Ann. For. Res. 66(1): 2681-2695, 2023
ISSN: 18448135, 20652445

ANNALS OF FOREST RESEARCH
www.e-afr.org

ESTIMATION OF DEGLACIATION IN THE SUB-BASIN OF THE QUILLCAY RIVER – PERU, IN THE FACE OF CLIMATE CHANGE

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Abstract

In recent decades, glaciers globally, and mainly tropical glaciers, have experienced an accelerated retreat in snow cover due to climate change. In the tropical glaciers of Peru, it has generated the development of numerous lagoons and an increase in their volume over the years. In this research, a methodology with new improved indices is proposed: Normalized Difference Snow Index without water information (NDSInw) and Normalized Difference Water Index without snow cover (NDWIns). The changes that occurred through a multi-temporal analysis of the snow surface in the Quillcay River sub-basin during 1986 to 2021 are identified using satellite images from the Landsat 5, 8 and 9 collection 2 of the Google Earth Engine data catalog and processing spatial data using the rgee Application Programming Interface (API). The results obtained from the deglaciation of the snow-capped mountains in the 35 years of analysis resulted in a decrease of 27.82% compared to 1986.

1. Introduction

The world of tropical glaciers has retreated during the last century (Rabatel et al., 2013), someof the areas of the world's glaciers are in constant reduction of their glacier surface, in some there is a partial increase, for example, the Karakoram in the Himalayas where it is manifested by the climatic variations of the place as the increase in rainfall (Kaltenborn et al., 2010). The main cause of the melting of glacier masses is attributed to the current increase in the temperature of the planet due to the consequences of climate change that is hitting different land covers and their progressive change (Mark et al., 2010).

The rapid decline of tropical glaciers has increased awareness of their importance as an important water resource, particularly during the dry season (Bradley et al., 2006; Ebi et al., 2007; Mark et al., 2010). As Andean glaciers retreat, there has been an increase in seasonal discharge and in basins with smaller glacier area and a decrease in total annual discharge (Juen et al., 2007; Mark et al., 2005).

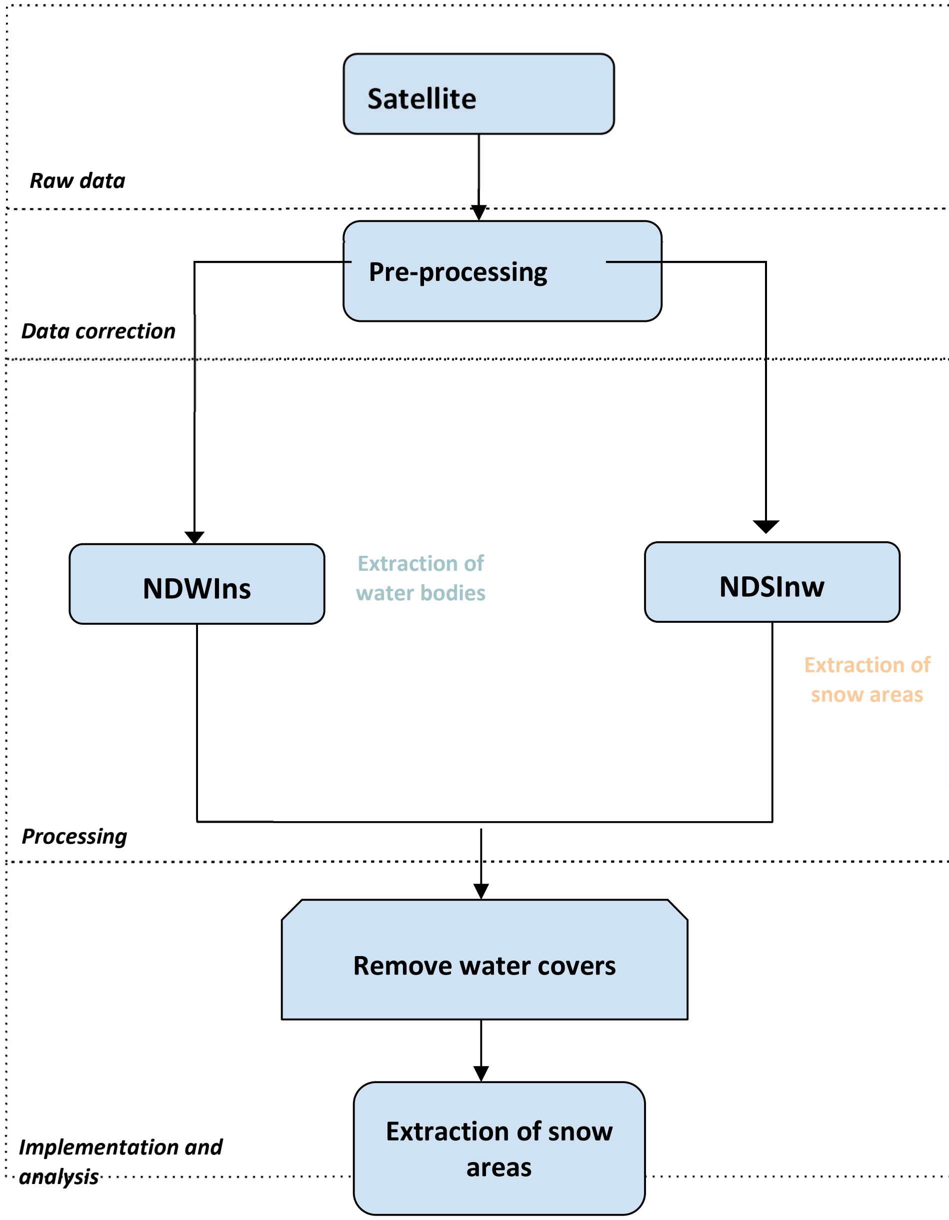
Climate change is altering the entire atmospheric ocean system globally and mainly in glaciers around the world, being observed with greatersusceptibility in the tropical glaciers of the Andes, whose visible result is their deglaciation and an accelerated melting in recent decades (Yap Arévalo, 2016) . Tropical glaciers are in greater extension in Peru, hosting about 1200 km^2, this makes it have the largest tropical glacier surface at the general level, approximately 71%, of which the white mountain range comprises 29% representing aroundl 43% with reference to Peru (Rabatel et al., 2013).

Today we can count on access to these tools and a wide variety of data such as those obtained by the Landsat or Sentinel missions that are indispensable for studies of land covers that are affected by climate change such as glaciers. In addition, the use of cloud processing such as that offered by the Google Earth Engine platform that meets the need to have a large own computer platform. Remote sensing-based techniques have provento be effective tools for detecting changes in land use and changes in the physical environment, quantifying natural ecosystemssuch as glaciers and cities It provides an integral vision of dynamic spaces, models of use and thus promote the development of regional development policies (Rogan & Chen, 2004).

2. **Methodology**

The development consists mainly of the generation of an algorithm that includes three main steps; 1) Obtaining preprocessed data from satellite images, 2) generation of improved land cover types in spectral indices, 3) extraction of cover class related to lagoons of glacial origin and snow cover. After data processing, we perform the implementation and analysis of glacier deglaciation.

Figure 1: Proposed model workflow for snow cover estimation



Source: Authors.

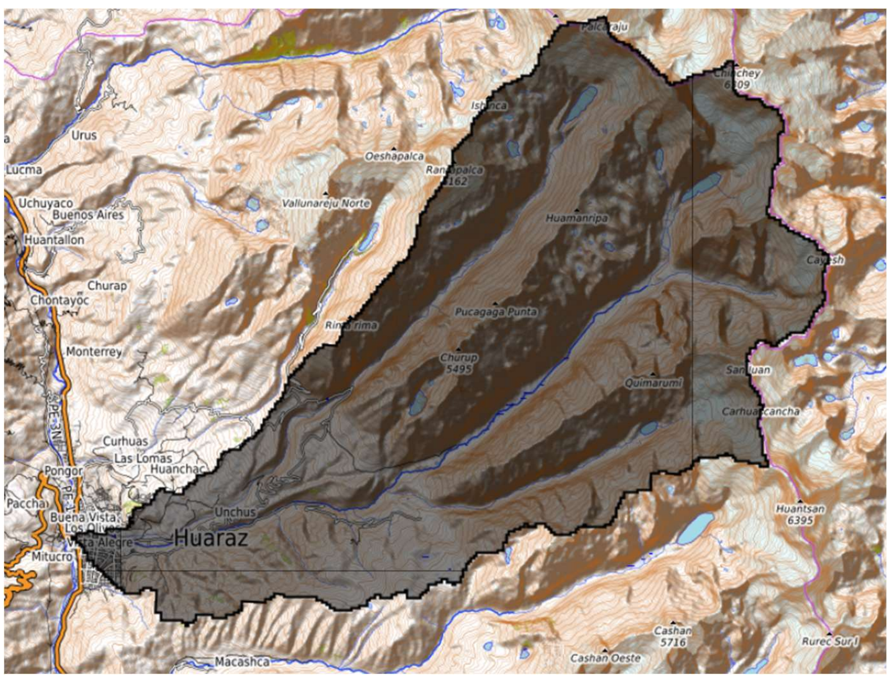
2.1 Case study and localization

The Cordillera Blanca has the largest glacial areain the tropics (Suárez et al., 2008). The glacier surface of the Cordillera Blanca has decreased from 800 - 850 km2 in 1930 to less than 600 km2 at the end of the 20th century (Georges, 2004). Subsequently, glaciers continued to shrink to reach an area of 482km2 in 2010 (Burns and Nolin, 2014). The region is characterized by heavy seasonal rainfall, which is typical of the outer tropical zone; More than 80% of precipitation falls between the months of October and April, with little or no precipitation during the austral winter months of June to August. In the upper Santa River basin, glacial melting (ice and snow melting glaciers)

provides 10 - 20% of the total annual river discharge and in the dry season, it can exceed 40% (Mark et al., 2005).
The Cordillera Blanca containsabout 70% of the world's tropical glaciers. Melting res provides 10 tol 20% of the total annual discharge from the Santa River, with 40% occurring in the dry season (J.A. Grande et al., 2019). This makes the basin vulnerable to drought, especially due to an accelerated process of glacial retreat (Mark et al., 2005; Baraer et al., 2009).

The sub-basin of the Quillcay River is located in the Santa River basin, which is located on the Pacific slope. Geopolitically it is located in the province of Huaraz district of Huaraz and Independencia. It has an area of 247.38 ^{km2} and 83.03km perimeter. The waters drain from the right bank of the Santa River basin, born from the Cojup River and form the Paria River, which joins downstream with the Auqui River and is called Quillcay. The river runs through the main city of Huaraz and flows into the Santa River (Meza et al., 2016).

Figure 2: Study area, the sub-basin of the Quillcay River



Source: Authors.

2.2 Data source

The Landsat Surface Reflectance (SR) corrected time series are provided by the United States Geological Survey (USGS) and are fully available and ready to use in Google Earth Engine (GEE) for Landsat 4-9, Collection 2 that has improvements to the data, processing and algorithm development.

***Table 1**: Landsat Collection 2 Features 5, 8, and 9*

Satellite	Landsat-5	Landsat-8	Landsat-9
Bands of sensors	Band 1 (blue)	Band 1 (coastal aerosol)	Band 1 (ultra blue, coastal aerosol)
	Band 2 (green)	Band 2 (blue)	Band 2 (blue)
	Band 3 (red)	Band 3 (green)	Band 3 (green)
	Band 4 (near infrared)	Band 4 (red)	Band 4 (red)
	Band 5 (shortwave infrared 1)	Band 5 (near infrared)	Band 5 (near infrared)
	Band 6 (Thermal Infrared 1)	Band 6 (shortwave infrared 1)	Band 6 (shortwave infrared 1)
	Band 7 (shortwave infrared 2)	Band 7 (shortwave infrared 2)	Band 7 (shortwave infrared 2)
		Band 8 (Panchromatic)	Band 8 (Panchromatic)
		Band 9 (Cirrus)	Band 9 (Cirrus)
		Band 10 (Thermal infrared 1)	Band 10 (Thermal infrared 1)
		Band 11 (Thermal infrared 2)	Band 11 (Thermal infrared 2)
Spatial resolution	30m	30m	30m
Sensor	TM	OIL-/SHOTS	OIL-/SHOTS-2
Type of application fix	Surface Reflectance (SR)	Surface Reflectance (SR)	Surface Reflectance (SR)

Source: Authors.

Landsat images provided by GEE contain Landsat 1-5 Multispectral Scanner (MSS) sensors from 1972 to 1999; Landsat 4 and 5 Thematic Mapper (TM) from 1982 to 1993; Landsat 7 Enhanced Thematic Mapper Plus (ETM+) from 1999 to 2021; Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) from 2013 to present; and recently launched Landsat 9

Operational Land Imager 2 (OLI-2) and Thermal Infrared Sensor 2 (TIRS-2) from 2021 to the present. The bands of the Landsat images mostly have a spatial resolution of 30m and temporal resolution for the sensors of 16 days.

Table 2: Information and source of images

Quillcay River sub-basin			
Image	Collection	Cloudiness (%)	Fountain
Median 1986	LANDSAT/LT05/C02/T1_L2	15	Dataset Earth Engine
Median 1994	LANDSAT/LT05/C02/T1_L2	15	Dataset Earth Engine
Median 1999	LANDSAT/LT05/C02/T1_L2	15	Dataset Earth Engine
Median 2007	LANDSAT/LT05/C02/T1_L2	15	Dataset Earth Engine
Median 2014	LANDSAT/LC08/C02/T1_L2	15	Dataset Earth Engine
Median 2021	LANDSAT/LC08/C02/T1_L2	15	Dataset Earth Engine

Source: Authors.

2.3 Procedure and application of the methodology

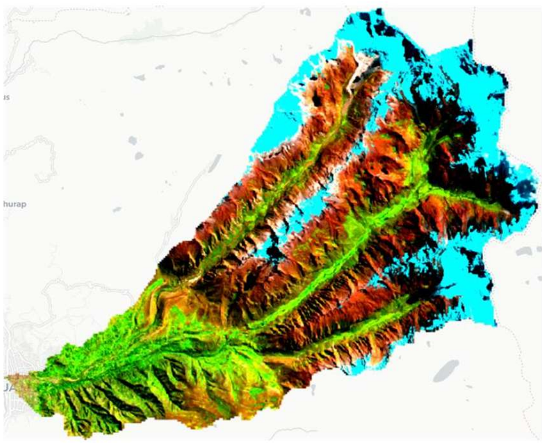
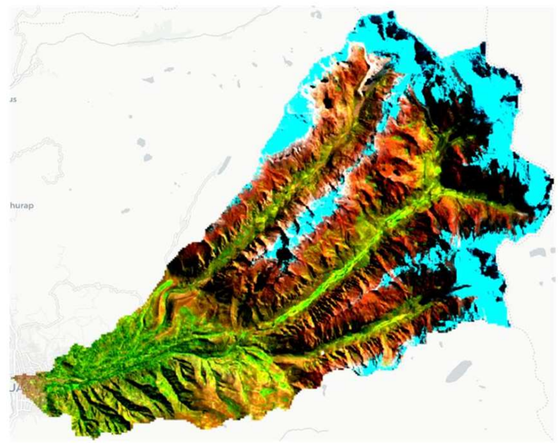
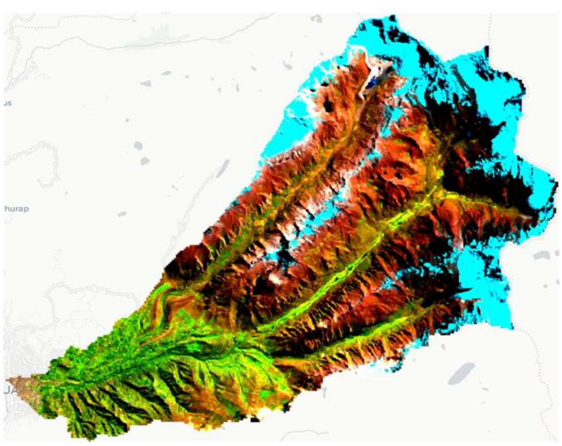
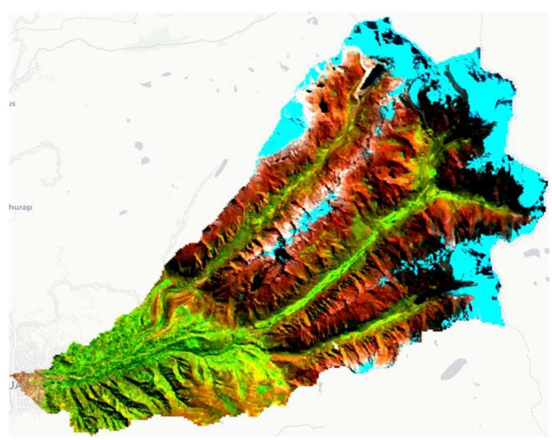
We initialize with the choices of the Landsat 5, 8 and 9 satellite images of the 30 m resolution collection 2 provided by the Google Earth Engine (GEE) data catalog, the images are corrected at surface level. We chose to choose Landsat 5 images from 1986, 1994, 1999, 2007 Sensors, Landsat 8 from OLI and TIRS sensors from 2014 and Landsat 9 from OLI-2 and TIRS-2 sensors from 2021. The series of selected images are obtained in the dry season (dry season) from May 1 to September 1 of every year.

A scale factor was applied for the selected images, the factors are different for both collection 1 and collection 2 Landsat Level-2 of surface reflectance and surface temperature products. The surface reflectance of Landsat Collection 2 has a scale factor of 0.0000275 and an additional compensation of -0.2 per pixel. For example, a pixel value of 18,639 is multiplied by 0.0000275 for the scale factor and then added -0.2 for additional offset to obtain a reflectance value of 0.313 after applying the scale factor (*USGS Landsat 8 Level 2, Collection 2, Tier 1 | Earth Engine Data Catalog | Google Developers*, n.d.) . We used the rgee API that integrates Google Earth Engine with R and through a script the scale factor was applied to the series of images by creating a calculation function.

The processing of the Landsat imagery was done in the cloud using the Google Earth Engine (GEE) platform using a portion of Google's supercomputer.

The images are filtered by date of acquisition for the established years; is filtered by study area of the Quillcay River sub-basin, metadata filtering is established using a cloud cover of less than 15% that allows clean and unaltered images of clouds, the scale factor is applied for Landsat 5 and Landsat 8 and 9 together since it has similar scaling for the bands; A median was applied for all images for each year reducing it to one image, and finally the cut was set for the study area.

Figure 3: Collectible Landsat 2 Surface Reflectance Combinations of Shortwave Infrared 1, Near Infrared Band and Red

Landsat 5 (1986)	**Landsat 5 (1994)**
 **Combination SR_B5, SR_B4 and 'SR_B3'**	 **Combination SR_B5, SR_B4 and 'SR_B3'**
Landsat 5 (1999)	**Landsat 5 (2007)**
 **Combination SR_B5, SR_B4 and 'SR_B3'**	 **Combination SR_B5, SR_B4 and 'SR_B3'**
Landsat 8 (2014)	**Landsat 9 (2021)**

Source: Authors.

We use the normalized differential equation without water information (NDSInw). The equation uses the near-infrared band (NIR) and the short-wavelength band 1 (SWIR1). Normalizing the difference between the NIR band and the SWIR1 band keeps the index value at a high level in the snow cover areas and at a low value in the lake water areas.

To further reduce lake water information, a positive value (0.05) is subtracted from the value of the difference between the NIR band and the SWIR1 band. Therefore, the NDSInw is proposed to extract areas of snow and suppress noise from lake water bodies to a less relevant level (Yan et al., 2020).

$$NDSInw = (p_{nir} - p_{swir1} - b)/(p_{nir} + p_{swir1})$$

Once the proposed index is made, the threshold that obtains the difference between snow and non-snow is 0.4. This threshold typically changes by seasons (Salcedo, 2011).

We propose the normalized differential water index without snow cover (NDWIns). The equation uses the green band and the NIR band remains at a high level in the water areas of the lake, but at a low level in the SCG areas. In addition, the contrast values between the water bodies of the lake and snow are excellent at normalizing the difference between the green band and the NIR band. This index is excellent for eliminating noise generated from water coverage with the NDSInw index. The empirical parameter that is multiplied to the NIR band, the value of 2 will be used (Yan et al., 2020).

$$NDWIns = (p_{green} - a * p_{nir})/(p_{green+p_{nir}})$$

In the calculation of the different indices the values obtained are between -1 and 1 and the values that are above 0 means the presence of similar characteristics observed and below the value means the absence or lack of analyzed characteristic. In other words, all positive values from 0 to 1 are considered to represent surfaces with the target characteristics and all negative values from -1 to 0 are considered to represent terrains of different characteristic type (Dolean et al., 2020).

The procedural script of the proposed methodology for the research can be found here:
https://drive.google.com/file/d/1JOBFcn3_jKudvG05HHQdcEg-lPTj4a4G/view?usp=sharing

Obtained the area of the glacier surface, for the processing method with Google Earth Engine in Rstudio, the average volume of glaciers in the sub-basin was estimated with the following formula (Klein & Isacks, 1998):

$$V = C * A^b$$

Where V is glacier volume in km3, A is the area of the glacier surface in km2, the value of C and b as empirical, C = 0.048 and b = 1.36.

3. Results and discussion

Glacier area estimation

The visual representation of the dynamics of glacier deglaciation in the face of climate change is possible through a multitemporal analysis of snow cover. The results obtained show the decrease of snow cover in their spatial analysis for 35 years. Applying the methodology proposed for this research, the results of snow cover areas for the year 1986, 1994, 1999, 2007, 2014 and 2021 in the sub-basin of the Quillcay River were obtained; The areas 41.47 km 2, 38.55 km 2, 35.16 km 2, 32.89 km 2, 31.39 km 2 and 29.93 km ^{2}, respectively, as shown in Figure 4.

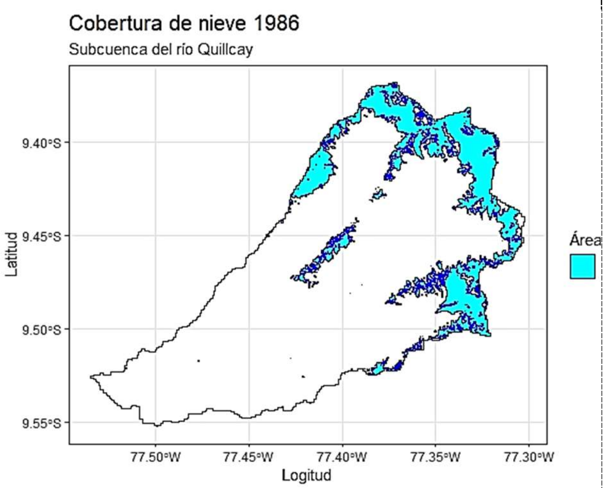
The result of the deglaciation of snow cover in the 35 years of analysis resulted in a decrease of 27.82% compared to 1986. In all the peaks covered by the sub-basin of the Quillcay River there is a partial decrease in coverage, the drastic decrease in snow cover due to climate change is evidenced in the coverage of the Huamanripa ravine of 5258 m.a.s.l. and a considerable decrease in the peaks Pucagaga Punta 5461 m.a.s.l., Churup 5495 m.a.s.l. and Cerro Cachijirca, As shown in Figure 5.

To improve the estimation of snow cover for the sub-basin, a comparison with traditional snow and water calculation indices such as the Normalized Differential Snow Index (NDSI) and the Normalized Differential Water Index (NDWI) is necessary. In addition, other indices such as the Normalized Differential Snow and Ice Index (NDSII), Normalized Differential Glacier Index (NDGI) and Normalized Differential Snow and Ice Index (NDSII 2) can be implemented to map ice and snow covers in different classes (Monterroso-Tobar et al., 2018). For the most accurate mapping, Machine Learning algorithms are implemented as well as unsupervised and supervised classifications, also using Convolutional Neural Networks (CNN) as the U-Net model in the estimation of glacier area (Caillahua & Elbis, 2020).

Quantification of glacier volume

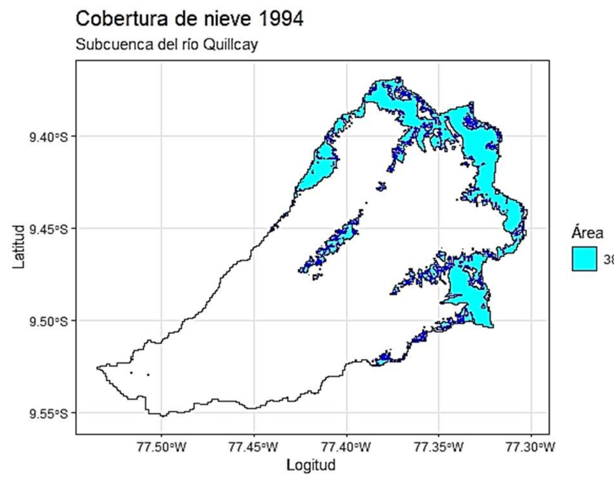
The volume of glaciers in the sub-basin has been decreasing, as shown in Table 2. This quantification of glacier volume shows that tropical glaciers in the sub-basin lost 2.73 of volume representing an average of 36% of melted glacier in the last 35 years of analysis, as can be seen in Table 2.

Landsat 5 (1986)



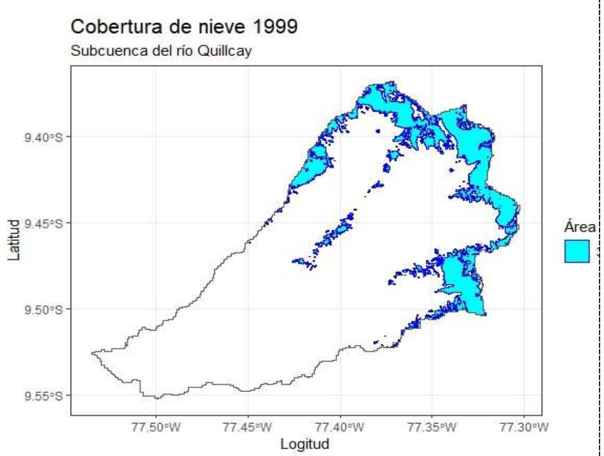
Area: 41.47 km2

Landsat 5 (1994)



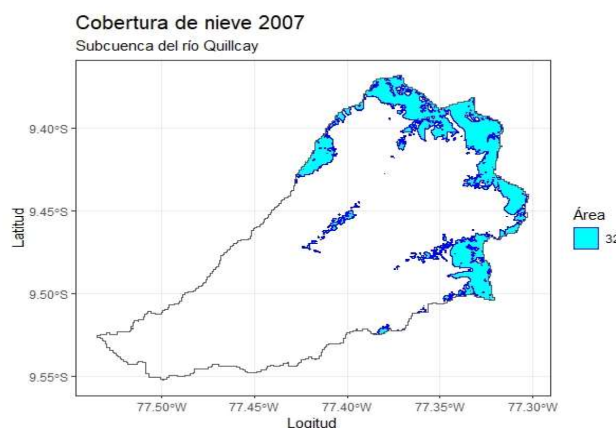
Area: 38.55 km2

Landsat 5 (1999)



Area: 35.16 km2

Landsat 5 (2007)



Area: 32.89 km2

Landsat 8 (2014)

Landsat 9 (2021)

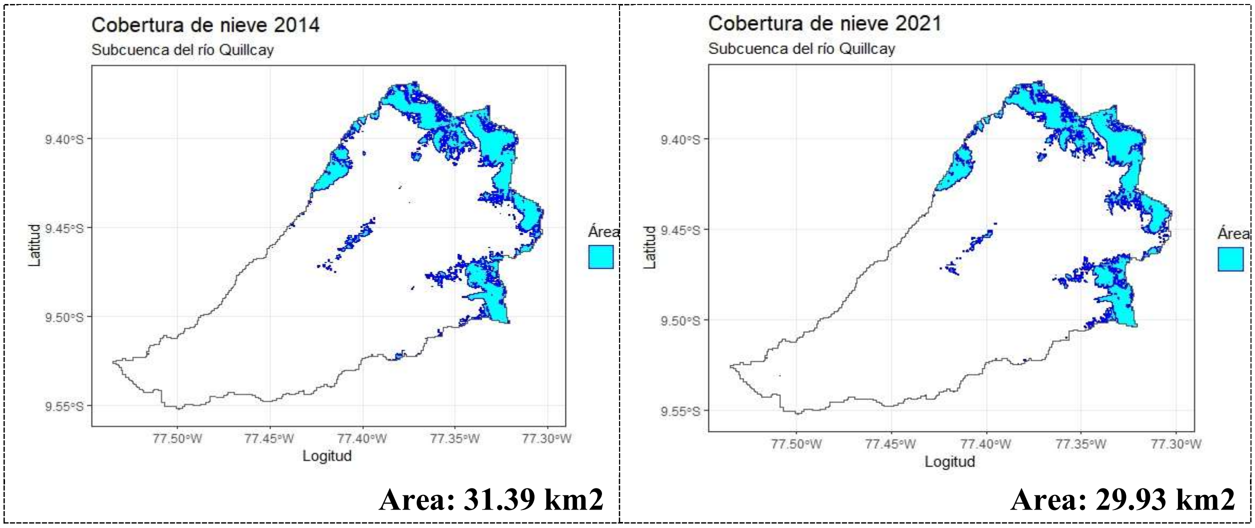


Figure 4: Snow cover analysis results from 1986 to 2021
Source: Authors.

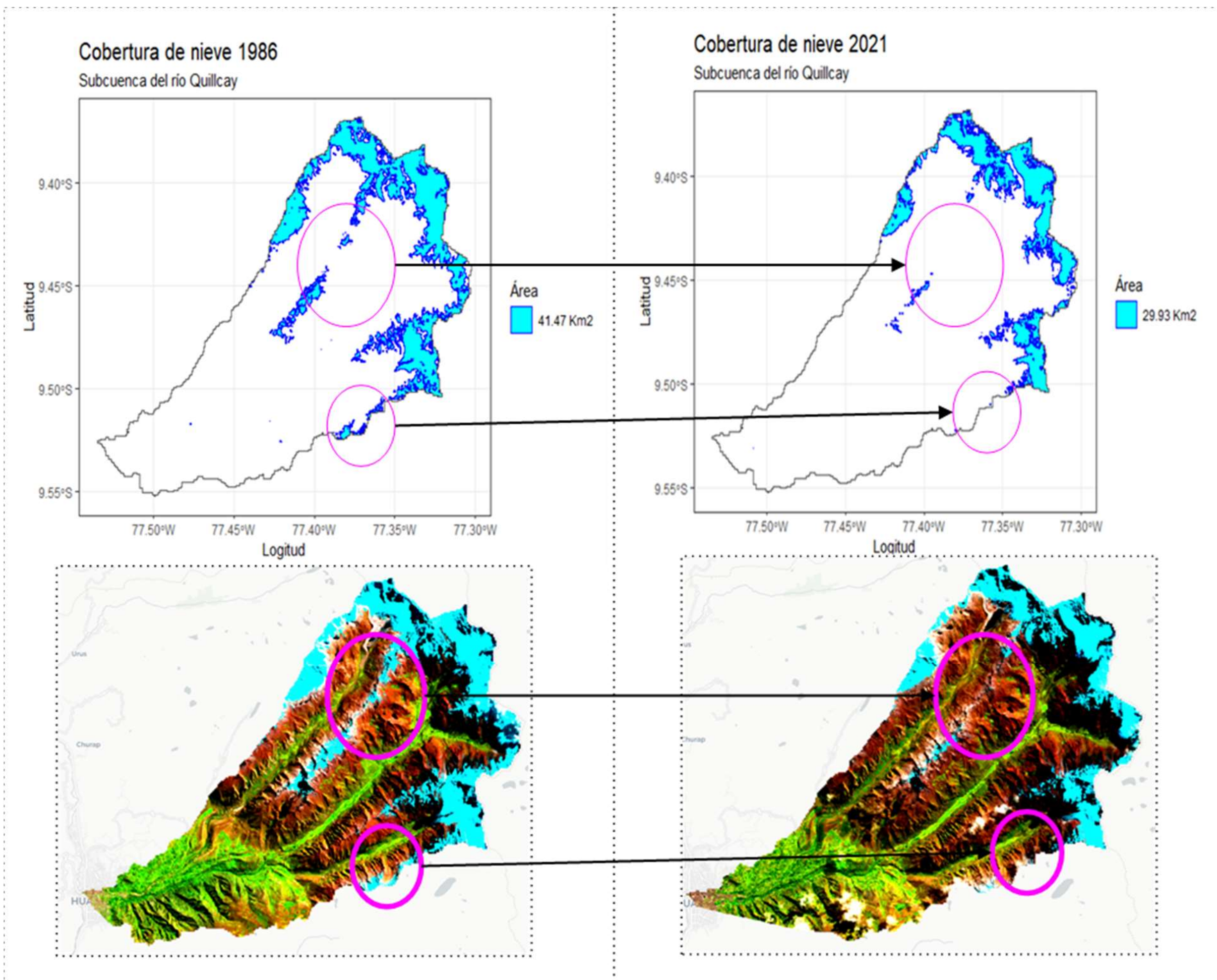


Figure 5: Comparison of snow cover for the year 1986 and 2021
Source: Authors.

Table 3: Variation of the glacier volume of the Quillcay River sub-basin

Quillcay River sub-basin			
Years	Area (km^2)	Volume (km^3)	Percentage (%)
1986	41.47	7.61	100
1994	38.55	6.89	90
1999	35.16	6.08	80
2007	32.89	5.55	73
2014	31.39	5.21	68
2021	29.93	4.88	64

Source: Authors.

Glacier cover projection

For the projection of the estimation of glacier cover, it was performed using the linear regression method where the R^2 is 0.9614. The projection was made until 2056 and the trend of glacier cover is to decrease its volume by 69.5% compared to 1986 due to the constant deglaciation of glaciers due to climate change.

Table 4: Variation of the glacier volume of the Quillcay River sub-basin

Quillcay River sub-basin			
Years	Area (km2)	Volume (km3)	Percentage (%)
1986	41.47	7.61	100
1994	38.55	6.89	90.55
1999	35.16	6.08	79.89
2007	32.89	5.55	72.96
2014	31.39	5.21	68.47
2021	29.93	4.88	64.18
2028	26.65	4.17	54.81
2035	24.32	3.68	48.39

2042	21.99	3.21	42.19
2049	19.65	2.76	36.22
2056	17.32	2.32	30.50

Source: Authors.

4. Conclusion

Thereis a trend in the melting of the glaciers that houses the sub-basin of the Quillcay River and generating an increase in the volume of lagoons of glacial origin, this caused mainly by climate change that is being evidenced in recent decades.

According to what was proposed in the research, we consider that it was fulfilled, developing an adequate methodology for the analysis of the snow surface for the analysis of deglaciation in the tropical glaciers that houses the sub-basin of the Quillcay River in the city of Huaraz. In the 35 years of multitemporal analysis with Landsat satellite imagery from 1986 to 2021, the area of snow cover decreased by 11.54%, which may be related to climate change. As for its volume, a total of 2.73 km3 was lost, representing 35.82% of deglaciation in the 35 years of analysis, which may be related to climate change. At the same time, the projection of the glacier cover estimate was made using the linear regression method where the R^2 is 0.9614, it was carried out until 2056 and the glacier cover trend is to decrease its volume by 69.5% compared to 1986.

The methodology developed can be applied to other high Andean areas of tropical glaciers or polar areas where the territory is with glacier cover related to the criorsfera.

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