The Baspa Bamak glacier has undergone significant retreat from 1994 to 2015, with a total recession of 279.5 meters. On average, the glacier receded at a rate of approximately 13.30 meters per year over this two-decade period. However, the rate of retreat varied considerably across different intervals.

From 1994 to 1997, the glacier receded at a rate of 14.83 meters per year. This rate decreased to 6.77 meters per year between 1997 and 2001. The period from 2001 to 2003 saw an increase in the recession rate to 19.26 meters per year. The glacier reached its maximum recession rate between 2003 and 2008, retreating at 20.4 meters per year. Following this period, the recession rate declined to 10.96 meters per year from 2008 to 2011. Between 2011 and 2014, the glacier exhibited its minimum recession rate of 3.93 meters per year. However, the rate surged again to 19.73 meters per year in the year 2014-2015.

The variability in these rates underscores the complex interactions between climatic and local factors influencing glacier dynamics. The early period of accelerated retreat (1994-1997) could be attributed to a combination of rising temperatures and potentially lower snowfall rates, which would reduce accumulation and enhance ablation. The subsequent slower rate of retreat (1997-2001) might indicate a phase of relative climatic stability or increased snowfall, temporarily balancing the glacier's mass budget.

Area Loss

The study reveals that the Baspa Bamak glacier lost 0.18 square kilometers of area between 1994 and 2015. This area loss is indicative of the substantial retreat and thinning of the glacier front. The temporal variations in glacier retreat rates highlight the influence of different climatic and environmental factors over time.

The loss of glacier area has broader implications beyond the immediate physical changes observed. Glacier area reduction affects the glacier's albedo effect, where the reflective surface of the ice is reduced, leading to higher absorption of solar radiation and further accelerating the melting process. This feedback loop can lead to a more rapid and sustained glacier retreat, which has been observed in other regions globally.

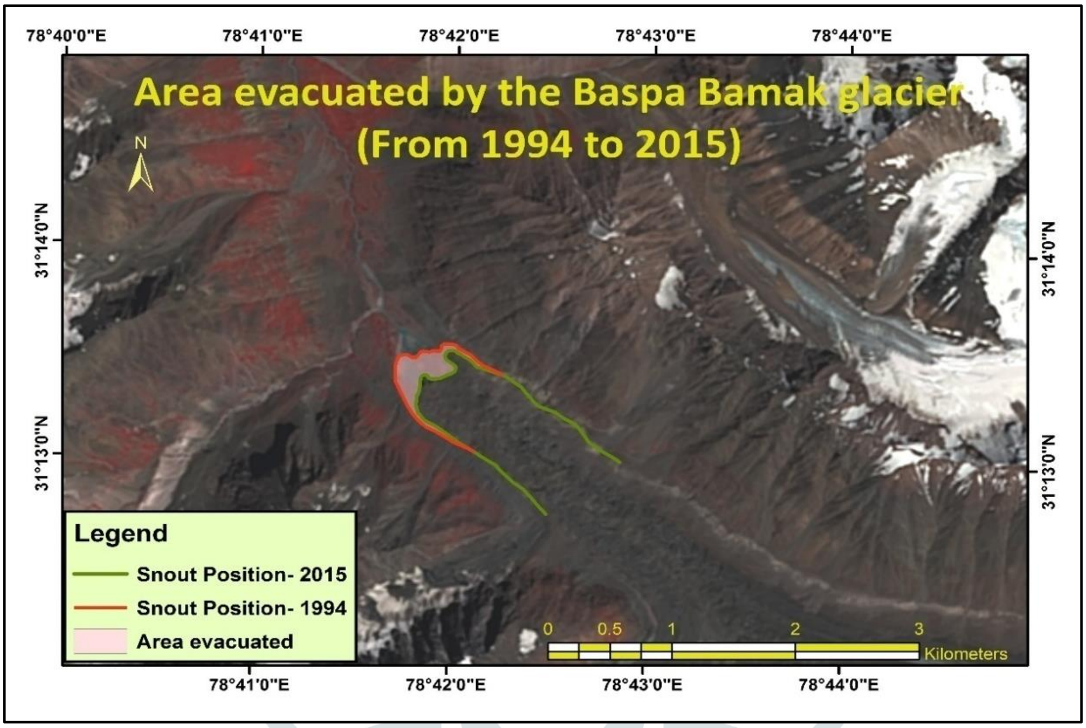


Figure 3: Area evacuated by the Baspa Bamak glacier during the period of 1994-2015.

Factors Influencing Glacier Retreat

The variability in the retreat rates of the Baspa Bamak glacier can be attributed to several factors. Climatic conditions, such as temperature and precipitation patterns, play a crucial role in glacier dynamics. Warmer temperatures and changes in precipitation directly affect the glacier's mass balance, leading to increased melting and reduced accumulation. Additionally, glacier flow dynamics and internal deformation contribute to the observed variations in retreat rates.

One significant factor influencing the retreat is the presence of thick debris cover on the glacier surface. The debris cover acts as an insulating layer, reducing the ablation rate by shielding the ice from direct solar radiation. This not only slows down the melting process but also causes differential ablation across the glacier, leading to oscillations in the east and west lobes of the glacier.

Changes in Glacier Terminus

The analysis indicates that the concave shape of the glacier terminus has increased over time, further signifying the glacier's recession. During the studied period, the Baspa Bamak glacier's snout exhibited both vertical lowering and horizontal shortening. The most pronounced impact of ice mass loss due to melting was observed at the snout and lower lateral margins of the glacier. These areas serve as crucial indicators for assessing the impact of microclimate changes on the glacier.

The increased concavity of the terminus is a clear indicator of the differential melting processes occurring across the glacier. The central part of the glacier often experiences higher flow velocities and, consequently, more significant vertical lowering. In contrast, the lateral margins, insulated by thicker debris cover, exhibit slower melting rates but still contribute to the overall horizontal shortening of the glacier.

Implications of Glacier Retreat

The retreat of the Baspa Bamak glacier ultimately results in an upward shift in the location and elevation of the glacier snout. This has significant implications for the region's water resources, as glaciers are a vital source of freshwater. The reduction in glacier volume and extent can lead to decreased water availability, impacting agriculture, hydropower generation, and domestic water supply downstream.

Furthermore, the retreat of glaciers can lead to the formation of new glacial lakes, which pose a risk of glacial lake outburst floods (GLOFs). These floods can have catastrophic impacts on downstream communities, infrastructure, and ecosystems. The study highlights the need for continuous monitoring and the implementation of early warning systems to mitigate the risks associated with GLOFs.

Climate Change Implications

The retreat of the Baspa Bamak glacier highlights the broader implications of climate change on Himalayan glaciers. The observed recession is consistent with other studies in the region, which report significant glacier retreat due to rising temperatures and changes in precipitation patterns. The continuous monitoring of glaciers using remote sensing technology is crucial for understanding glacier behavior and predicting future changes.

Broader Impact on Water Resources

The retreat of Himalayan glaciers has significant implications for water resources in the region. These glaciers are a critical source of freshwater for millions of people, particularly during the dry season when glacial meltwater sustains river flows. The reduction in glacier volume and extent can lead to decreased water availability, impacting agriculture, hydropower generation, and domestic water supply. Understanding the rate of glacier retreat and the factors influencing it is essential for developing adaptive strategies to manage water resources effectively.

Conclusion

This study reveals that the Baspa Bamak glacier has experienced considerable retreat and area loss over the past two decades. The observed retreat rates and variations highlight the complex interplay of climatic and environmental factors influencing glacier dynamics. Continuous monitoring and analysis using remote sensing technology are essential for understanding glacier behavior and predicting future changes. The findings underscore the importance of effective water resource management strategies to mitigate the impacts of glacier retreat on downstream communities and ecosystems.

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