MULTI-TEMPORAL ANALYSIS OF THE GLACIER RETREAT USING LANDSAT SATELLITE IMAGES IN THE NEVADO OF THE AMPAY NATIONAL SANCTUARY- PERU

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Glaciers are humanity's most extraordinary reservoirs of water, covering approximately 10% of the total surface of the earth. The investigation of the retreat of the glacier surface in the Ampay National Sanctuary is carried out using the historical series of Landsat images and applies the normalized snow difference index between the years 1991 to 2017. To determine the situation of deglaciation and quantification from the retreat of Nevado Ampay, the meteorological data from the Tamburco and Abancay stations has been considered. The supervised classification spatial visualization method for the Landsat 2MSS image and the normalized snow difference index have been used to determine the glacier cover area with Landsat 5, Landsat 7 and Landsat 8 Operational Land Imagery /Thermal Infrared Sensor images. The results show a significant decrease in the surface of the Ampay glacier due to the increase in temperature. The surface of the Ampay glacier in 1991 has been 2.13 km² and in 2017 it has been 1.09 km², showing a loss of 1.04 km² (48.92%) in recent years as a consequence of significant climate variability (temperature and precipitation). In 2015, an apparent accumulation of snow was recorded on the Ampay glacier, reaching 2.595 km², but in the following years it has been decreasing until reaching 1.086 km² of the glacier surface in 2017. It is concluded that the glacial retreat of the Ampay National Sanctuary in the last 25 years it has been 1.04 km² with a tendency to continuous deglaciation, putting the water resource at risk.

KEYWORDS

Glacial retreat, satellite Landsat images, glacier surface, Multi-temporary analysis, temperature, Normalized Snow Difference Index

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INTRODUCTION

Glaciers are large masses of fresh water in solid state, which have been formed from snow and recrystallized ice, which have accumulated and compacted due to low temperatures, over a long period of time in certain geographical areas of the planet [1]. As a consequence of climate change, one of the great impacts that has been observed throughout the world is the melting of glaciers; establishing itself as an indicator in this regard.

In Latin America, tropical glaciers are mostly located in the Andes mountain range: 72% in Peru, 20% in Bolivia, 4% in Ecuador and 4% in Colombia. This tropical glacier has shown an accelerated decline since the mid-1970s.

The influence of climate on glaciers is more important when they are located in temperate zones, such as in the Andes mountain range, where the ice sheet is at a melting temperature: a small increase in temperature is capable of causing the ablation process. Most Andean glaciers fall into this category, with the exception of the parts that exceed 5,800/6000 m in height, which are generally “cold” glaciers [2]. Glacier retreat is evidence of anthropogenic-climate change, however glacier response times are typically decades or more, implying that current glacier retreat is a mixed response to natural climate variability and current anthropogenic forcing [3]. Remote sensing, using satellite images is a very viable tool to study glacial areas or surfaces [4]. During the last 40 years the glaciers of the Peruvian Andes have been reduced by 42.6% [5]. Through multi-temporal analysis in satellite images, it is possible to observe the evolution of snow-capped mountains and glaciers and collect data of great importance to determine the influence of climate change processes on them [6]. The retreat of glaciers in the Peruvian Andes is accelerated during the years that the Niño phenomenon occurs; however, in the years of La Niña they tend to be stable or increase their coverage [7].

The greatest acceleration of the retreat of glaciers has been in the last decades of the 20th century. Tropical glaciers are the main source of fresh water for some of the largest cities in South America [8]. The Andes are home to more than 99% of tropical glaciers and Peru contains approximately 70% of them [9]. That since the late 1970s, glacial retreat can be attributed to human influences on the global climate [10] mention that since the end of the 70s, glacial retreat can be attributed to human influences on the global climate. Likewise, [11] it indicates that, at the end of the 70s, the glaciers seem to have crossed an invisible line towards a state of decline that can be considered unnatural. Ice volumes are known only to a few of the approximately 160,000 glaciers worldwide, but they are important components of many studies on climate and sea level that require estimates of water flow [12]. Tropical glaciers are sensitive to climate change on a spatio-temporal scale and are an important source of hydrological resources [13].

Tropical glaciers have experienced a setback in recent decade. However, going back several centuries and rebuilding the entire process of deglaciation since the “Little Ice Age” the last maximum glacier that occurred in this part of the Andes between the 17th and 18th centuries-, the retreat of the glaciers Andean began around 1730-1750.
Therefore, it has been before humanity could have a significant influence on the climate [14]. However, the decrease in glaciers has increased in the second half of the 20th century, especially after 1976. It can be said that, in the last decades, deglaciation took an unprecedented rate since the last three centuries, since the glaciers have lost between 35% and 50% of their surface and volume in thirty years. Tropical glaciers in Peru cover an area of 2,500 square kilometers (km²), but they are particularly important, first because of the water resources they grant to the populations. Glaciers constitute solid freshwater reserves and because of their great sensitivity to climate change, tropical glaciers represented excellent indicators of climate evolution.

The environmental services of rocky glaciers are similar to those of white glaciers [15]. Among the services related to its use value, it is mainly its use as a source of water, its contribution to climate regulation, its content of information on the geological and climatic past [16], and its appreciation in tourism [17]. However, the components of the cycle are subject to natural variability, in interannual to ten-year time scales [18]. Some variations in the water cycle, on a global scale, have been related to climate change [19]. On the other hand, human activities especially changes in land use, constructions among others can influence processes.

For Latin America and the Caribbean, agriculture is an economic activity that represents about 10% of gross domestic product (GDP) and contributes 12% of world agricultural exports [20]. The retreat of glaciers is balanced with the smallest increase in temperature and is accelerated with the increase in air temperature. The results coincide with studies conducted in the Andes of Peru [21].

Remote sensing, through the use of satellite images, is a very viable and useful tool to study areas or surfaces of glaciers [22]. Similarly, the use of images from active sensors makes it even easier to obtain information on displacement surfaces, such as Differential Radar Interferometry –DInSAR–, a technique that has been used in different parts of the world to study glaciers [23].

On July 23, 1987, the Ampay National Sanctuary is established, by Supreme Decree No. 042-87-AG, with the aim of conserving the species, Intimpa, within its ecosystem; Podocarpus glomeratus, the only genus of South American conifer [12].

Tropical glaciers are sensitive to climate change on a spatio-temporal scale and are an important source of hydrological resources [24]. These changes are significantly altering the availability of water in the region and pose critical risks to local populations that are highly dependent on these resources for their livelihoods [25].

The investigation of the retreat of the glacier surface in the Ampay National Sanctuary is carried out using the historical series of Landsat images and applies the normalized snow difference index between the years 1991 to 2017. To determine the situation of deglaciation and quantification from the retreat of Nevado Ampay, the meteorological data from the Tamburco and Abancay stations has been considered [26];

The use of these tools facilitates obtaining information on glacial surfaces. It has been hypothesized that the snowy Ampay presents an evident glacial retreat in the last 25 years due to the variability of climatic factors (precipitation and temperature), endangering the water resource.

**Characteristics of the study area**

The Ampay glacier is part of the Cordillera de Vilcabamba, it is located in the region of Apurimac, province of Abancay, its maximum altitude is 5,235 meters above sea level, and it is located geographically at the coordinates 72 ° 55 ' to 72 ° 54 ' from latitude west and 13 ° 33 ' to 13 ° 34 ' south longitude. Access to the Ampay glacier from the city of Abancay is by paved road and road, traveling 51 kilometer (km) to Karcatera, where it is possible to find informative signs, then follow a 6-hour road to reach the base camp. The climate in Abancay is 16.7 ºC annual average temperature and 685 milimetres (mm)
annual average rainfall [27]. The investigation has been carried with duration of 12 months in the mountain of the Ampay glacier; the area of the ice caps has been visited.

Land use has strong restrictions in this area due to its proximity to the Ampay National Sanctuary protected natural area, a buffer zone.

The glacier is a water reserve that allows the productive activities of the peasants to be prolonged, in the buffer zone of the Ampay National Sanctuary and the valley of the Pachachacca River. The rural populations near the Ampay National Sanctuary are grouped into Peasant Communities; (C.C.) and in Associations of Small Agricultural Producers; (A.P.A.) that make a total of nine [28].

![Location of the glacier in the Ampay National Sanctuary](image)

**MATERIALS AND METHODS**

This work seeks to determine the changes in the area of the glacial surface that has suffered the between 1991 to 2017, through the use and processing of optical satellite images [29] There are different techniques for the extraction and mapping of snow cover on a satellite image [30]. Spectral Indices (IE) techniques [31] have been used in satellite images of the Landsat 8 OLI TIRS (Operational Land Imagery /Thermal Infrared Sensor) [32], which is a method that compares the spectral information of one band with another, to distinguish the coverage of snow among other covers [33]. Trend design and evolutionary analysis has been used. Landsat images files union has been used, the atmospheric correction has been obtained, the supervised classification and the filter have been obtained, and the raster format has been converted to vector and the area of the glacier to get images of glacial retreat [34].

For the analysis of the multi-time evolution of the Ampay glacier the images are shown:

A. Band 2 green: (0.52 – 0.60). Specially designed to evaluate the vigor of healthy vegetation, measuring its green reflectance peak (or radiance). It is also useful to differentiate types of rocks and, like band 1, to detect the presence or not of limonite.

B. Band 3 red: (0.63 – 0.69). It is a chlorophyll absorption band, very useful for the classification of the vegetation cover. It also serves in the differentiation of the different rocks and to detect limonite.

C. Band 4 IR nearby: (0.76 – 0.90). It is useful to determine the content of biomass, for the delimitation of bodies of water and for the classification of rocks of the
different years, but also to see the perception of glacial retreat. The statistical evaluation (Person) has been performed to correlate glacier retreat with as well as precipitation and temperature data for the correlation climatic variability (temperature and precipitation) of the study area.

The determination of the glacier retreat in the study area has been through the use of satellite images of Landsat 6 type 5, 7 and 8. The satellite images allow obtaining the information required to determine the retreat of the glacier, and the volume of ice lost.

To [35] estimate glacier coverage in the study area from Landsat 5 Landsat Thematic Mapper (TM) and Landsat 8 OLI / TIRS images, the Normalized Snow Difference Index (NDSI) [30] has been used [31].

The multi-temporal evolution of each one of the mentioned periods, the analysis shows the images of Landsat 8 (bands, 7, 5, 4), Landsat 7 (bands 5, 4, 2) Landsat5 (bands 4, 3, 2) all these natural color combinations, for light visible to the human eye, which has allowed differentiating the glacier cover to determine glacial retreat in the Ampay. For the assignment of the thresholds, the NDSI (Normalized Difference Snow Index) raster, raster to polygon were used, these elements were main in order to avoid confusion of shadows with glaciers and to have a reliable result, satellite images were introduced available in Arcgis 10.3.

**Data base to estimate glacier cover**

The information used is based on satellite images Landsat 2 MSS (Multispectral Scanner), Landsat 5 TM (Thematic Mapper) and Landsat 8 OLI / TIRS (Operational Land Imagery / Thermal Infrared Sensor), with spatial resolution of 60 m (meters), 30 m. and 30 m. respectively, included between the periods 1991-2017 with projection of UTM map, WGS84 datum, zone 19 south in Geotiff format and geographic coverage (path 002, 003 and row 070).

The Landsat 2 MSS satellite is made up of four spectral bands; two in visible and two in near infrared. Landsat 5 TM operates simultaneously in seven spectral bands, three being visible, one in the medium infrared, two in the near infrared and one thermal band [32]. Landsat 8 is made up of nine spectral bands on the OLI (Operational Land Imager) sensor and two bands on the TIRS (Thermal Infrared Sensor).

**Geometric correction**

At this stage, the ND (Normal Difference) pixels were moved to their geo referenced positions without modifying the values of the Landsat MSS image, so that they coincide precisely with the Landsat OLI image. The MSS image captured by Landsat 2 has been corrected using the empirical control point method, based on the Landsat 8 OLI/TIRS image. For this methodology, it has been necessary to establish control points coordinate transformation using a polynomial function and the use of the cubic convolution method to transform gray levels [35].

**Creation of the file in. pcidsk**

The Smart Ware Physical Index, PIX of each Image is carried out, generating a single file with the information of the 5 bands of each image.

**Atmospheric correction**

In this process, the radiance values are converted to reflectance values, using the FLAASH tool (Fast Line-ofsight Atmospheric Analysis of Hypercubes) of ENVI 5.3 [36] being necessary the average elevation of the area in kilometers, satellite imaging date, solar elevation angle, solar azimuth, sensor type, and sensor height, shown. Table 2

**Estimate of areas covered by glacier**
Estimate of areas covered by glacier to estimate glacier coverage in the study area from Landsat 5 TM (Thematic Mapper) and Landsat 8 OLI/TIRS images, the Normalized Snow Difference Index (NDSI) has been used [37]. The NDSI (Normalized Difference Snow Index) is calculated using Eq. (1) for Landsat 5 and Landsat 8 images respectively [31].

\[
NDSI = \frac{VIS - NIR}{VIS + NIR}
\]  

\(NDSI\) = Normalized Snow Difference Index  
\(VIS\) = VIS = Visible light (380-780mm)  
\(NIR\) = NIR = Near Infrared (780mm-2,5um)

The NDSI is an index that is used to detect the presence of snow in a specific area. To obtain it must operate with the bands of the image as follows:

NDSI LANDSAT 4/5 = Band2 -Band5 /Band2 – Band5  
INDEX NDSI: LANDSAT 7 -5 NDSI = (Band2 -Band5) / (Band2 + Band5)  
INDEX NDSI: LANDSAT 8 NDSI= (Band3-Band6) / (Band3+Banda6)  

Where, B2, B3, B5 and B6 are bands 2, 3, 5 and 6 respectively. For the identification of snow [38] indicate that the NDSI > 0.4. Shadow and cloud interference were removed manually, according to the procedure carried out by [39]. Field trips have been made to the Ampay glacier for the in situ execution of the experimental part and to validate the results obtained from satellite images.

**Climate data analysis**

The climatic factors analyzed have been: temperature and precipitation from 1991 to 2017, for the study of the retreat of the Ampay glacier surface, data obtained from the National Meteorology and Hydrology Service (SENAMHI) from the San Antonio station.

![Annual Average Temperature Period 1991-2017](image)

**Figure 2.** Annual average temperature period 1991-2017

The temperature data have been extracted from the National Meteorology and Hydrology Service (SENAMHI) from the San Antonio station in the Tamburco-Abancay District. Figure 2 shows the temperature variability over the years, from 1991 to 2017. It is relevant to note that in 2010 the maximum annual temperature of 16.84 °C is reached.
From this record a clear decreasing trend is shown until 2017. The variability of the temperature has been more noticeable in the last three years from 2015 to 2017, where the lowest temperatures have been recorded within the last ten recorded years.

Table 1. Total monthly precipitation in millimeters San Antonio station - Abancay

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<th>APR.</th>
<th>MAY.</th>
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<th>JUL.</th>
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In Table 1 the annual rainfall data for the last 20 years records that in 2015 there were 1072.4 millimeters (mm) in 1999 with 117.80 mm and in 2000 with 1109.30 mm, high figures for the last 20 years from 1991 to 2017. The data shows that in recent years, annual rainfall has increased in reference to 1991.
The precipitation data has been collected from the National Meteorological and Hydrological Service (SENAMHI) of the San Antonio station in the Tamburco-Abancay District. The (Table 1) shows annual precipitation for the last 20 years and (Figure 3) shows the total monthly precipitation, produced between the years 1991 to 2017. In the years 1991 to 1993 low rainfall is shown with an average of 344 mm. In the years 1998 to 2001 the increase in rainfall in an average of 972 mm, in 2015 the precipitation increased to 1072.4 mm.

RESULTS

The application of glacier surface estimation methods, from Landsat images, demonstrates the existence of historical data from 1975 to the present day in the Ampay glacier, maintaining that the increase in temperature and precipitation have broken the natural balance in the thawing of the glacier, the data obtained from SENAMHI being those that indicate the increase in temperature and average precipitation between (1991-2017) which are the years considered in the present investigation.

The area of the glacier is established in Kilometers$^2$ (Km$^2$) per year. In 1991 there were 2.126 (Km$^2$), in 2001 (2.595 Km$^2$), 2015 it has decreased to (1.919 Km$^2$) and in 2017 there has been 1,086 Km$^2$, a decrease of 1.0405 Km$^2$ from 1991 to 2017, which represents 48.92% loss of the surface of the Ampay glacier.
Figure 5. Evolution multi-time of the glacier de 1991 al 2017 by images. Glacier area: a) 2.126 Km² 1991, b) 1.402 Km² 1993, c) 1.777 Km² 1995, d) 1.826 Km² 1996, e) 1.542 Km² 1998, f) 2.595 Km² 2001, g) 1.468 Km² 2004, h) 1.919 Km² 2015, i) 1.086 Km² 2017.

In Figure 5 (5a, 5b, 5c, 5d, 5e, 5f, 5g, 5h, 5i), and Figure 5 the variations of glacial melting for the Ampay snowfall under study between 1991 and 2017 are presented using optical images. According to the results, they have presented a significant decrease in the glacial surface in a period from 1991 to 2017.

Making an analysis of the main components made with the bands of the images of 1991, 1993, 1996, 2001, 2015, 2016 and 2017, 10 components has been obtained, presented in 10 Landsat figures 5, 7 and 8, the investigation has been based on the results of the multi-temporal evolution of each of the periods mentioned. The analysis shows the images of Landsat 8 (bands 7, 5, 4), Landsat 7 (bands 5, 4, 2), Landsat 5 (bands 4, 3, 2); all these combinations of natural color, for the light visible to the human eye, which has allowed us to differentiate the glacier cover for the determination of the glacial retreat.

Table 2. Glacier retreat as a function of time

<table>
<thead>
<tr>
<th>Year</th>
<th>Area glacier Km²</th>
<th>Retreat glacier (Km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991</td>
<td>2.126</td>
<td>1.04</td>
</tr>
<tr>
<td>2017</td>
<td>1.086</td>
<td></td>
</tr>
</tbody>
</table>

The glacial retreat from 1991 to 2017 has been 1.04 Km², during this time the evolutionary curve has been very varied because there has been years of recovery and others of retreat of the glacial surface. This difference in glacial retreat shows that there are other indicators that are allowing the glacial surface to decrease Table 2.

Tabla 3. Multi-temporal evolution of the glacier 1991 to 2017

<table>
<thead>
<tr>
<th>Launching and product</th>
<th>Glacial (Km²)</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landsat TM 5</td>
<td>2.126</td>
<td>1991</td>
</tr>
<tr>
<td>Landsat TM 5</td>
<td>1.402</td>
<td>1993</td>
</tr>
<tr>
<td>Landsat TM 5</td>
<td>1.777</td>
<td>1995</td>
</tr>
<tr>
<td>Landsat TM 5</td>
<td>1.826</td>
<td>1996</td>
</tr>
<tr>
<td>Landsat TM 5</td>
<td>1.542</td>
<td>1998</td>
</tr>
<tr>
<td>Landsat TM 5</td>
<td>2.595</td>
<td>2001</td>
</tr>
<tr>
<td>Landsat TM 7</td>
<td>1.468</td>
<td>2004</td>
</tr>
<tr>
<td>Landsat TM 7</td>
<td>1.919</td>
<td>2015</td>
</tr>
<tr>
<td>Landsat TM 8</td>
<td>1.053</td>
<td>2016</td>
</tr>
<tr>
<td>Landsat TM 8</td>
<td>1.086</td>
<td>2017</td>
</tr>
</tbody>
</table>

From the table it is analysed that the glacier surface in 1991 shows 2.126 km², having progressively decreased with slight recoveries in 2001 (2.595 km²) and in 2015 (1.919 km²), and in 2017 there is a decrease in the surface with 1.086 km² Table 3.
Figure 6. Evolution of the Ampay glacier surface (1991–2017)
In Figure 6 it is observed the evolution of the retreat of the surface from 1991 to 2017, it is evident, there is a visible difference of the glacier surface of 1991 (figure 6 a) with respect to the glacial surface of 2017 (figure 6 i).

DISCUSSION

The investigation of the retreat of the glacier surface in the Ampay National Sanctuary is carried out using the historical series of Landsat images and applies the normalized snow difference index between the years 1991 to 2017. To determine the situation of deglaciation and quantification from the retreat of Nevado, the meteorological data from the Tamburco and Abancay stations has been considered.

The Landsat 5 TM (Thematic Mapper) images operate simultaneously in seven spectral bands, three being visible, one in the middle infrared, two in the near infrared and one thermal band [31]. The retreat of the glaciers is balanced with the lower increase in temperature and is accelerated with the increase in air temperature [32]. Temperature within climate change has been a determining factor in the retreat of the Ampay glacier during the last twenty-five years (1991-2017).

The NDSI (Normalized Difference Snow Index), raster calculator and raster to polygon has been used to assign the thresholds; these three elements were used to avoid the confusion of shadows with glaciers and thus have a reliable result [29]. Satellite images have been introduced, available in ArcGIS 10.3 [40]. To estimate glacier coverage in the study area from Landsat 5 TM and Landsat 8 OLI / TIRS images, the Normalized Snow Difference Index (NDSI) has been used [37].

At the beginning of 2000, tropical glaciers covered a total of 1.920 km² and almost all were in the Andes between Colombia and Bolivia, with predominance in Peru (70%) and Bolivia (20%) [38]. Despite their small size in terms of volume - equivalent to less than 0.3 millimeters of rise in sea level, these glaciers are important for two reasons: 1) they are excellent indicators of the trend, evolution and climatic fluctuations over several decades, being without doubt the best of the tropical zone, and 2) play a prominent role in the hydrology of upper basins and contribute to water resources.

The surface of the glacier in 1991 shows 2.126 km², having progressively decreased with slight recoveries in 2001 (2.595 km²) and in 2015 (1.919 km²), and in 2017, the total decrease in the surface has been 1.086 km². The acceleration of the deglaciation that has begun to affect the water resource is indisputable. However, the issue is complex [41]. On the one hand, the decrease in the ice reserve increases the availability of the resource; but on the other hand, the reserves diminish when the ice masses are reduced too much to maintain them, particularly during the dry season. However, the continuous deterioration of the glaciers will have inevitable consequences in the upper glacial basins and not only in the water resource, but also undoubtedly in ecosystems linked to ice masses [39].

The highest percentage of loss of glacial surface in the Ampay glacier occurs in times of ablation where the maximum and minimum temperatures are higher, so it is established that there is an inverse relationship between the temperature and the decrease in the glacier surface, which indicates that, at higher temperatures, smaller surface area [42]. The loss of glacial surface is associated with an increase in temperature, a consequence of greenhouse gases [43].

There is an inverse relationship between precipitation and loss of glacial volume, the higher the liquid precipitation, the lower the increase in the volume of snow in glaciers. The greatest impact of the loss of glacial volume occurs in seasons of ablation where rainfall is scarce, the behavior of the glacier shows a tendency to recede, which leads to the conclusion that the scarce precipitation that occurs in the season of ablation does not contribute to the stability of the glacier since it does not generate accumulation on its surface [44].
The Ampay glacier is a source of water supply that accumulates in several lagoons that are part of the Pachachaca river basin. The potential of spatial visualization methods to monitor glacier covers is a fairly effective method, which can significantly help to understand and track glacier mass movements [45].

In recent years the glacial surface of the Ampay has receded, revealing its "fresh" moraines. The current distance from the glacier has contributed to the fact that three lagoons that are part of the melt chain have dried up and those that are still reservoirs have decreased their volume by up to 50% with respect to the volume of 1997. The accelerated deglaciation of the Ampay constitutes a threat to the population, as a reserve water resource for the city [46] the parameters of temperature, precipitation and relative humidity have a significant influence on the behavior of the Ampay glacier [47].

CONCLUSIONS
Through the use of the historical series of landsat images and the normalized snow difference index, the situation of deglaciation and quantification of the retreat of the Ampay glacier has been determined. The use of the Normalized Differential Snow Indices –NDSI tool has allowed the delimitation of the glacier surface. The multi-temporal analysis of the glacier surface estimated from satellite images shows a significant decrease in the coverage of the Ampay glacier area in the last twenty-five years (2001-2017) with a loss of 1.04 km² (48.92%), as a consequence of climate variability (meteorological components of precipitation and temperature), in 2015 a recovery is shown in the area of the Ampay glacier 2.595 km², but in the following years it has been decreasing reaching 1.086 km² in 2017, without forecasting that the glacial retreat will continue in the coming years, putting at risk the availability of water resources as a water reserve.

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