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Conference Paper

Glacier Volume Estimation Using the Glaptop Model in the Cordillera Blanca of Peru

Estimación del volumen glaciar utilizando el modelo Glaptop en la Cordillera Blanca del Perú

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Abstract

The spatial retreat of glaciers located in the Peruvian Andes is closely linked to global climate change. The glaciers of the Checquiaraju micro-basin of the Cordillera Blanca are the main sources of water for the Andean zone; however, they have been suffering an accelerated space retreat. Remote sensing and geographic information systems (GIS) techniques have been applied to estimate the variation in glacier area and volume from LANDSAT 5 images. Glacier area and volume results are correlated with normalized difference snow index (NDSI) data to discriminate the snow cover from the rest of the elements in the image through the digital numbers (DN) of two bands: the TM blue band and shortwave infrared. The glacial zone was separated from the non-glacial zone for a better fit with the glacier limits seen in the composite color image. Subsequently, the delimitation of the glacier cover was refined through supervised classification, and finally, the determination of the volume of the glacier was estimated using the Glabtop model. The evolution of the glacier area of the Checquiaraju micro-basin tends to retreat. In the period 1989–2004, the glacier area of the study area decreased by 0.44 km^2 (representing 11.3% of the glacier area in 1989), considering a rate of decrease of 0.0275 km^2/year, which shows the retreat of glaciers in the area, which is a source of supply.

Keywords: *Checquiaraju, SIG, LANDSAT 5, NDSI, Glabtop.*

Resumen

El retroceso espacial de los glaciares ubicados en los Andes peruanos está estrechamente vinculado al cambio climático global. Los glaciares de la microcuenca de Checquiaraju de la Cordillera Blanca son una fuente de agua muy importante para la zona andina; pero ellos vienen sufriendo un retroceso espacial acelerado. Se ha aplicado las técnicas de la Teledetección y Sistemas de Información Geográfica (SIG) para estimar la variación del área y volumen glaciar a partir de imágenes LANDSAT 5. Los resultados de área y volumen glaciar se correlacionan con datos de NDSI (Normalized Difference Snow Index) para discriminar la cobertura nival del resto de los elementos en la imagen, a través de los números digitales (DN) de dos bandas TM banda en azul e infrarroja de onda corta. Se separó la zona glaciar de la zona no – glaciar para un mejor ajuste con los límites de glaciar visto en la imagen de color compuesta. Posterior se refinó la delimitación de la cobertura glaciar a través de la clasificación supervisada y finalmente la determinación del volumen del glaciar se estimó mediante el modelo Glabtop. La evolución del área glaciar de la microcuenca de Checquiaraju tiene una tendencia al retroceso.

En el periodo 1989 – 2004, el área glaciar de la zona de estudio se redujo 0,44 km^2 (lo que representa el 11,3 % del área glaciar en 1989), considerando una tasa de disminución de 0,0275 km^2/año, lo que evidencia el retroceso de los glaciares en la zona, la cual es fuente de abastecimiento.

Palabras Clave: *Checquiaraju, SIG, LANDSAT 5, NDSI, Glabtop.*

1. Introduction

The continuous increase in global average temperature has caused a substantial decline in most of the world's glaciers [1]. The accelerated loss of glaciers in high mountain regions can have strong environmental and economic repercussions on a local, regional and even global scale [2, 3]. Glacial retreat is a global and alarming problem in the Cordillera Blanca [4], whose causes and solutions cannot be determined by a single country. The current situation regarding the pollution problem and accelerated climate change in the world foresees a pessimistic future for glaciers. [5].

Tropical glaciers are particularly sensitive to global warming [6]. The countries in which these are located are those with the highest risk of water supply, where glaciers supply the different users of water resources, especially in the dry season, such as in the Santa basin - Peru [7].

The glaciers in the Cordillera Blanca act as a temporary water store for precipitation that falls as snow at high altitudes during the wet season from October to April [7]. The stored water is partly released during the dry season, compensating for the lack of water due to the low rainfall recorded between May and September [8], which represents an important source of water [9].

Multi-temporal analysis of satellite images is an important tool in determining glacier surface variation [10, 11]. It is effective when complemented within a Geographic Information System, allowing the results obtained to be refined [12, 13]. The GlabTop model is an effective tool used to calculate the basal topography of glacier beds [14]. This is important for monitoring and studying glaciers that can be applied to large glacier samples in a computationally efficient way [15].

The objective of this work is to determine the area and volume of the glaciers in the Checquiaraju micro-basin with the help of satellite images (Landsat 5) and the GlabTop model.

2. Materials and Methods

2.1. Study area description.

The evaluated glaciers are located in the Cheqcquiaraju micro-basin, which belongs to the Cordillera Blanca. A mountain system that owes its name to high-altitude glacial formations (the highest in Peru). According to the Glacier inventory, they are assigned the national code 1376938 and numerals from 24 to 27 (Table I). Politically, the study area is located in the department of Ancash, province of Carhuaz, district of Shilla and between the UTM coordinates (Datum WGS 84 – Zone 18L) 8 982 160 N – 8 985 170 N and 218 910 E – 222 060 E with elevations between 4778 – 5769 m.a.s.l. (Figure **1**), the Checquiaraju micro-basin (6.23 km2) is shown within the Cordillera Blanca.

Tabla 1

Glaciers in the study area.

Code		Glacier Name	Altitude (masl)			Surface (Km^2)	ALS (masl)
International	**National**		**Max.**	**Avg.**	**Min.**		
G282442E9175S	1376938-23	Tullparaju 1	5266	5094	4922	0,33	5104
G282449E9173S	1376938-24	Tullparaju 2	5116	4991	4866	0,15	5017
G282464E9180S	1376938-25	Checquiaraju 1	5472	5052	4631	1,83	4988
G282469E9190S	1376938-26	Checquiaraju 2	5550	5451	5352	0,02	5470
G282463E9194S	1376938-27	—	5769	5274	4778	1,11	5172

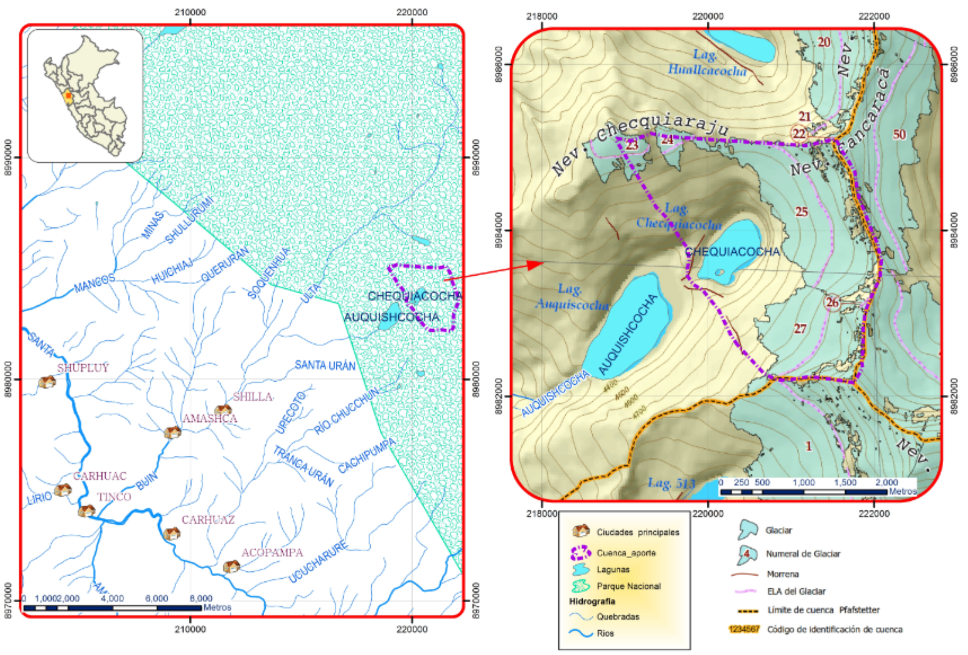

Figura 1

Study area location in the national territory of Peru (a), cuenca Checquiaraju (b).

MethodThe National Glacier Inventory was taken as an initial source to select the study area, subsequently LANDSAT 5 images were used, which were downloaded from: https://glovis.usgs.gov/app and they are free and have a level of correction that allows their direct use. The downloads were carried out with little cloud cover, as shown in table II.

The DEM of the study area was downloaded from: http://geoservidorperu.minam.gob.pe. In addition, ArcGis software with its respective spatial geoprocessing extensions was used as tools in the remote sensing process.

Tabla 2

Selected Landsat images.

Type	Date		Resolution	Format	Cloudiness
Landsat 5	30-dic	1989	30 x 30 m	GeoTiff	18 %
Landsat 5	13-may	2004	30 x 30 m	GeoTiff	7 %

2.2. NDSI Determination

According to [16], The NDSI allows spectral discrimination between snow, soil, rock and cloud cover, with adequate and fairly accurate intercomparison of exposed ice (bare ice) and glacier tongue positions in different years. [11].

The NDSI (Normalized Difference Snow Index) is an index that discriminates snow cover from the rest of the elements in the image. NDSI takes advantage of the fact that snow has high reflectance and absorption in the visible and shortwave infrared channels. [17]

The normalized differential snow index (NDSI) can be determined using digital numbers (DN) of two bands TM (combination of bands) from the following equation [18] Equation 1 is valid for calculating the NDSI for LANDSAT 5 images.

$$NDSI = \frac{B2 - B5}{B2 + B5} (1)$$

Where:

$B2$ = Band in blue

$B5$ = Short wave infrared

NDSI value ranges from -1 to +1.

The glacial zone was separated from the non-glacial zone because these criteria give the best fit with the glacier boundaries seen in the composite color image. For this development, the NDSI of the glacial zone of the study area was obtained. See Table III and Figure **2**.

Tabla 3

NDSI for the study area.

Year	NDSI (Glacier and Lagoon Cover)
1989	> 0,20
2004	> 0,15

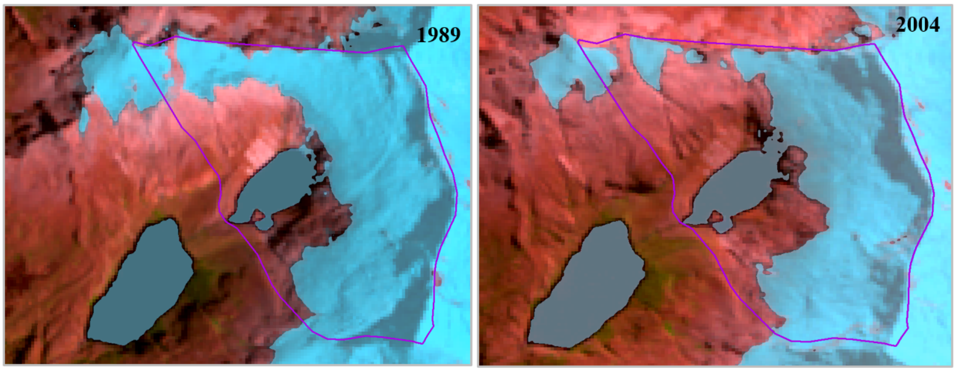

Figura 2

Spectral classification of Landsat 5 images: NDSI limit (celestial areas) and study area limit (violet color).

2.3. Supervised Classification

With the previous step, an approximation of the glacier cover in the study area was obtained. Additionally, the delimitation of the glacier coverage was refined with a supervised classification using the software ArcGis for the spectral signature registration.

This procedure was applied using the spectral signature capture technique, in which a relationship of signatures corresponding to the different glacier coverages is indicated. Considering that this methodology requires a clear separation between glacial and non-glacial coverage (soil, bodies of water, vegetation, and rocky outcrops, among others), Obtaining a new classification between different signatures corresponding to glacial and non-glacial coverage (Figure **3**).

2.4. Glacier volume calculation

The glacier volume is estimated using the GlabTop model, which was used to estimate the distribution of ice thickness [19, 20] from the analysis and combination of the DEM,

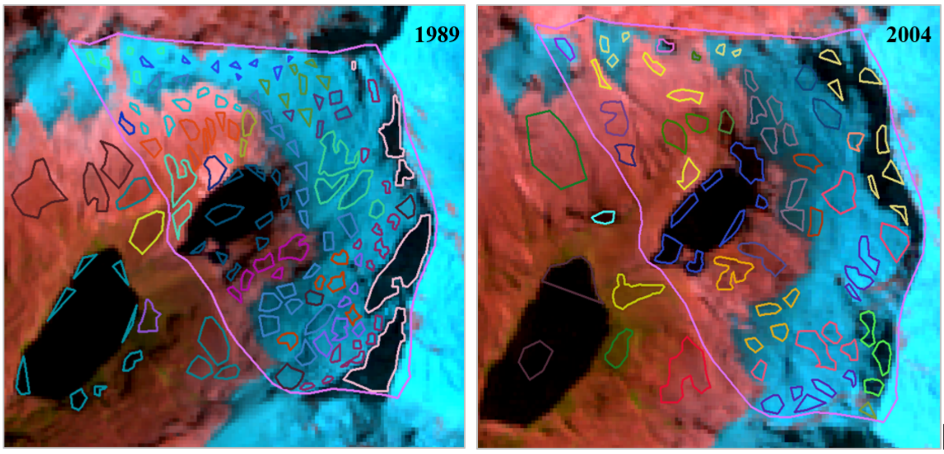

Figura 3

Supervised classification of Landsat 5 images: spectral signatures for the study area.

the glacier cover area and the flow lines (Figure **2**). Ice depth estimation using GlabTop, with an uncertainty range of ±30%, can only provide an approximate order of magnitude assessment of potential lagoon depths and volumes [14, 19].

Figura 4

GlabTop Model.

3. Results and Discussion

According to the methodology, it was possible to determine the area of glacial coverage and the glacial volume of the glaciers in the Checquiaraju microbasin.

3.1. Glacier surface and volume calculations.

After delimiting the glacial coverage for the selected years (1989 and 2004) with the classification supervised by spectral signatures with the ArcGis software, the glacier surface was determined. Table IV shows the variations in mass loss and glacier volume:

Tabla 4

Glacier Variation.

Year	Glacier Area (km^2)	% Glacier Area	Glacier Volume (km^3)	% Glacier Volume
1989	3,90	100 %	0,095	100%
2004	3,46	88,70 %	0,085	89,50%

Regarding the glacier area, in a period of 16 years (1989–2004), a retreat of 0.44 km2 was observed, that is, 11.3%. Figure **3** and Figure **4** show the variation of the glacial area, as well as the general overlap of the analyzed periods.

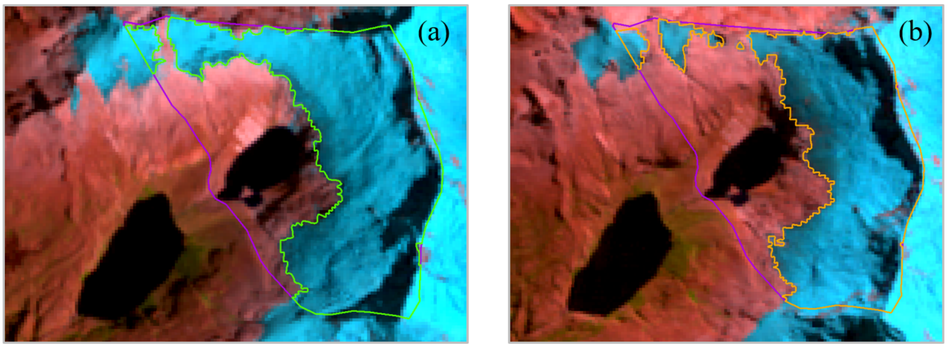

Figura 5

Delimitation of glacier coverage, (a) 1989; (b) 2004.

The variation in the initial glacier surface volume was observed over a period of 16 years (1989–2004). There was a volume decrease of 0.010 km3, that is, 10.5% of unrecoverable melted ice. (Figure **5**).

4. Conclusions

In the present work, Landsat 5 satellite images were used to map glacial retreat for 16 years (1989–2004) of the Checquiaraju micro-basin belonging to the Cordillera Blanca through a supervised classification of spectral bands. According to our estimates, taking the year 1989 as a reference, an area of 3.90 km2 was obtained, representing the initial percentage of 100%. Based on this, by the year 2004, there were 3.46 km2 (88.7%), of which a 11.3% loss of glacier mass was observed during the period 1989–2004, respectively.

The glacier volume was estimated based on the GlabTop model, in which there was variable behavior over time. The average reduction in glacier volume for the year 1989 was 0.095 km3 (base year) and subsequently 0.085 km3 (89.5%) for the years 1995

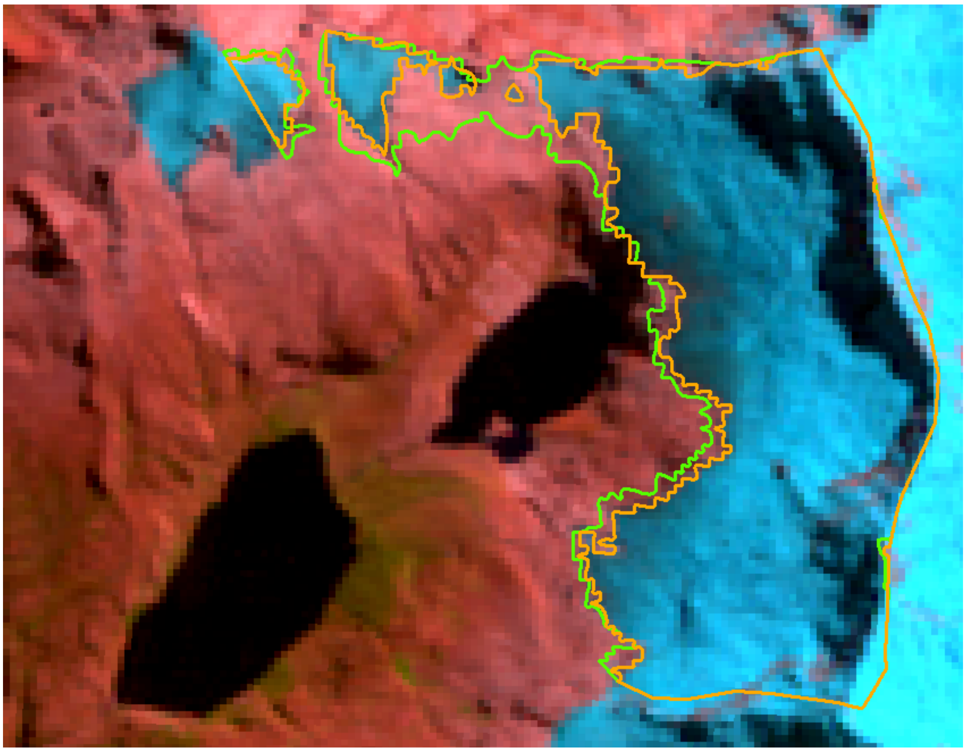

Figura 6

General superposition of glacier area in the years 1989 (green line) and 2004 (orange line), detail of glacier retreat.

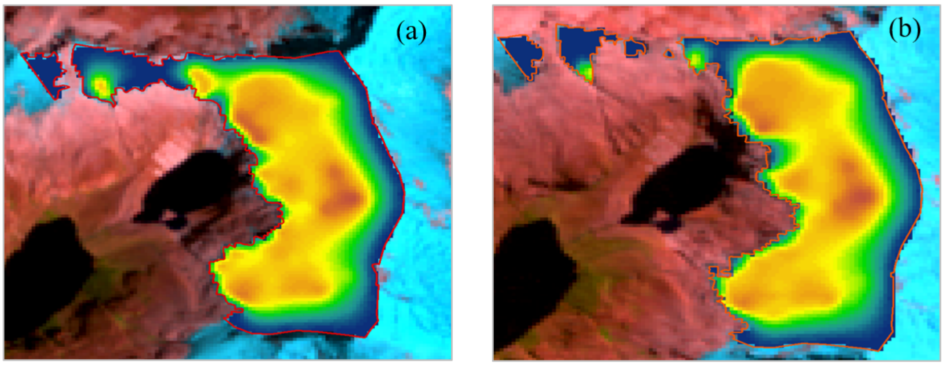

Figura 7

Glacier volume (GlabTop Model) in the years: 1989 (a) and 2004 (b).

and 2004, respectively. Indicating a decrease in the volume of unrecoverable melted ice of 0.010 km3 (10.5%) between the years 1989 and 2004, respectively.

Conflict of Interests

The authors declare not having financial or personal conflicts of interest that could inappropriately influence the development of this research.

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