Journal of Sustainable Development of Energy, Water and Environment Systems

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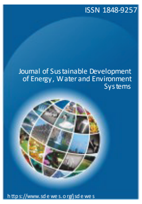

Year 2021, Volume 10, Issue 1, 1080380

Original Research Article

Multi-Temporal Analysis of the Glacier Retreat Using Landsat Satellite Images in the Nevado of the Ampay National Sanctuary, Peru

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Cite as: Soto Carrión, C , et al., Multi-Temporal Analysis of the Glacier Retreat Using Landsat Satellite Images in the Nevado of the Ampay National Sanctuary, Peru, J. sustain. dev. energy water environ. syst., 10(1), 1080380, 2022, DOI: https://doi.org/10.13044/j.sdewes.d8.0380

ABSTRACT

Glaciers are humanity's most extraordinary water reservoirs, covering approximately 10% of the total Earth surface. 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 applying the normalized snow differential index between the years 1991 to 2017. The meteorological data from the Tamburco and Abancay stations have been considered to determine the deglaciation and quantify the retreat of the Ampay glacier. The supervised classification spatial visualization method for the Landsat 2 Multispectral Scanner image and the normalized snow differential index have been used to determine the glacier cover area with Landsat 5, Landsat 7, and Landsat 8 Operational Land Imager/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 was 2.13 km^2 and in 2017 – 1.09 km^2, showing a loss of 1.04 km^2 (48.92%) 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 km^2, but in the following years, the glacier surface has been decreasing until it reached 1.086 km^2 in 2017. It is concluded that the glacial retreat of the Ampay National Sanctuary in the last 25 years with a tendency to continuous deglaciation puts the water resource at risk.

KEYWORDS

Glacial retreat, Satellite Landsat images, *Glacier surface, Multi-temporary analysis, Temperature, Normalized Snow Difference Index.*

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 time in some geographical areas of the planet [1]. As a consequence of climate change,

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one of the significant impacts observed throughout the world is the melting of glaciers, establishing itself as an indicator of change.

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. These tropical glaciers have 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, except for the parts that exceed 5,800–6000 m elevation, 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 has 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 main factors that influence the amount of rain and its distribution and result in droughts or floods are natural cycles of the climate, especially the El Niño and La Niña phenomena. Both are caused by the displacement of a gigantic mass of warm water located in the middle of the Pacific Ocean, at the latitude of Ecuador. El Niño occurs when the warm water of the sea moves to the east, towards South America (Ecuador and Peru), while La Niña occurs when the water slides towards the western end of the Pacific (Australia and Indonesia). This reciprocating displacement of marine currents is called the El Niño Southern Oscillation. The heat and water vapor exiting the hot water body generate storms so large that they affect air currents that blow through mid-latitudes [7].

The greatest acceleration of the retreat of glaciers has been in the last decades of the 20th century. Tropical glaciers are the primary 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]. Since the late 1970s, the glacial retreat can be attributed to human influences on the global climate [10]. Likewise, [11] 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 the recent decade. However, going back several centuries and rebuilding the entire process of deglaciation since the "Little Ice Age", the last maximum glaciers that occurred in this part of the Andes were between the 17th and 18th centuries; the retreat of the Andean glaciers 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 accelerated 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 previous three centuries, as 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 kilometer (km^2), but they are critical, 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 represent excellent indicators of climate evolution.

The environmental services of rocky glaciers are similar to those of white glaciers [15]. Among the services related to their use-value, it is mainly their use as a source of water, contribution to climate regulation, the content of information on the geological and climatic past [16], and appreciation in tourism [17]. However, the cycle components are subject to natural variability in inter-annual 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 like changes in land use and 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 temperature increase and accelerates with the increasing 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 was established in Peru by Supreme Decree No. 042-87-AG to conserve the species Intimpa (*Podocarpus glomeratus*) within its ecosystem. The Intimpa is the only genus of South American conifer [12].

Tropical glaciers are sensitive to climate change on a spatio-temporal scale and are essential for hydrological resources [24]. These changes significantly alter water availability 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. It applies the normalized snow difference index between the years 1991 to 2017. The meteorological data from the Tamburco and Abancay stations have been considered for determining the situation of deglaciation and quantification of the glacier retreat in Nevado Ampay [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.

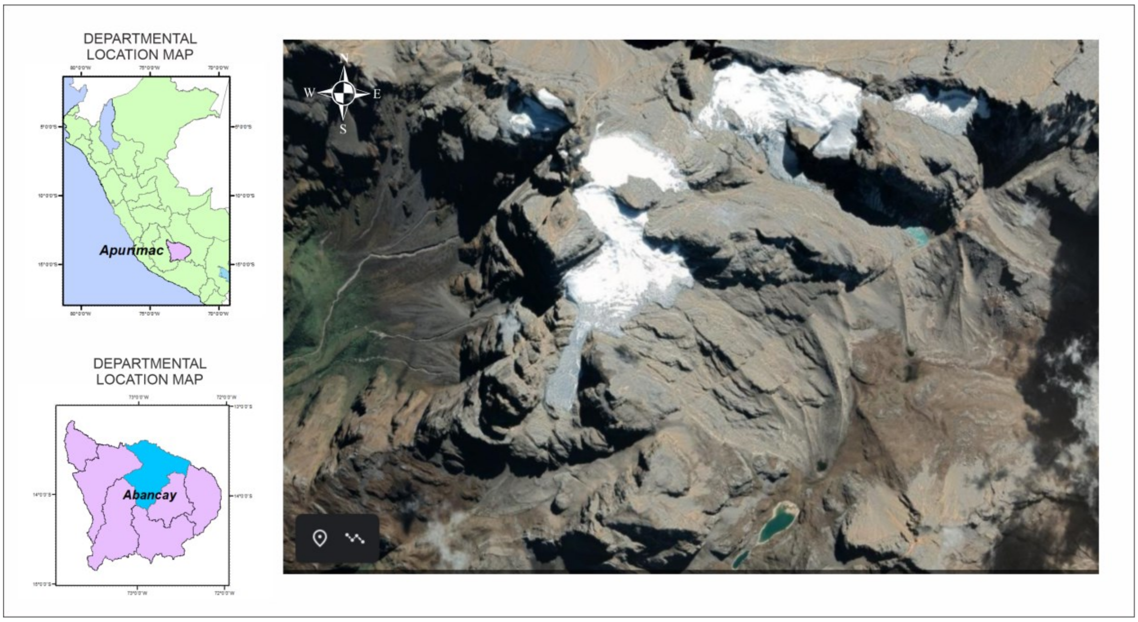

Figure 1. Location of the glacier in the Ampay National Sanctuary

Characteristics of the study area

The Ampay glacier is part of the Cordillera de Vilcabamba 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' west longitude and 13°33' to 13°34' south latitude. Access to the Ampay glacier from the city of Abancay is by paved road and road travelling 51 kilometer (km) to Karcatera, where it is possible to find informative signs, and then follow a 6-hour road to reach the base camp. The climate in Abancay is 16.7 ºC annual average temperature and 685 millimeter (mm) annual average rainfall [27]. The investigation has been carried out with a duration of 12 months in the mountain of the Ampay glacier; the area of the ice caps has been visited.

Land use has substantial 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 Pachachaca 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 groups [28].

MATERIALS AND METHODS

The present study has determined the changes in the glacial surface area between 1991 and 2017 by using and processing optical satellite images [29]. There are different techniques for extracting and mapping 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 Imager / 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 have 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 the vector one and the glacier area to get images of glacial retreat [34].

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

- Band 2 green: 0.52–0.60 micrometer (μm); 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 like band 1, to detect the presence or not of limonite.
- Band 3 red: 0.63–0.69 μm. 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.
- Band 4 infrared (IR) near: 0.76–0.90 μm. It is useful to determine the content of biomass, for the delimitation of water bodies and for classification of rocks of different ages, but also to see the perception of glacial retreat. The statistical evaluation (Pearson's test) has been performed to correlate glacier retreat with precipitation and temperature data for the correlated climatic variability of the study area.

The determination of the glacier retreat in the study area has been carried 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 estimate glacier coverage in the study area from Landsat 5 Thematic Mapper (TM) and Landsat 8 OLI/TIRS images, the Normalized Snow Difference Index (*NDSI*) [29] has been used [30].

Regarding 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), and Landsat 5 (bands 4, 3, 2); all these in natural colour combinations of 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 conversion were used; these elements were main. To avoid confusion of shadows with glaciers and have a reliable result, satellite images were introduced available in ArcGIS 10.3 software.

Database 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 Imager / Thermal Infrared Sensor), with a spatial resolution of 60 m (meters), 30 m and 30 m, respectively, included between the periods 1991–2017 with projection of UTM (Universal Transverse Mercator) map, WGS (World Geodetic System) 84 datum, zone 19 south, in GeoTIFF format and Geographic Coverage (path 002, 003 and row 070).

The Landsat 2 MSS information 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).

<u>Geometric correction</u>. 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 cubic convolution method to transform gray levels [35].

<u>Creation of the file in pcidsk</u>. The Smart Ware Physical Index, PIX of each image is carried out, generating a single file with the information of 5 bands of each image.

<u>Atmospheric correction</u>. In this process, the radiance values are converted to reflectance values and indices of spectral bands, using the FLAASH tool (Fast Line-of-sight Atmospheric Analysis of Hypercubes) of ENVI 5.3 software [36]. The necessary input data include the average elevation of the area in kilometers, satellite imaging date, solar elevation angle, solar azimuth, sensor type, and sensor altitude.

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]. It is calculated using Eq. (1) for Landsat images [30] as follows:

$$NDSI = \frac{VIS-NIR}{VIS+NIR} \tag{1}$$

where: *VIS* – index of visible light band (380–780 nm), *NIR* – index of near infrared band (780 nm–2.5 μm).

The *NDSI* is an index used to detect the presence of snow in a specific area. To obtain its value using spectral bands defined for the different Landsat satellites, the indices of the image bands must be processed as follows:

$$\text{LANDSAT 4/5:} \quad NDSI = \text{Band2} - \text{Band5} / \text{Band2} - \text{Band5} \tag{2}$$

LANDSAT 5–7: $NDSI = (Band2 – Band5) / (Band2 + Band5)$ (3)

LANDSAT 8: $NDSI = (Band3 – Band6) / (Band3 + Band6)$ (4)

For the identification of snow, the authors of [38] indicated that $NDSI > 0.4$. Shadow and cloud interference were removed manually, according to the procedure carried out by [39]. Field trips were made to the Ampay glacier for the in-situ execution of the experimental part and validation of the results obtained from satellite images.

Climate data analysis

The analyzed climatic factors included temperature and precipitation from 1991 to 2017, and for the study of the retreat of the Ampay glacier surface, the data including temperature and precipitation were obtained 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 three years from 2015 to 2017, where the lowest temperatures have been recorded within the last ten-year period.

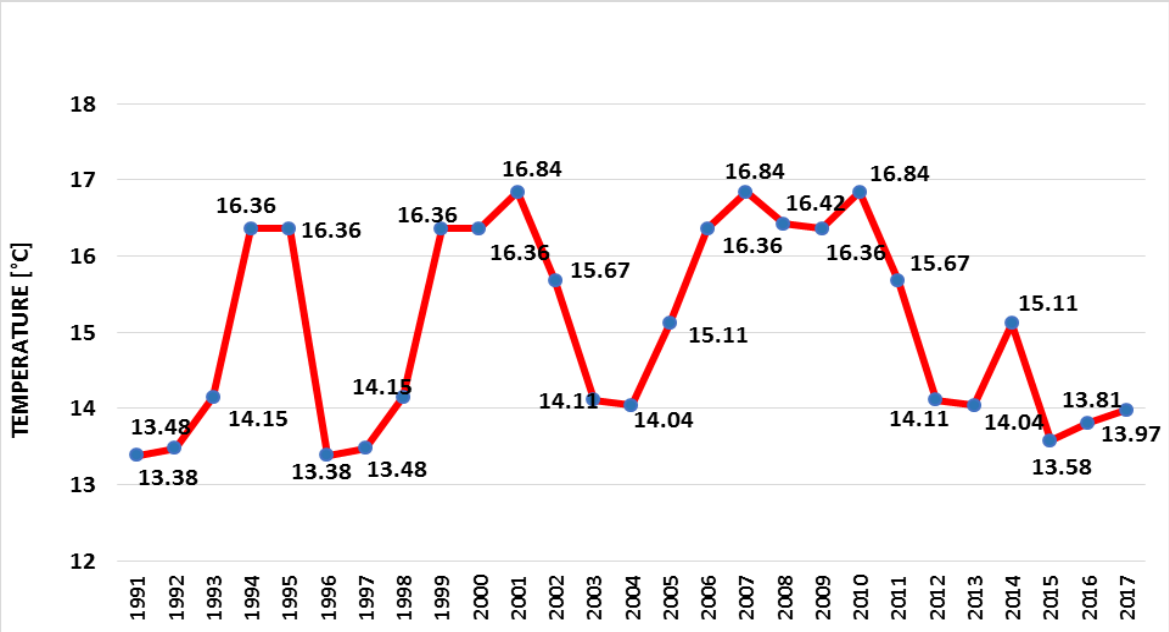

Figure 2. Annual average temperature in the period 1991–2017

Table 1 shows the total monthly precipitation produced between the years 1991 and 2017, and **Figure 3** shows annual precipitation for the last 20 years. 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 was to an average of 972 mm; in 2015, the precipitation increased to 1072.4 mm. The data show that in recent years, the annual rainfall has increased relative to 1991.

Table 1 Total monthly precipitation in millimeter (m), San Antonio station – Abancay

TOTAL MONTHLY PRECIPITATION IN (mm) SAN ANTONIO STATION													
YEAR	JAN.	FEB.	MAR.	APR.	MAY.	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.	Total annual precipitation
1991	51.40	48.80	94.40	0.90	14.50	8.70	0.00	0.00	8.70	45.40	32.00	16.60	**321.40**
1992	15.20	80.10	37.10	18.90	0.00	31.20	0.00	47.90	0.00	43.60	24.20	49.90	**348.10**
1993	126.60	92.30	77.90	49.20	5.00	0.00	11.00						**362.00**
1996	275.60	247.50	114.70	64.00	4.50	2.00	6.00	28.10	23.00	66.70	51.80	62.50	**946.40**
1997	226.00		180.40	56.60	21.20	2.70	0.00	35.00	25.60	25.40	85.20	86.90	**745.00**
1998	171.90	102.10	157.80	22.00	9.10	3.00	0.00	1.00	9.00	92.00	52.10	89.60	**709.60**
1999	203.30	291.60	162.00	77.90	12.20	9.30	3.40	0.00	71.10	80.60	73.60	132.80	**1117.80**
2000	213.50	299.20	115.30	49.90	7.10	18.90	19.50	28.80	16.90	92.90	51.20	196.10	**1109.30**
2001	256.20	180.00	193.80	37.70	51.40	1.10	29.50	24.60	10.60	32.60	33.10	102.10	**952.70**
2002	125.60	202.30	133.90	76.00	22.80	11.00	58.00	16.30	63.20	81.80		130.10	**921.00**
2003	208.20	182.90	199.60	20.50	6.70	0.00	1.60	35.80	35.70	94.90	35.50	136.60	**958.00**
2004	138.70	217.20	81.70		10.50	22.20	37.00	17.90	34.90	23.30	40.40	145.30	**769.10**
2005	78.70	150.60		57.10		0.00	16.30		24.80	83.40	69.20	137.00	**617.10**
2006	210.30	143.00	87.90	42.00	0.00	13.30	0.00	0.00	4.00		129.30	136.40	**766.20**
2007	153.10	125.50	177.00	17.80	16.50		17.90		1.30	69.40	46.10	200.00	**824.60**
2008	154.10	109.80	101.90		22.00		0.00	10.30					**398.10**
2009	151.80	209.70	119.70	76.20	4.50	0.00	17.40	16.10	0.00	0.00	145.10	54.90	**795.40**
2015	215.60	247.70	162.00	78.10	20.20	1.10	12.30	33.30	1.60	42.40	93.80	164.30	**1072.40**
2016	72.70	303.00	56.30	103.40	1.90	7.20	7.50	15.70	15.20	70.00	72.30	155.40	**880.60**
2017	238.40	219.00	167.60	52.50	42.50	1.60	0.70	15.20	21.50	54.00	24.30		**837.30**

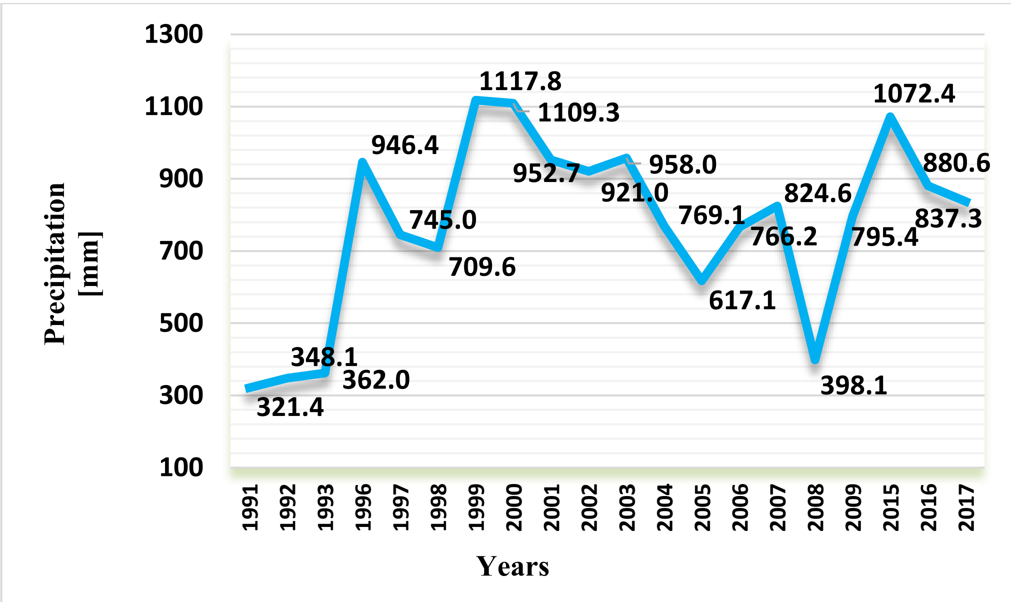

Figure 3. Total annual precipitation in the period 1991-2017

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. Considering the data obtained from SENAMHI that indicate the increase in temperature and average precipitation between 1991 and 2017, the rise in temperature and precipitation have broken the natural balance in the thawing of the glacier.

The area of the glacier is established in square kilometers (km^2) per year. In 1991 there were 2.126 km^2, in 2001 – 2.595 km^2, in 2015 it decreased to 1.919 km^2, and in 2017 there were 1.086 km^2. A decrease of 1.040 km^2 occurred from 1991 to 2017, representing a 48.92% loss of the surface of the Ampay glacier.

Figure 4 (4a–4i) presents the variations using optical images of glacial melting for the Ampay snowfall understudy between 1991 and 2017. According to the results, they show a significant decrease in the glacial surface from 1991 to 2017.

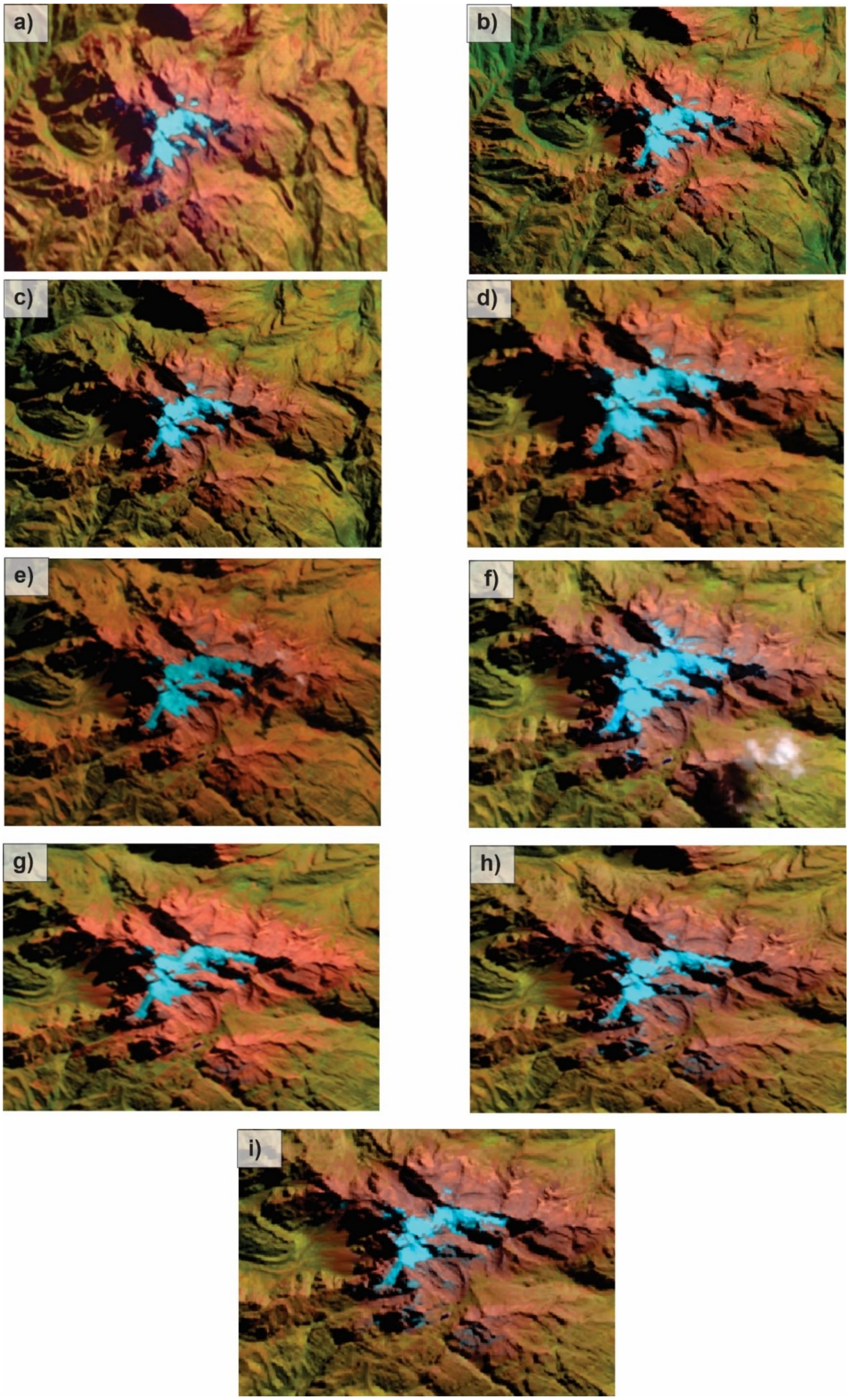

Figure 4. Multi-temporal evolution of the glacier by area images: 2.126 km^2 in 1991 (a), 1.402 km^2 in 1993 (b), 1.777 km^2 in 1995 (c), 1.826 km^2 in 1996 (d), 1.542 km^2 in 1998 (e), 2.595 km^2 in 2001 (f), 1.468 km^2 in 2004 (g), 1.919 km^2 in 2015 (h), 1.086 km^2 in 2017 (i)

By analysing the main components with the bands of the images from 1991, 1993, 1996, 2001, 2015, 2016, and 2017, 10 components have been obtained as presented in **Figure 5** and **Figure 6**. 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 colour, for the light visible to the human eye, which has allowed to differentiate the glacier cover for the determination of the glacial retreat.

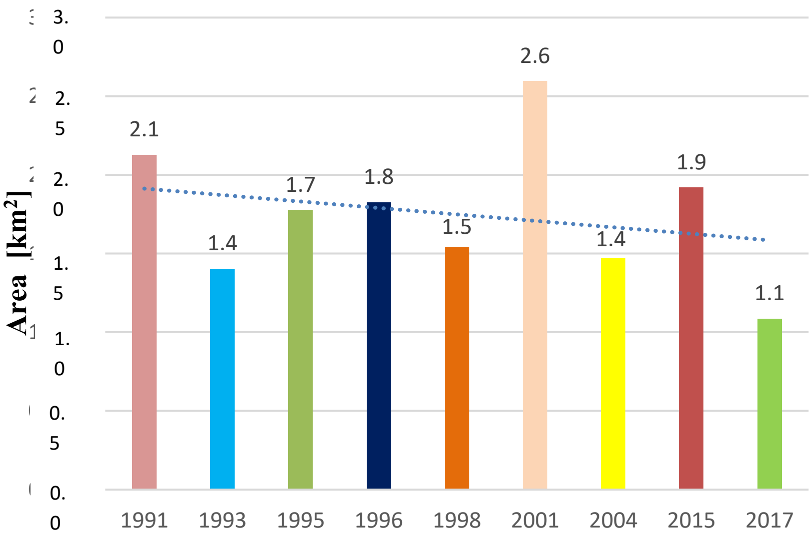

Figure 5. Multi-temporal evolution of the retreat of the Ampay glacier

Table 2 shows the retreat of the glacier from 1991 to 2017 has been 1.04 km^2. During this time, the evolutionary curve has significantly varied because there have been years of recovery and others retreating the glacial surface. This differences in the retreat rate of the Ampay glacier show that more factors are allowing the glacial surface to decrease as shown in **Table 3**.

Table 2. Glacier retreat as a function of time

Year	Glacier area [km^2]	Glacier retreat [km^2]
1991	2.126	1.04
2017	1.086	

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

Launching and product	Glacier [km^2]	Year
Landsat TM 5	2.126	1991
Landsat TM 5	1.402	1993
Landsat TM 5	1.777	1995
Landsat TM 5	1.826	1996
Landsat TM 5	1.542	1998
Landsat TM 5	2.595	2001
Landsat TM 7	1.468	2004
Landsat TM 7	1.919	2015
Landsat TM 8	1.053	2016
Landsat TM 8	1.086	2017

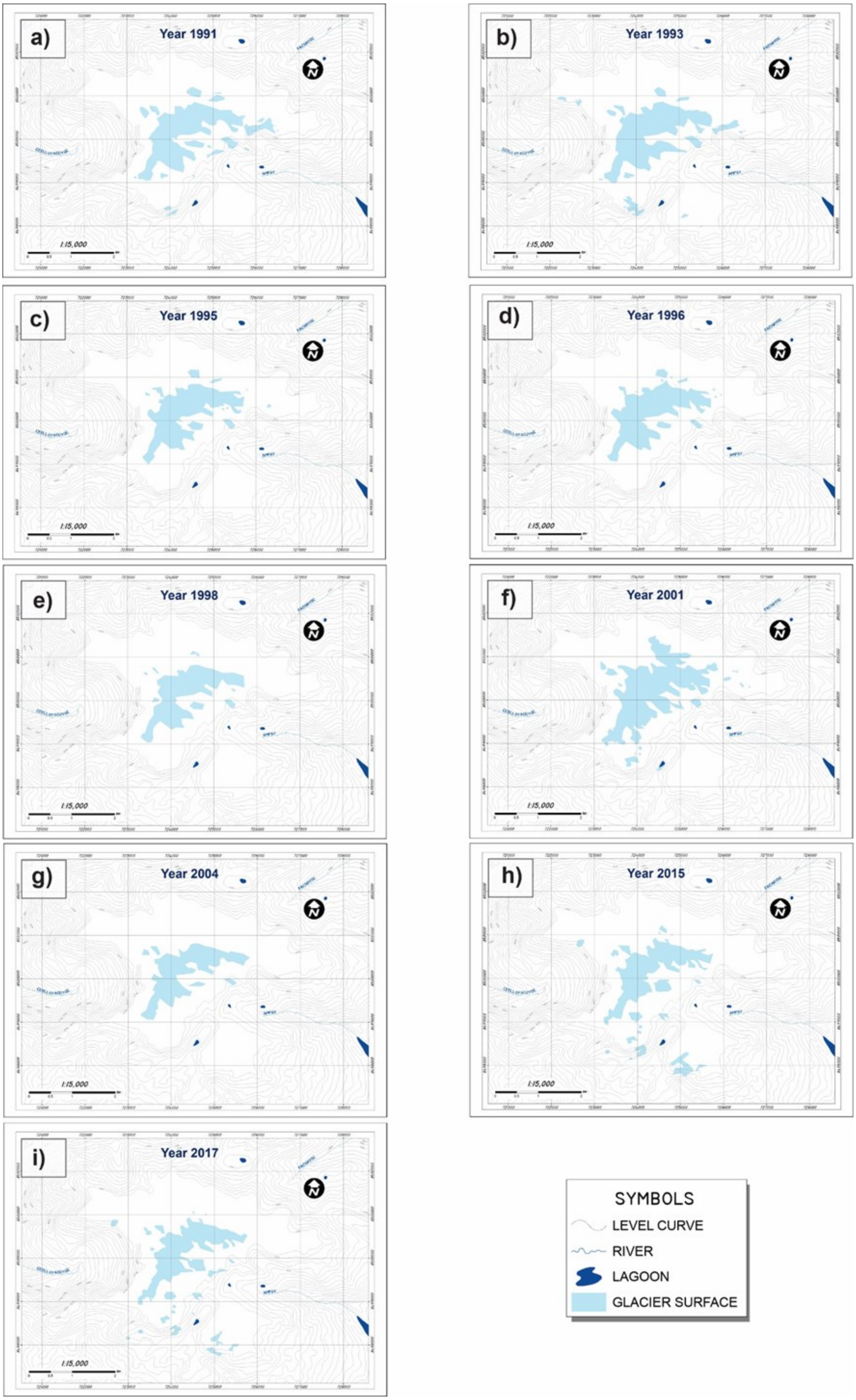

Figure 6. Evolution of the Ampay glacier surface, 1991–2017

The table shows that the glacier surface in 1991 was 2.126 km^2 and progressively decreased with slight recoveries in 2001 (2.595 km^2) and 2015 (1.919 km^2). In 2017 there was a decrease in the surface to 1.086 km^2.

Figure 6 illustrates the evolution of the retreat of the surface from 1991 to 2017. There is a visible difference in the glacier surface of 1991 (**Figure 6a**) compared with the glacier surface of 2017 (**Figure 6i**).

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. It applies the normalized snow difference index between the years 1991 to 2017. The meteorological data from the Tamburco and Abancay stations have been considered to determine the deglaciation and quantify the glacier retreat.

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 in the 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 two decades (1991–2017).

The *NDSI* (Normalized Difference Snow Index), raster calculator and raster to polygon have 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 software **[40]**. To estimate glacier coverage in the study area from Landsat 5 TM and Landsat 8 OLI/TIRS images, the *NDSI* has been used **[37]**.

At the beginning of 2000, tropical glaciers covered 1920 km^2 in total. Almost all of them 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 millimeter rise in sea level, these glaciers are essential for two reasons: firstly, they are excellent indicators of the trend, evolution, and climatic fluctuations over several decades, being, without doubt, the best of the tropical zone; secondly, they play a prominent role in the hydrology of upper basins and contribute to water resources.

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 resource availability. Still, on the other hand, the resources 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 the water resource and 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. There is an inverse relationship between the temperature and the decrease in the glacier surface, which indicates a smaller surface area at higher temperatures **[42]**. The loss of glacial surface is associated with temperature increase, resulting from greenhouse gases **[43]**.

There is also an inverse relationship between precipitation and loss of glacial volume – the higher the rainfall, the lower the increase in the snow volume of glaciers. The greatest impact on the loss of glacial volume occurs in seasons of ablation where rainfall is low, and the glacier's behavior shows a tendency to recede. This leads to the conclusion that the scarce precipitation in the ablation season does not contribute to the glacier's stability 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. Due to the current distance from the glacier, 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% compared with 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 two decades (2001–2017) with a loss of 1.04 km^2 (48.92%), as a consequence of climate variability (meteorological components of precipitation and temperature). In 2015 a recovery occurred in the area of the Ampay glacier to 2.595 km^2. Still, in the following years, it has been decreasing to reach 1.086 km^2 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.

ACKNOWLEDGMENT

To the Swiss Cooperation, through the Andean Forests program, who have sponsored the culmination of the research.

NOMENCLATURE

NDSI	normalized differential snow index	[-]
NIR	index of near infrared band	[-]
VIS	index of visible light band	[-]

Abbreviations

IR	Infrared
MSS	Multispectral Scanner
OLI	Operational Land Imager
SENAMHI	National Meteorology & Hydrology Service
TIRS	Thermal Infrared Sensor
TM	Thematic Mapper

REFERENCES

1. "The Colombian Glaciers, Expression of Global Climate Change" Inst. Hydrol. Meteorol. Environ. Stud. IDEAM, vol. 0, no. 0, pp. 3–4, 2000, [Online]. Available: https://www.devex.com/organizations/institute-of-hydrology-meteorology-and-environmental-studies-ideam-150126 [Accessed: 10-Dec-2020]
2. M. Romero, S. Flantua, and J. L. Ceballos, "Glaciers of Colombia, more than mountains with ice" Glaciers Colomb. More than Mt. snow, vol. 1, no. 0, p. 0, 2012, [Online]. Available: https://www.devex.com/organizations/institute-of-hydrology-meteorology-and-environmental-studies-ideam-150126 [Accessed: 10-Dec-2020]
3. J. Arbelaez, "Detection of changes in the area of the Nevado glacier between 1985 and 2014 using Landsat images," Dep. Geogr. Univ. del Valle, Cali, Colomb., 2014, [Online]. Available: http://bibliotecadigital.univalle.edu.co/bitstream/ [Accessed: 10-Dec-2020]

4. N. W. Authority, "National Glacier and Lagoon Inventory," 2014, [Online]. Available: https://repositorio.ana.gob.pe/bitstream/handle/20.500.12543/4802/ANA0003322.pdf?sequence=1&isAllowed=y [Accessed: 10-Dec-2020]
5. R. Díaz Aguilar, S. Sanchez Larico, E. Lujano Laura, and A. Lujano Laura, "Multi-temporal analysis between 1975 and 2015 on changes in glacier coverage in the snowy Allin Capac and Chichi Capac, Peru," Altoandinas Research magazine, 2017
6. J. I. Lopez-Moreno, B. Valero-Garcés, T. Mark, B. Condom, J. Revuelto, C. Azorín-Molina, and J. Alejo-Cochachin, "Hydrological and depositional processes associated with recent glacier recession in Yanamarey Catchment, Cordillera Blanca (Perú)" Sci. Total Enviroment, 2017, doi: https://doi.org/10.1016/j.scitotenv.2016.11.107
7. G. Kaser, "A Review of the Modern Fluctuations of Tropical Glaciers" Glob. Planet. Change, vol. 22, no. 1–4, pp. 93–103, 1999, [Online]. Available: https://doi.org/10.1016/S0921-8181(99)00028-4
8. M. Vuille et al., "Climate change and tropical Andean glaciers: Past, present and future" Earth-Science Rev., 2008, doi: https://doi.org/10.1016/j.earscirev
9. B. Marzeion, A. H. Jarosch, and J. M. Gregory, "Feedbacks and mechanisms affecting the global sensitivity of glaciers to climate change" Cryosphere, 2014, doi: https://doi.org/10.5194/tc-8-59-2014
10. S. Marshall, "Glacier retreat crosses a line" Science (80-.)., 2014, doi: https://doi.org/10.1126/science.1258584
11. Bahr, M. Mier, and S. Peckham, "The physical basis of glacier area-volume scaling" Journal of Geophysical research, USA, 1997, https://doi.org/10.1029/97JB01696
12. B. G. Mark, "Tracing tropical Andean glaciers over space and time: Some lessons and transdisciplinary implications" Glob. Planet. Change, vol. 60, no. 12, 2008, [Online]. Available: https://doi.org/10.1016/j.gloplacha.2006.07.032
13. Rabatel et al., "Current state of glaciers in the tropical Andes: a multi-century perspective on glacier evolution and climate change" Cryosph., vol. 7, no. 1, pp. 81–102, 2013, [Online]. Available: https://doi.org/10.5194/tc-7-81-2013
14. J. Kronenberg, "Global warming, glaciers and gold mining" 2009
15. Barsch, "Rockglaciers: Indicators for the Present and Former Geoecology in High Mountain Environments" Springer-Verlag Berlin Heidelberg, Berlin, Ger., p. 331, 1996, [Online]. Available: Google Scholar
16. P. Canada, "Kluane National Park and Reserve of Canada Summary of Trails and Routes: Rock Glacier Trail," [Online]. Available: http://www.pc.gc.ca/eng/pn-np/yt/kluane/activ/activl/activlb/v.aspx [Accessed: 10-Dec-2020]
17. IPCC, "Intergovernmental Group of Experts on Climate Change" Clim. Chang., 2007.
18. W. Gary and J. Richard, "The Stern Review and the economics of climate change: an editorial essay" Clim. Change, vol. 89, pp. 231-240, 2008, https://doi.org/10.1007/s10584-008-9431-z
19. H. Huan, M. von Lampe, and F. von Tongeren, "Climate change and trade in agriculture," Food Policy, pp. S9–S13, 2011, https://doi.org/10.1016/j.foodpol.2010.10.008
20. IPCC, "Intergovernmental Panel of Experts on Climate Change. Climate Change and Water," 2008
21. W. Bank, "Latin American responses to the challenge of climate change," 2009
22. Z. Xiaobing, N. Chang, and L. Shusun, "Applications of SAR interferometry in earth and environmental science research," Sensors, vol. 3, no. 9, pp. 1876–1912, 2009, [Online]. Available: http://www.mdpi.com/1424-8220/9/3/1876 [Accessed: 10-Dec-2020]
23. R. G. of Apurímac, Regional Strategy for Biological Diversity of the Apurímac Region PARDB-APURIMAC. 2014
24. J. T. Bury et al., "Glacier recession and human vulnerability in the Yanamarey watershed of the Cordillera Blanca, Peru," Clim. Change, vol. 1, no. 105, 2011, [Online]. Available: https://doi.org/10.1007/s10584-010-9870-1
25. M. Carey, M. Baraer, J. French, K. . Bury, and M. Young, "Toward hydro-social modeling: Merging human variables and the social sciences with climate-glacier runoff models (Santa River, Peru)," J. Hydrol., vol. 0, no. 518:60–70, p. 0, 2014, [Online]. Available: http://dx.doi.org/10.1016/j. jhydrol.2013.11.00
26. K. . Young, "Change in tropical landscapes: Implications for health and livelihoods," Ecol. Polit. Heal. Routledge, New York, vol. 0, No. 0, pp. 55–72, 2013
27. C. Soto Carrión and W. Jiménez Mendoza, "Potential Phytoremediator of Native Species in Soils Contaminated by Heavy Metals in the Garbage Dump Quitasol-Imponeda Abancay," J. Sustain.

Dev. Energy Water Environ. Syst, vol. 7, no. 4, pp. 584–600, 2019, [Online]. Available: https://doi.org/10.13044/j.sdewes.d7.0261

28. Sanchez and H. Washington, "Bases for the elaboration of the Project Master Plan: Ampay National Sanctuary, Abancay Province, Apurímac Department," 2001
29. K. Manoj, S. Aparna, and P. Ravi, "Digital image information extraction techniques for snow cover mapping from remote sensing data," Encycl. Snow, Ice Glacers, pp. 213-232, 2011, https://doi.org/10.1007/978-90-481-2642-2_498
30. B. Rakesh and B. Tobias, "Glacier mapping: a review with special reference to the Indian Himalayas," Prog. Phys. Geogr., pp. 672-704, 2009, https://doi.org/10.1177/0309133309348112
31. E. Magsar, K. Pandi, D. Gombo, and O. Moondoi, "Glacier change estimation using Landsat TM," Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci., vol. 36, 2006, [Online]. Available: https://www.researchgate.net/publication/267979161_Glacier_change_estimation_using_Landsat_TM_data [Accessed: 10-Dec-2020]
32. J. Hendriks and P. Pelikka, "Semi-automatic glacier delineation from Landsat imagery over Hintereisferner in the Austrian Alps," Zeitschriftur Gletscherkd. Undglazial Geol., pp. 55–75, 2007, [Online]. Available: https://researchportal.helsinki.fi/en/publications/semi-automatic-glacier-delineation-from-landsat-imagery-over-hint [Accessed: 10-Dec-2020]
33. D. K. Hall, G. A. Riggs, and V. V Salomonson, "Development of methods for mapping global snow cover using moderate resolution imaging spectroradiometer data," Remote Sens. Environ., vol. 52, no. 2, pp. 127–140, 1995, [Online]. Available: https://doi.org/10.1016/0034-4257(95)00137-P
34. J. Dozier, "Spectral signature of alpine snow cover from the landsat thematic mapper," Remote Sens. Environ., vol. 28, pp. 9–22, 1989, [Online]. Available: https://doi.org/10.1016/0034-4257(89)90101-6
35. M. H. Polk et al., "Exploring hydrologic connections between tropical mountain wetlands and glacier recession in Perus Cordillera Blanca," Appl. Geogr., vol. 78, no. 94103, 2017, [Online]. Available: https://doi.org/10.1016/j.apgeog.2016.11.004
36. Chander, B. Markham, and D. Helder, "Summary of current radiometric calibration coefficients for Landsat MSS, TM, ETM+, and EO-1 ALI sensors," Remote Sens. Environ., vol. 113, 2009, [Online]. Available: https://doi.org/10.1016/j.rse.2009.01.007
37. Monsef and S. E. Smith, "A new approach for estimating mangrove canopy cover using Landsat 8 imagery," Comput. Electron. Agric., vol. 135, no. 183194, 2017, [Online]. Available: https://doi.org/10.1016/j.compag.2017.02.007
38. Y. Shimamura, T. Izumi, and H. Matsuyama, "Evaluation of a useful method to identify snow covered areas under vegetation comparisons among a newly proposed snow index, normalized diference snow index, and visible reflectance," Int. J. Remote Sens., vol. 27, no. 21, 2006, [Online]. Available: https://doi.org/10.1080/01431160600639693
39. B. Francou, "The rapid retreat of glaciers in the tropical Andes: A challenge for studying the dynamics of high mountain ecosystems" Ecol. en Boliv., vol. 48, no. 2, pp. 69–71, 2013, [Online]. Available: http://www.scielo.org.bo/scielo.php?script=sci_arttext&pid=S1605 [Accessed: 10-Dec-2020]
40. G. Medina and A. Mejía, "Multitemporal and multifractal analysis of the deglaciation of the Cordillera Parón in the Andes of Peru," Análisis multitemporal y multifractal la deglaciación la Cordillera Parón en los Andes Perú. Ecol. Apl., vol. 13, no. 1, pp. 35–42, 2014, [Online]. Available: http://www.scielo.org.pe/scielo.php?pid=S1726-22162014000100004&script=sci_arttext [Accessed: 10-Dec-2020]
41. K. Young, "Ecology of Land Cover Change in Glaciated Tropical Mountains," Rev. Peru. Biol., vol. 21, no. 3, pp. 259–270, 2014, [Online]. Available: http://dx.doi.org/10.15381/rpb.v21i3.10900
42. Y. Tarazona, "Application of Remote Sensing as a tool for Multitemporal analysis of glacier retreat in the Nevado Pastoruri due to Climate Change," 2012
43. C. Perez and K. . Gómez, "Analysis of the glacial retreat of the Nevado del Ruíz volcano, through a multitemporal study of satellite images from the period 1999-2016" Rev. Topogr. Azimut, vol. 9, pp. 9–16, 2018, [Online]. Available: https://revistas.udistrital.edu.co/index.php/azimut/article/view/13214 [Accessed: 10-Dec-2020]

44. E. Castillo, "Environmental factors of temperature and precipitation that affect the dynamics of the Pastoruri glacier mountain," 2017
45. P. Sierra, "Glacier Water Availability in the Mariño Micro basin, taking into account the glacial retreat in the years 1970-2017 with a projection to 2050," 2017
46. Lizarzaburu and J. Deza, "Glacier retreat in the mountains of the Peruvian Andes Case: National Sanctuary of Ampay, Apurimac," Sci. Dev., vol. 16, no. 1, pp. 5–16, 2013, [Online]. Available: http://dx.doi.org/10.21503/CienciayDesarrollo.2013.v16i1.01
47. M. R. Serrano Chuima, "Impact of climate change on the glacial retreat of the Sahuanay river sub-basin, province of Abancay in 2017," 2018

Paper submitted: 03.04.2020
Paper revised: 10.12.2020
Paper accepted: 15.12.2020