MAPBIOMAS
COLOMBIA

MAPBIOMAS
[AGUA]

Appendix – Glacier and Snow Cover

Algorithm Theoretical Basis Document - ATBD

Cross-cutting Theme in Collection 4.0
Version 1.0
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1. Executive Summary

Fundación Gaia Amazonas, through the collaborative initiative MapBiomas—which strives to contribute to the understanding, dissemination, and open access of land cover and land use dynamics through rapid, reliable, low-cost, and continuously improving methodologies—has worked on generating the fourth collection of maps of Tropical Andean Glaciers and snow cover located within Colombian territory, characterized by the improvement of Collection 1 results and the inclusion of the year 2025. Starting with their identification from national and international references, study areas and/or units were generated from them, within which a 40-year time series from 1985 to 2025 is analyzed through the MapBiomas methodology. In this workflow, mosaics are generated through satellite selection and cloud and cloud-shadow masking, for subsequent classification using configurations of the spectral bands most sensitive to the land cover in question, empirical decision trees, and Random Forest. This gives way to a post-classification stage based on algorithms designed according to the behavior of this land cover, ultimately yielding valuable maps and data that depict the decline of glacier and snow mass in Colombia, thereby contributing to the dissemination and open access of information on the behavior of this land cover.

2. Introduction

Glaciers constitute key indicators for the study of climate change (Carvalho Resende et al., 2022). Consequently, monitoring their evolution over time is of vital importance to understand glacier mass loss (Francou et al., 2013). Specifically, Tropical Andean Glaciers (TAG), distributed between Colombia and Bolivia, are undergoing a rapid decline in surface extent (Turpo et al., 2022) due to their relatively rapid response to perturbations in climatic variables such as precipitation, air temperature, and atmospheric humidity (Kaser & Osmaston, 2002), for which reason they have been termed "sentinels of climate change" (Carvalho Resende et al., 2022).

Glacier and snow cover in Colombia has decreased drastically; according to IDEAM (Instituto de Hidrología, Meteorología y Estudios Ambientales [Institute of Hydrology, Meteorology and Environmental Studies]), it declined from approximately 347.9 km^2 at the end of the Little Ice Age to 33.09 km^2 in 2022, which is equivalent to a 90% loss of its original extent relative to that period (IDEAM, 2023). According to reports prior to 2011, the areas with the greatest loss correspond to the Sierra Nevada de El Cocuy, Chita o Güicán, and Los Nevados National Natural Park, which includes the Nevado del Ruiz Volcano, the Nevado del Tolima Volcano, and the Nevado de Santa Isabel Volcano. The two remaining glacier covers in the country correspond to the Sierra Nevada de Santa Marta and the Nevado del Huila Volcano.

In this context, the detection of glaciers and snow cover through various digital image

processing and spatial analysis techniques is increasingly being promoted due to their high potential for monitoring large-scale changes (Paul & Kaab, 2005) without the need to conduct extensive fieldwork. For the present collection, this process involves: data acquisition via satellite imagery; selection of suitable scenes for the study area and analysis periods, ensuring broad coverage of glacier and snow cover, low cloud cover percentage, and freedom from atmospheric interference (Bolch et al., 2010); and finally, to achieve an accurate classification, the application of an empirical decision tree and Random Forest along with a series of filters to differentiate glaciers and snow cover from other land covers. This multitemporal analysis makes it possible to compare and identify patterns of change, such as glacier retreat, thereby contributing significantly to the knowledge of these formations (Zhen et al., 2019).

In this document, we present a description of the methodology applied for mapping glaciers and snow cover for Collection 3 of MapBiomas Colombia, using as a foundation the methodology of Collection 5 of glaciers from RAISG and other references (Turpo et al., 2022), noting that Colombia does not have glacier units within the Amazonian boundary defined by the network.

3. References

3.1 Global reference information

The operational classification regions used the Randolph Glacier Inventory (RGI) as a reference, as shown in **Figure 1**, created by a team of scientists from 18 countries in which satellite imagery and reference maps were used to obtain information on the location, size, shape, and health status of glaciers worldwide (RGI Consortium, 2017); specifically for Colombia, it reports information for Nevado del Cocuy, Sierra Nevada de Santa Marta, among others.

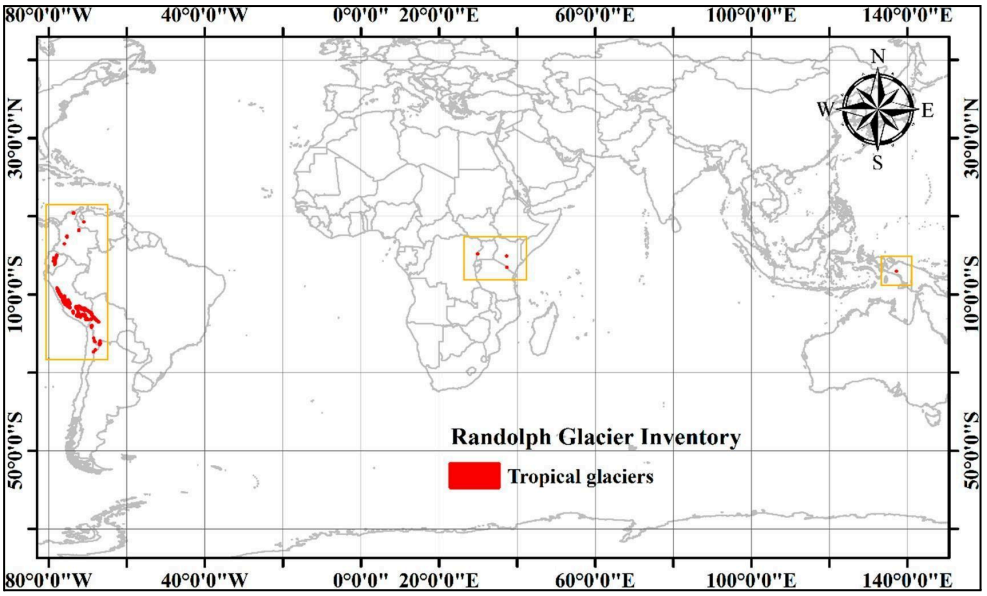


Figure 1. Distribution of tropical glaciers

Source: RGI Consortium, (2017) & Veettil & Kamp, (2019)

3.2 National reference information

At the national level, IDEAM conducts monitoring of the country's glacier areas through digital processing and interpretation of satellite imagery, complemented by field data analysis (IDEAM, 2020). Notable among the products generated are the multitemporal assessments of these areas, which were considered a key input for delineating the study zones. Additionally, the boundary of the general and synthetic ecosystem of Glaciers and Snow Cover defined by IDEAM was taken into account (IDEAM et al., 2017).

4. Study Area

Worldwide, 36 biodiversity hotspots are recognized—areas that harbor at least 1,500 endemic plant species but have suffered a 70% loss of their natural habitat. Standing out among them, the Tropical Andes emerge as the hotspot with the greatest biological richness on the planet. This region, renowned for its exceptional biodiversity, encompasses 130 ecosystems that sustain nearly 35,000 species (RIT, 2023).

Within these ecosystems, Tropical Andean Glaciers are especially sensitive to climate change due to the unique conditions of the zone. Colombian glaciers form part of this singularity, distributed across Venezuela, Colombia, Ecuador, Peru, and Bolivia. Colombia harbors approximately 4% of these glaciers (Lju, 2013). Over the past 160 years, the country has experienced a dramatic reduction in the number of glaciers, dropping from 19 in the 19th century to only 6 today. These glaciers are located within five protected areas under the category of National Natural Parks (**Figure 2**).



Figura 2: Parques Nacionales Naturales con Glaciares y nivales en Colombia.

5. Biogeography of Colombian Glaciers

Glaciers are surrounded by rocky outcrops and high-mountain ecosystems. They constitute a Neotropical ecoregion at altitudes ranging from the upper limit of the páramos to the perpetual snows (Hofstede, R., Vásconez, S., & Cerra, M. (Ed.), 2015). In addition, glacial lagoons—water bodies formed by glacier meltwater—are found here. These areas are distributed within the Orobiome of the Tropical Humid Zonobiome and the Páramo Orobiome, as observed in **Figure 3**, forming part of a pedogenetic environment characterized by low temperatures (IDEAM et al., 2017).

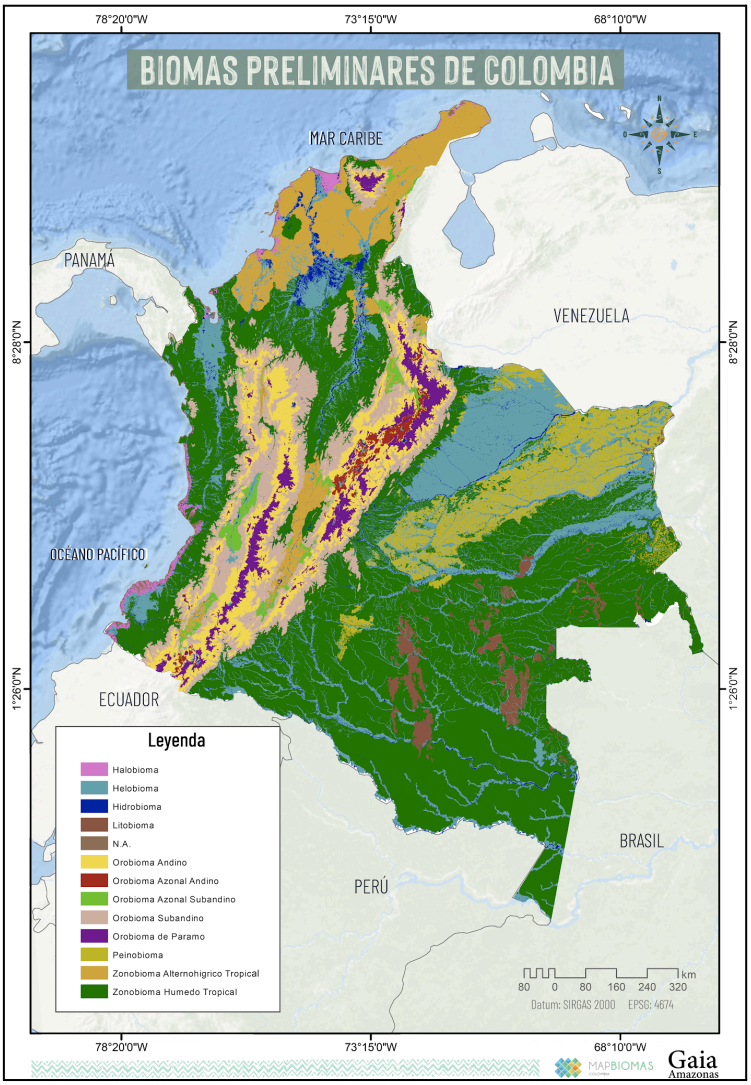


Figure 3. Preliminary biomes

6. Methodology

For the detection of glacier and snow cover, annual mosaics were first generated through: satellite selection and cloud and cloud-shadow masking; and the calculation of minimum NDSI in order to generate an image that represents the behavior of the land cover in the given year as accurately as possible. This served as the basis for subsequent classification using configurations of the spectral bands most sensitive to the land cover (NIR and RED), along with variables such as snow, slope, and clouds, through the use of an empirical decision tree and the Random Forest classifier. Finally, a post-classification stage is carried out, consisting of various types of filters that resolve temporal and spatial issues. The foregoing is illustrated in **Figure 4.**

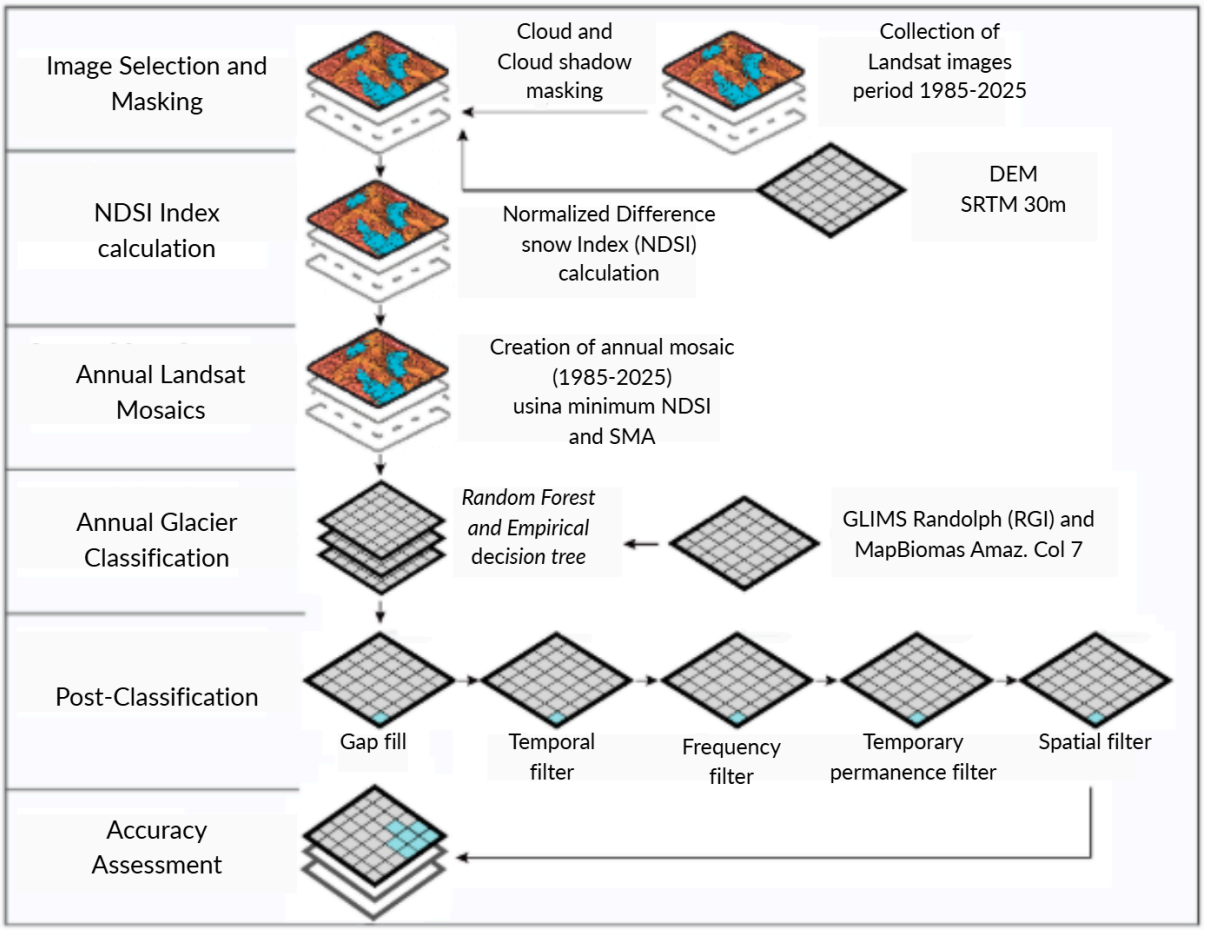


Figure 4. Methodological flowchart for obtaining glacier and snow land cover maps

7. Classification Regions

The classification of glaciers in Colombia was conducted based on the Randolph Glacier Inventory and IDEAM data, specifically the general glacier and snow cover ecosystem from the Continental, Coastal, and Marine Ecosystems Map (ECM), considering a defined study area adjusted with a 1.5 km buffer to account for the classification of glacier masses (RGI Consortium, 2017). For operational purposes and variable behavior, it was divided into a total of 6 regions, where some may be composed of more than one glacier and snow unit, as shown in **Table 1.**

Table 1. Classification regions

Code	Glacier
1001	Sierra Nevada de Santa Marta
1003	Sierra Nevada del Cocuy, Cumbal y Paramillo del Quindío
1019	Volcán Nevado del Huila
1016	Volcán Nevado del Ruiz
1018	Volcán Nevado del Tolima
1017	Volcán Nevado de Santa Isabel y Paramillo de Santa Rosa

Included among the aforementioned classification regions are nine glacier and snow units, namely: Sierra Nevada de Santa Marta, Sierra Nevada del Cocuy, Nevado del Quindío, Nevado del Ruiz Volcano, Paramillo de Santa Rosa, Nevado de Santa Isabel, Nevado del Tolima Volcano, Nevado de Puracé, Nevado del Cumbal, and Nevado del Huila. It is worth noting that, as a consequence of the deglaciation processes that have taken place over the decades, four of these snow-capped peaks (nevados) are currently considered extinct and are now designated as paramillos: Paramillo del Quindío, Paramillo de Santa Rosa, Puracé, and Cumbal. Therefore, across the entire time series, glacier and snow masses cannot be identified in these areas due to temporal and spatial limitations in the available data.

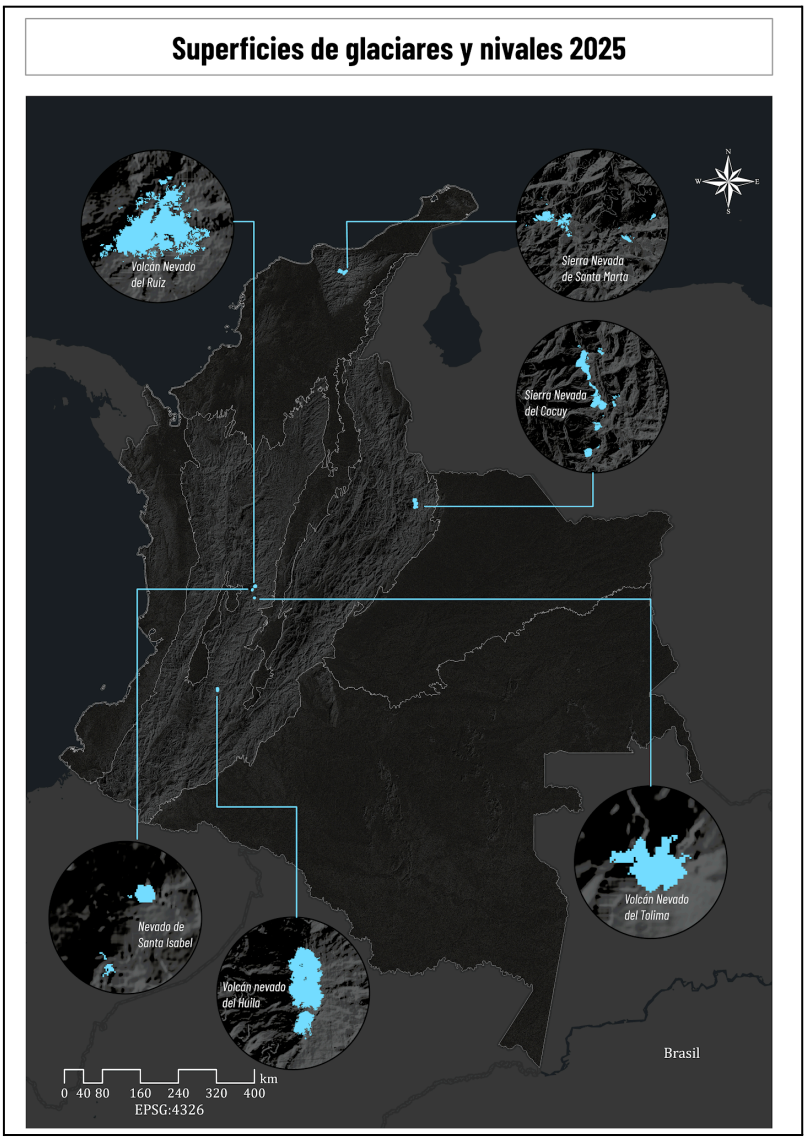


Figure 5. Glacier and snow cover surfaces 2025

8. Generation of Annual Mosaics

The classification of glaciers and snow cover was carried out using annual mosaics, which were generated with specific parameters designed for the detection of snow and glacier masses from imagery acquired by the L4, L5, L7, L8, and L9 satellites of the Landsat series. These scenes met the requirement of having a cloud cover percentage less than or equal to 70%, and were subsequently subjected to masking methods (the Cloud Score technique and the TDOM algorithm) and index calculation, which for the present methodology focused on the minimum NDSI (Normalized Difference Snow Index), in order to classify mosaics representing the minimum annual glacier and snow cover area, as shown in **Figure 6.**

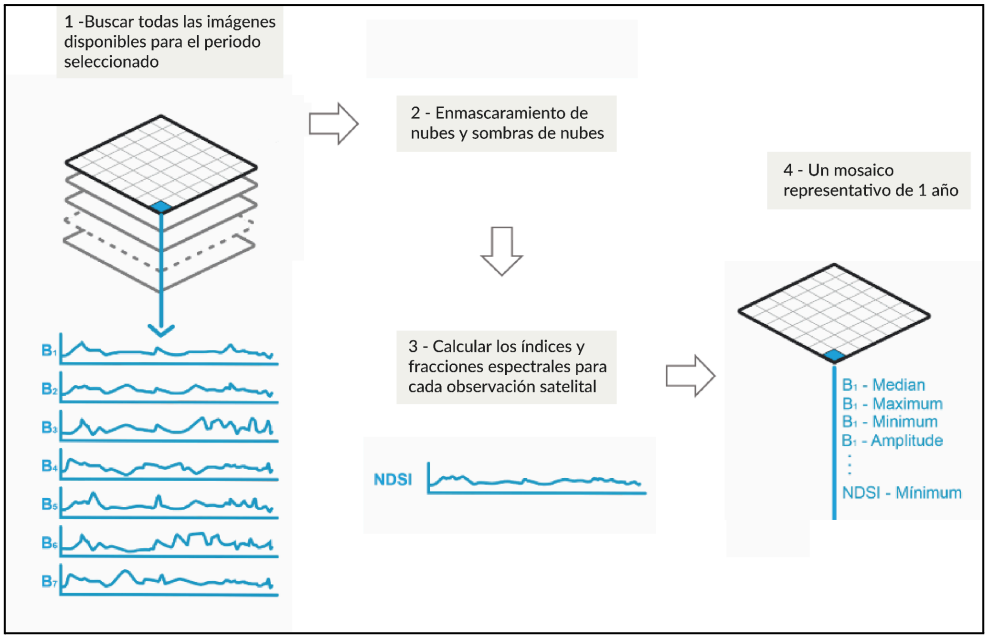
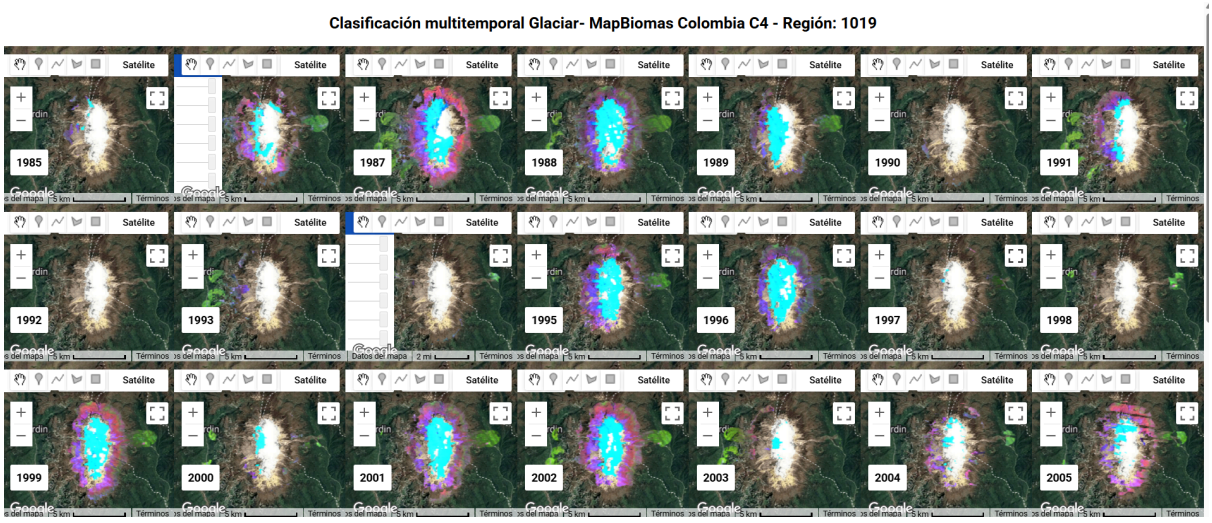


Figure 6. Creation of annual mosaics for glaciers and snow cover

In this way, the pixel used for classification corresponds to the minimum NDSI value, since the bands used for its calculation passed through a reducer to construct the final mosaic for interpretation. It is worth noting that, for certain study areas that had few available images, the median reducer was used to ensure greater data availability. **Figure 7** presents the mosaics for Nevado del Huila.



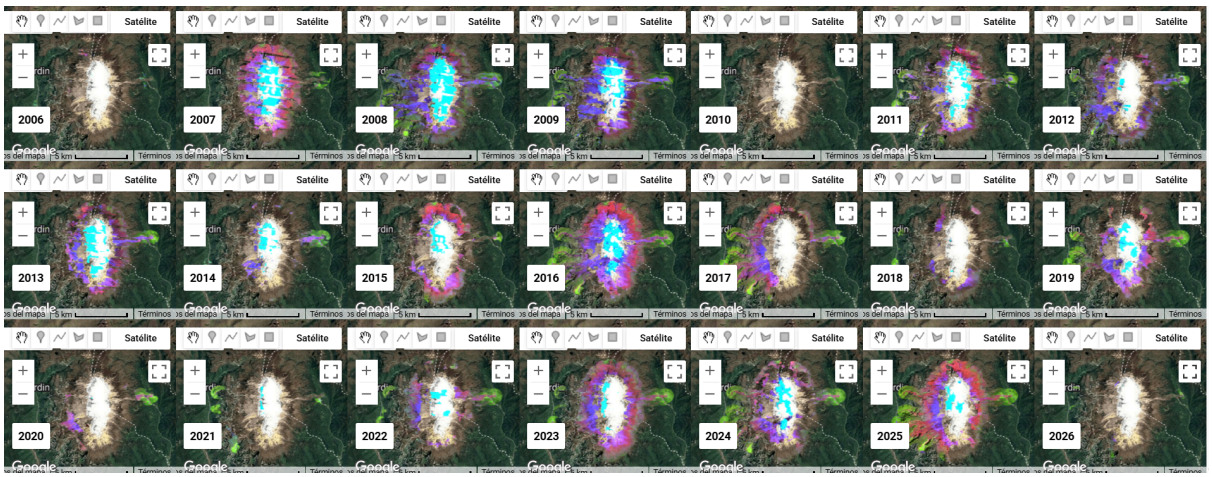


Figure 7. Minimum NDSI mosaics Collection 4 – MapBiomas Colombia Collection 4

9. Classification

The methodological process carried out in the classification stage for Collection 3, following the respective selection and masking of imagery, calculation of minimum NDSI, and creation of annual mosaics, comprises the use of an empirical decision tree combined with Random Forest (RF), based on a series of binary partitions. This makes it possible to generate predictions based on this classification and, through variable manipulation, achieve the optimal classification of glacier and snow cover, as illustrated in **Figure 8.**

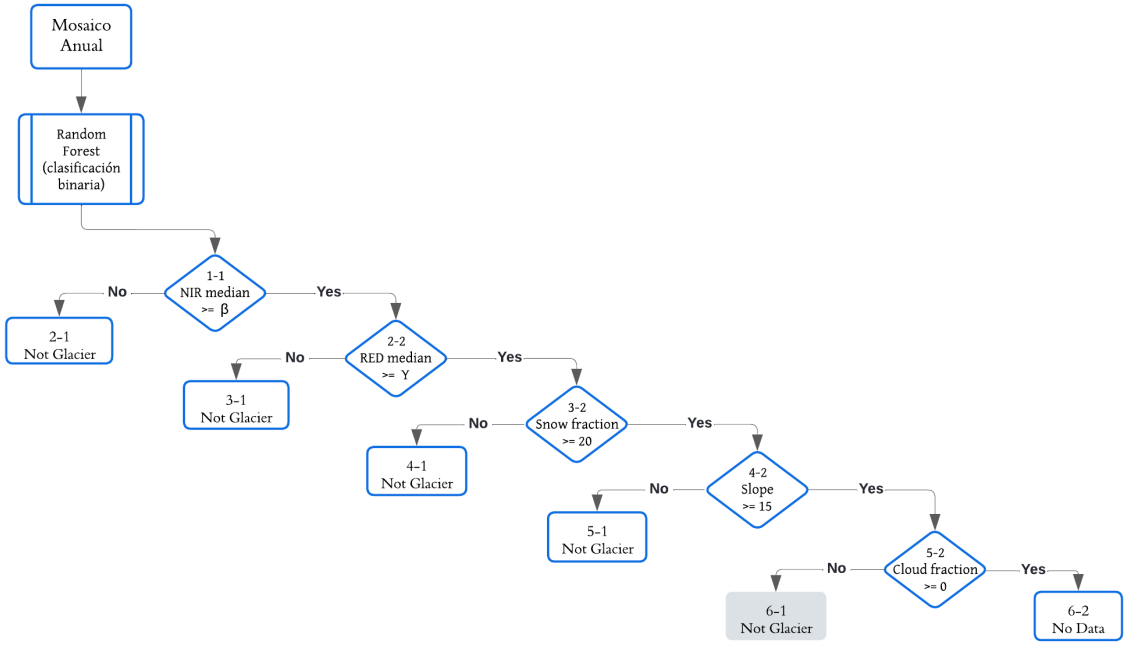


Figure 8. Empirical decision tree combined with Random Forest for glacier classification

Furthermore, various parameters have been established within the ranges for snow and glacier detection, which vary depending on the region, as detailed below.

Tabla 2. Classification parameters

Parameters						
Región	**Shadow Sum**	**Trees**	**Samples**	**Cloud**	**Snow**	**Slope**
1001	3500	80	3000,8000	20	20	15
1003	3500	80	3000,8000	20	40	15
1016	3500	80	3000,8000	20	20	15
1017	3500	50	3000,8000	20	40	15
1018	3500	80	3000,8000	20	18	15
1019	3500	80	3000,8000	20	20	15

In addition to the parameters shown, different values are assigned to cloud, NIR median, and RED median for each year to be classified, as shown in **Figure 9**.

```
//    [1985,  '15',      90,     2000,       2500],
// [1986,  '15',      60,     100,        100],
// [1987,  '15',      40,     100,        100],
// [1988,  '14',      75,     100,       100],
// [1989,  '14',      25,     100,       100],
// [1990,  '15',      75,     100,       100],
// [1991,  '15',      50,     100,       100],
// [1992,  '14',      75,     100,       100],
// [1993,  '15',      75,     100,       100],
// [1994,  '15',      75,     100,       100],
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// [2000,  '17',      75,     100,       100],
// [2001,  '17',      75,     100,       100],
// [2002,  '17',      50,     100,       100],
// [2003,  '17',      50,     100,       100],
// [2004,  '17',      50,     100,       100],
// [2005,  '17',      50,     100,       100],
// [2006,  '17',      45,     100,       100],
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// [2009,  '17',      50,     100,       100],
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// [2018,  '17',      75,     100,       100],
// [2019,  '18',      75,     100,       100],
// [2020,  '18',      60,     100,       100],
// [2021,  '17',      75,     100,       100],
// [2022,  '18',      50,     100,       100],
  [2023,  '19',      60,     1200,      3100],
    ]
```

Figure 9. Classification parameters

10. Variables de clasificación

For each classification region, specific spectral bands and indices have been defined, which are detailed in the following table:

Table 3. Spectral indices and bands used for classification

				Reductor[1]				
Type	**Name**	**Fórmula**	**Description**	**Median**	**Median_dry**	**Median_wet**	**Min**	**Max**

Band	Blue	B1 (L5 y L7); B2 (L8)	Blue visible spectrum		●	
	Green	B2 (L5 y L7); B3 (L8)	Green visible spectrum		●	
	Red	B3 (L5 y L7); B4 (L8)	Red visible spectrum	●	●	
	NIR	B4 (L5 y L7); B5 (L8)	Near-infra red	●	●	
	SWIR 1	B5 (L5 y L7); B6 (L8)	Short-wave infrared 1		●	
	SWIR 2	B7 (L5); B8 (L7); B7 (L8)	Short-wave infrared 2		●	
Indexes	NDSI	(green-swir1)/(green+swir1)	Normalized Difference Snow Index			●
Fractions	Cloud Fraction	SMA	Cloud fraction		●	
	Cloud Snow	SMA	Snow fraction		●	

11. Legend

Since Collection 2.0, snow-covered (nival) land covers were incorporated into the legend based on studies demonstrating the presence of fresh and old snow across a large part of the study area and, in some cases, along its margins. This pattern has been documented, for example, on the Ruiz, Santa Isabel, and Tolima snow-capped volcanoes for the year 2002, as seen in **Figure 10.** The distribution of these covers is conditioned by altitude: on Nevado de Santa Isabel it is recorded only along a narrow band of the glacier, whereas on the Tolima and Ruiz glaciers it is observed across most of the ice cap due to their higher elevations (INGEOMINAS, 2010).

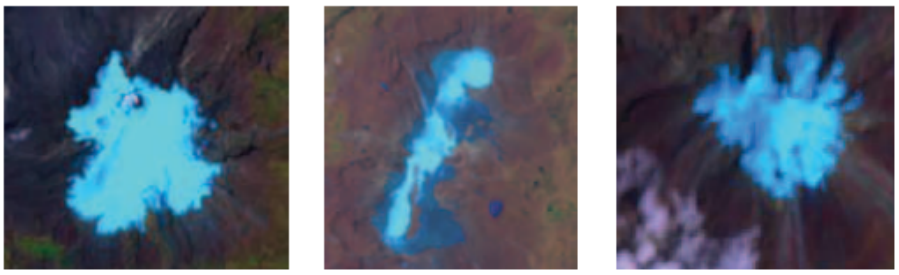

Figure 10. Detection of fresh and old snow on the Ruiz, Santa Isabel, and Tolima snow-capped volcanoes for the year 2002. (INGEOMINAS, 2010)

[1] El reductor está basado en el índice NDSI, percentil 75 y percentil 25 para Wet y Dry de NDSI respectivamente

Additionally, in terms of the MapBiomas methodology, this land cover follows the hierarchical structure shown in **Table 4**, and in terms of precedence, it ranks above all other land cover classes in the legend during map integration.

Table 4. MapBiomas legend

LEVEL 1				LEVEL 2				
ID	**Level 1 Class**	**Hexadecimal code**	**Color**	**ID**	**Clase nivel 2**	**Hexadecimal code**	**Color**	**COBERTURA / USO**
26	Water body	#2532E4		33	River, lake, or ocean	#2532E4		Land Cover/Use
				31	Aquaculture	#091077		Land Use
				34	Glacier and snow cover	#93DFE6		Land Cover

Finally, as shown in **Figure 11**, the appropriate combination of spectral bands makes it possible to highlight the distinctive features of glaciers in a bluish tone.

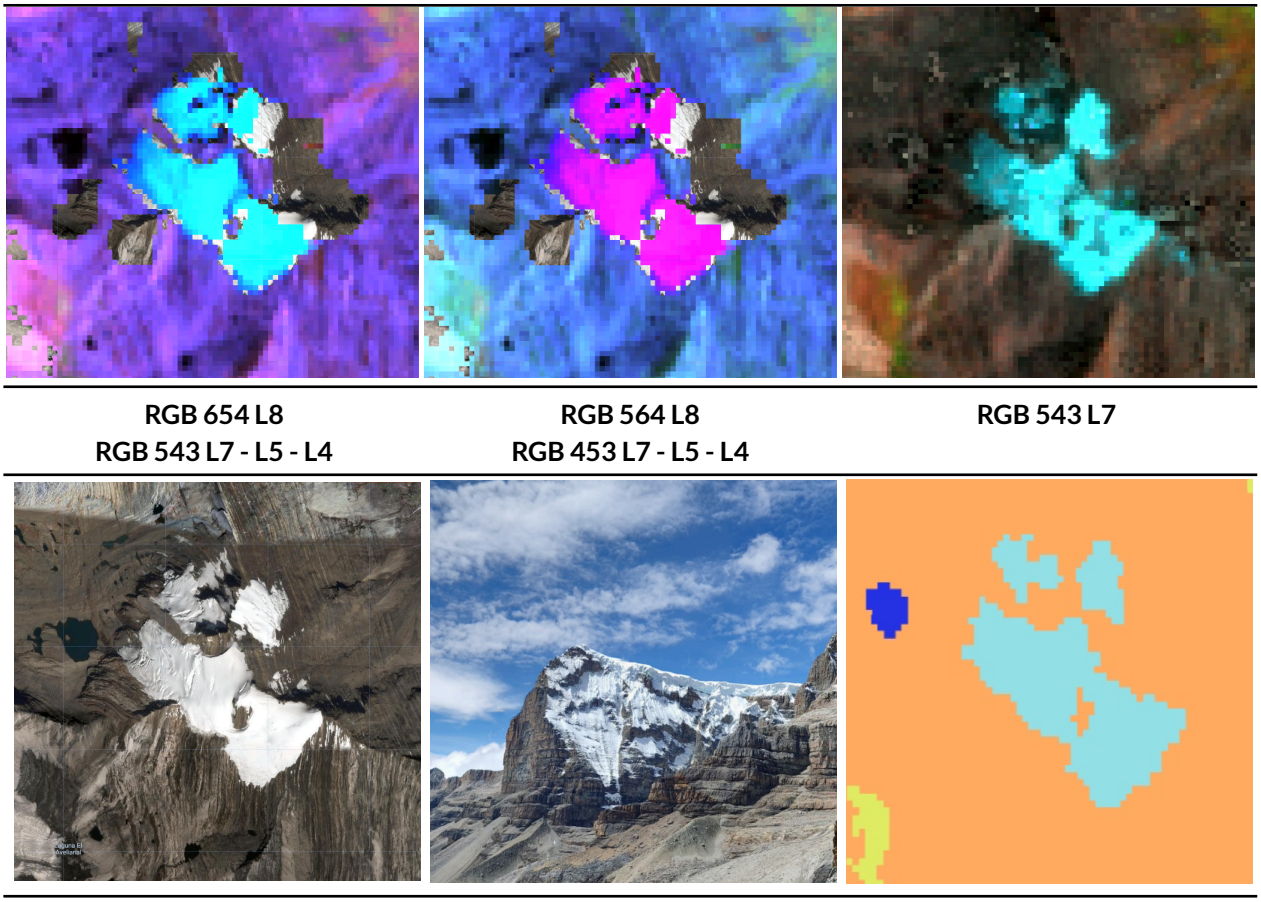

Figure 11. Spectral response of Glacier in the Andes biome. El Cocuy - Boyacá, Year: 2025, Scale: 100 m, Coordinate: -72.282054W, 6.515076N

12. Post-classification

Due to the pixel-based nature of the classification method and the processing over an extensive time series, a post-classification filter chain was applied. The post-classification process includes the application of gap-filling, temporal, spatial, and frequency filters.

Table 5. Filter order by region

Glacier	Region	1	2	3	4	5	6
Sierra Nevada de Santa Marta	1001	GP	FT	FF	FT	PT	FE
Sierra Nevada del Cocuy	1003	GP	FF	FT	FE	PT	FE
Volcán Nevado del Huila y Puracé	1019	GP	FT	FF	PT	FE	
Volcán Nevado del Ruíz	1016	GP	FT	FF	PT	FE	
Volcán Nevado de Santa Isabel y Paramillo de Santa Isabel	1017	GP	FT	FF	PT	FE	
Volcán Nevado del Tolima	1018	GP	FF	FT	PT	FE	

12.1 Gap Filling (Gap Fill)

The filter sequence begins with information gap filling. In a long time series of regions severely affected by cloud cover, gaps are expected to occur in the median composite output. In this filter, gaps are replaced by the temporally closest classification. In this procedure, if no value is available in the following year, the gap is replaced with the value from the preceding year. Therefore, gaps should only persist if a given pixel has been permanently classified as no data across the entire time series.

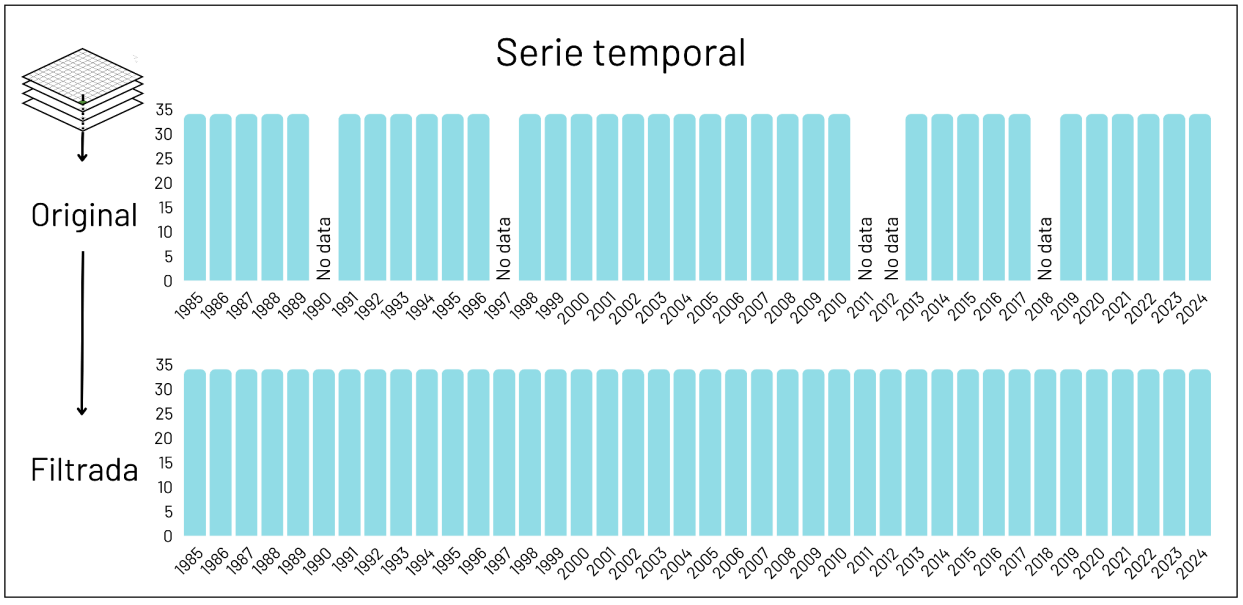

Figure 12. Gap Fill filter

12.2 Temporal Filter

The temporal filter uses sequential classifications within a unidirectional moving window of 3, 4, or 5 years to identify temporally inconsistent transitions, based on rules for intermediate years, the first year, and the last year.

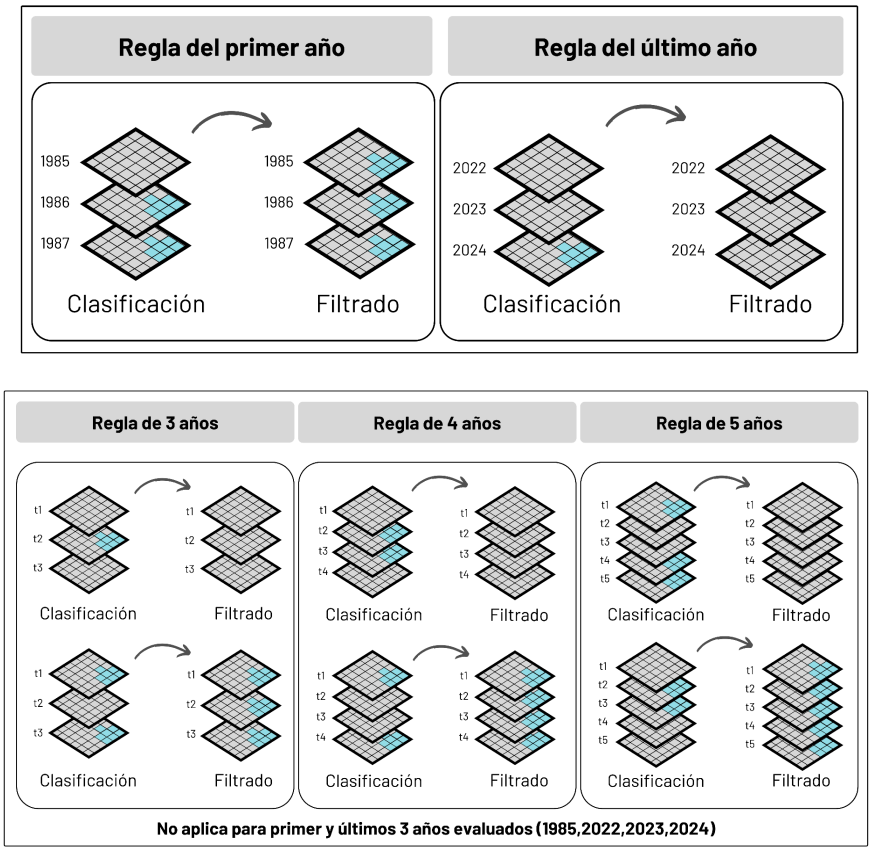

Figura 13. Filtro temporal

12.3 Spatial Filter

Next, the spatial filter is applied based on the “connected pixel count” function, which identifies the set of pixels (neighborhood) that share the same pixel value. Consequently, only pixels that lack connectivity considering a predefined minimum number of identical pixels are defined as isolated pixels and reclassified, as shown in **Figure 14.** For these areas, a minimum cluster size of 5 connected pixels was established.

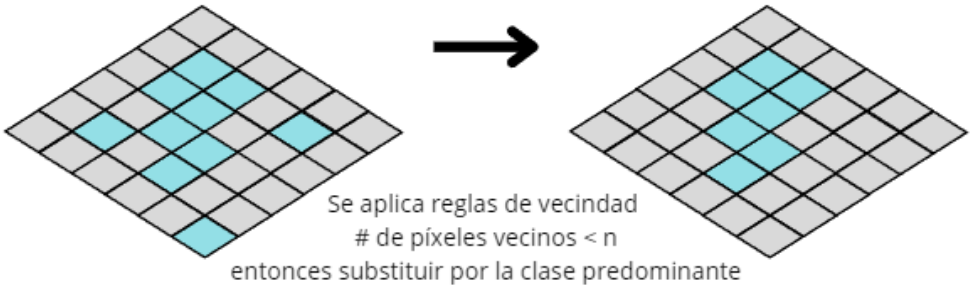

Figure 14. Effect of applying the spatial filter

12.4 Frequency and Temporal Permanence Filter

As shown in **Figure 14**, the frequency filter considers the occurrence of the class across the time series to clean up the classification output. In addition, a complementary temporal permanence rule is shown in **Figure 15.**

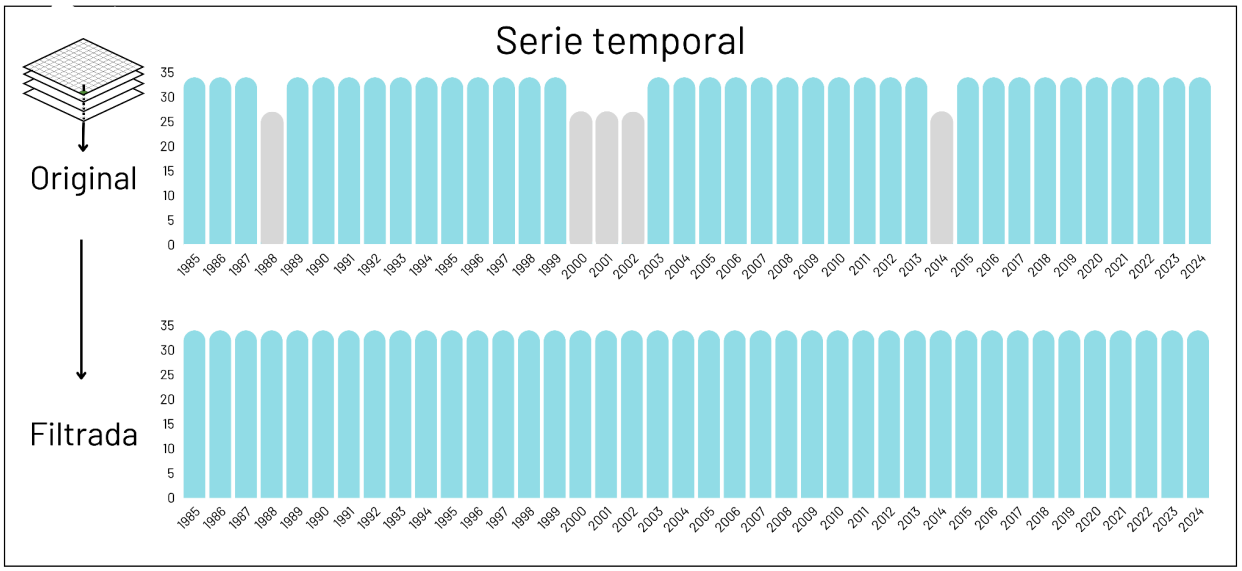

Figure 15. Effect of applying the temporal filter

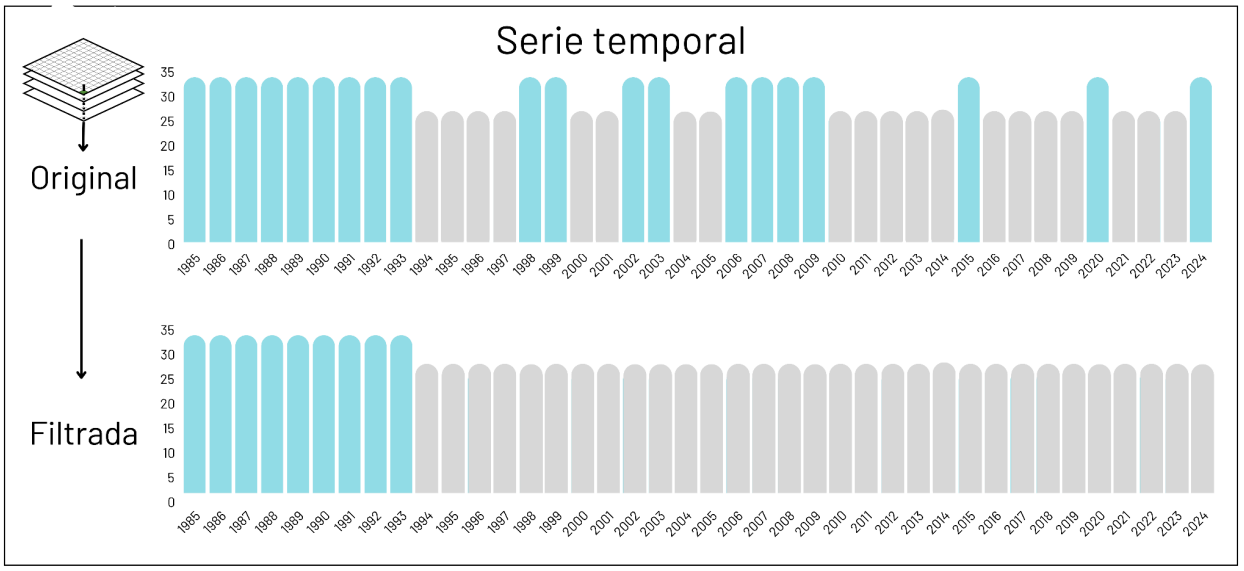

Figure 16. Application of the temporal permanence filter

12.5 Integration with Other MapBiomas Classes

Following the application of the filter sequence in the post-classification stage, the cross-cutting themes and general maps of each biome are integrated. This integration, as mentioned in the legend section, relies on a set of specific hierarchical rules that assign an order of prevalence. As a result of this stage, the annual glacier maps are obtained, as shown in

Figure 17.

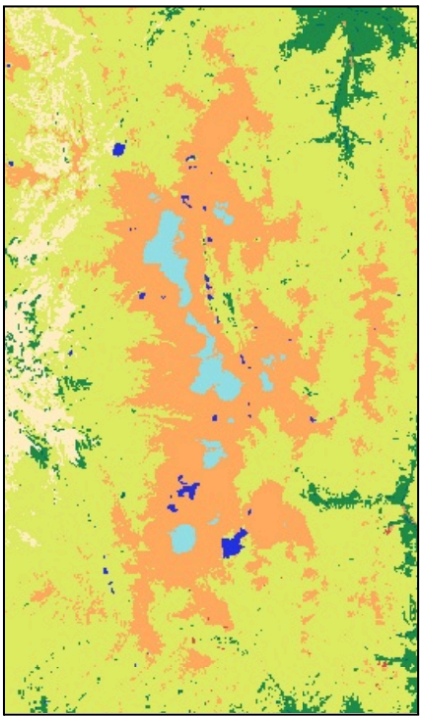

Figure 17. Integration of Glaciers with the other classes, Sierra Nevada del Cocuy

- **Multitemporal Santa Isabel**

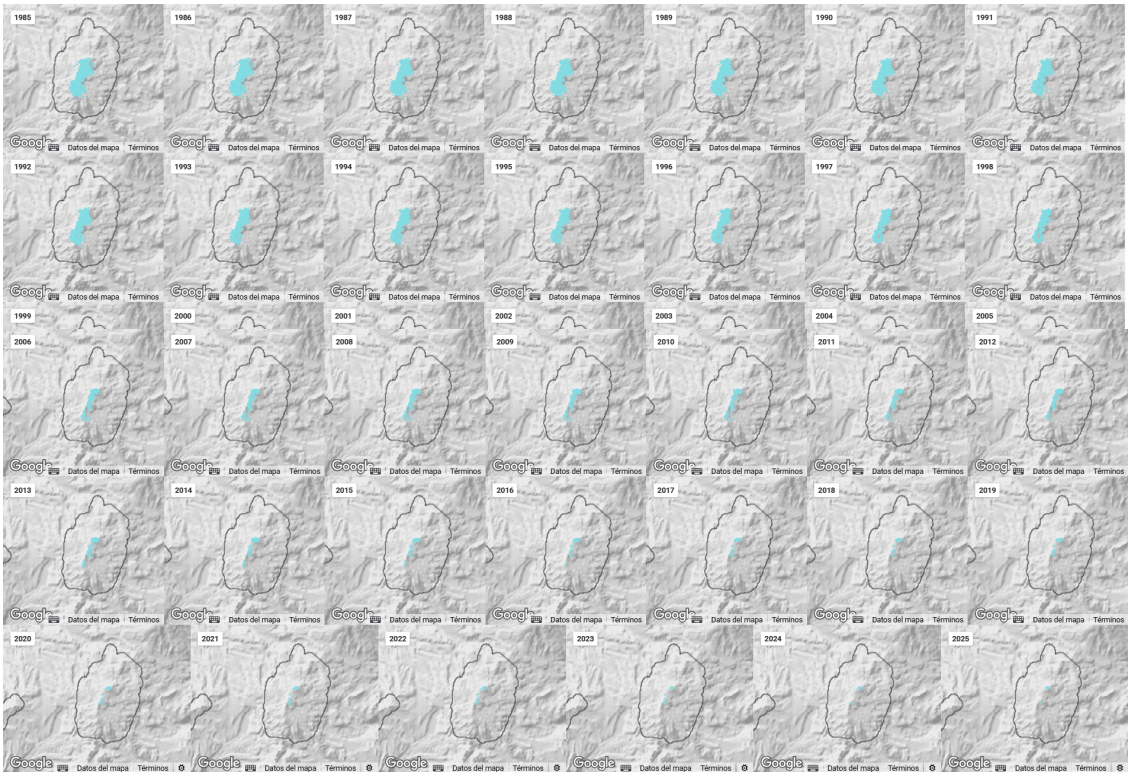

Figure 18. Multitemporal classification, Nevado de Santa Isabel Volcano

- **Multitemporal Cocuy**

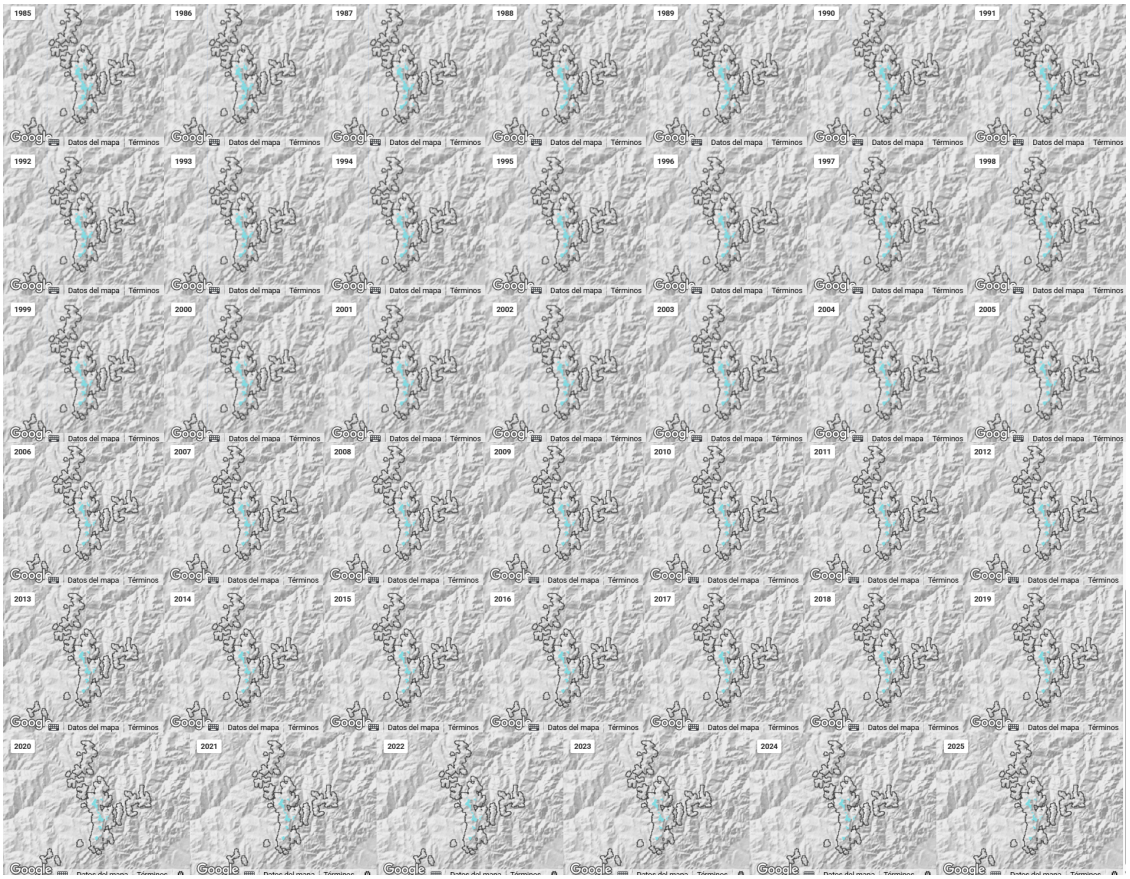

Figure 19. Multitemporal classification, Sierra Nevada del Cocuy

13. Location and Identification of Glacier Peaks: Methodology

Because an official national-coverage geographic layer containing the delineation and spatial location of Colombia's glacier peaks is not currently available, it was necessary to develop a geographic identification and approximation methodology through the integration of cartographic, documentary, and geospatial information from institutional and bibliographic sources.

Nevado / Sistema	Glaciar / Pico	Fecha de Extinción	Observaciones	Link de búsqueda
Nevado Santa Isabel	Conejeras	3/1/2024	Cierre de 18 años de monitoreo directo, primeros cambios en marzo de 2024	https://drive.google.com/drive/folders/1P_Tc20lPFwOE4JPAOrAIhC9
	El Cuadrado	6/1/2024	Primer semestre 2024	https://drive.google.com/drive/folders/1P_Tc20lPFwOE4JPAOrAIhC9
	El Hongo	N/A		file:///C:/Users/Lenovo/Downloads/informe-del-estado-de-los-glacia
	Laguna Verde	N/A		file:///C:/Users/Lenovo/Downloads/informe-del-estado-de-los-glacia
	El Escondido	N/A		file:///C:/Users/Lenovo/Downloads/informe-del-estado-de-los-glacia
	Otún Norte	Desaparecido a inicios de 2022		https://ideam.gov.co/nuestra-entidad/ecosistemas-e-informacion-a
	Otún Sur	Desaparecido a inicios de 2022		https://ideam.gov.co/nuestra-entidad/ecosistemas-e-informacion-a

Figure 20. Documentary and bibliographic identification of the glacier and snow systems of Colombia.

In a first stage, a bibliographic and documentary review of official sources, scientific publications, thematic cartography, and technical documentation generated by competent institutions was conducted in order to identify the country's glacier and snow systems, as well as to establish the correspondence between each glacier unit and its respective peak. This review made it possible to consolidate a preliminary inventory of glacier peaks—including those associated with currently extinct glacier masses—whose identification is necessary for the historical and spatial analysis of national glacier distribution.

Subsequently, in order to establish a spatial reference for the approximate location of each glacier peak, the polygons corresponding to the year 1985 from MapBiomas Water Collection 4 were downloaded, using this information as a cartographic reference to recognize historical glacier extent areas. Selecting this period provided a spatial baseline for identifying the areas associated with the glaciers and snow-capped mountains under study.

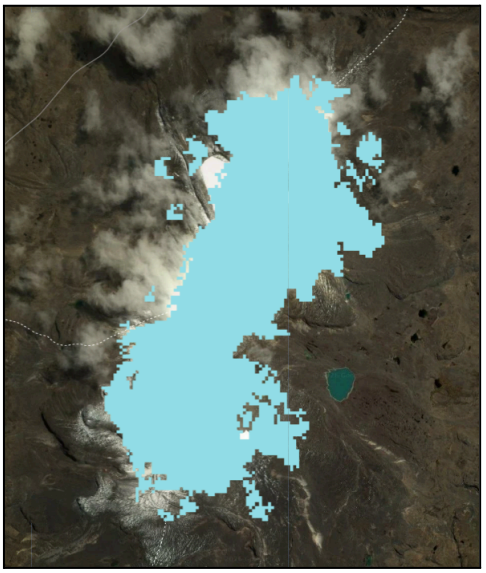

Figure 21. Distribution of the MapBiomas Water Collection 4 classification polygon corresponding to the year 1985 for Nevado Santa Isabel.

In a subsequent stage, the downloaded polygons were imported into a Geographic Information System (GIS) environment and overlaid with national-coverage contour lines, considering the topographic information corresponding to each previously identified glacier or snow system. This cartographic overlay made it possible to analyze terrain relief configuration, altitudinal variations, and the spatial relationship between historical glacier areas and surrounding topographic units.

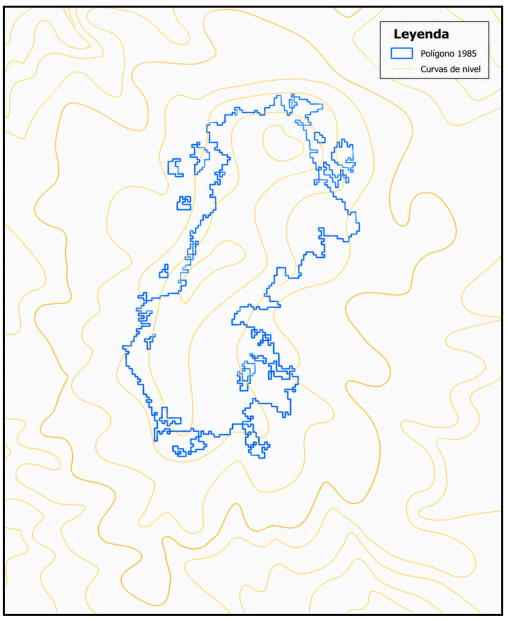

Figure 22. Overlay of MapBiomas Water C4 Glacier and snow cover classification polygons with national coverage contour lines for the identification of glacier peaks.

Based on the joint interpretation of these inputs, the approximate delineation of reference areas for each glacier/snow unit (glaciar nival) was carried out, and vector files were generated in shapefile (SHP) format, corresponding to polygon geometries in the WGS 84 (EPSG:4326) geographic coordinate reference system, in accordance with the projection parameters used for incorporating MapBiomas Colombia vectors. On this cartographic base, the approximate location of each glacier peak was digitized and assigned its respective name according to the previously conducted documentary and bibliographic identification. It should be noted that the locations obtained correspond to approximate geographic references rather than precision topographic delineations or official summit coordinates; therefore, their use is intended to facilitate the identification, representation, and spatial analysis of glacier peaks at a national scale.

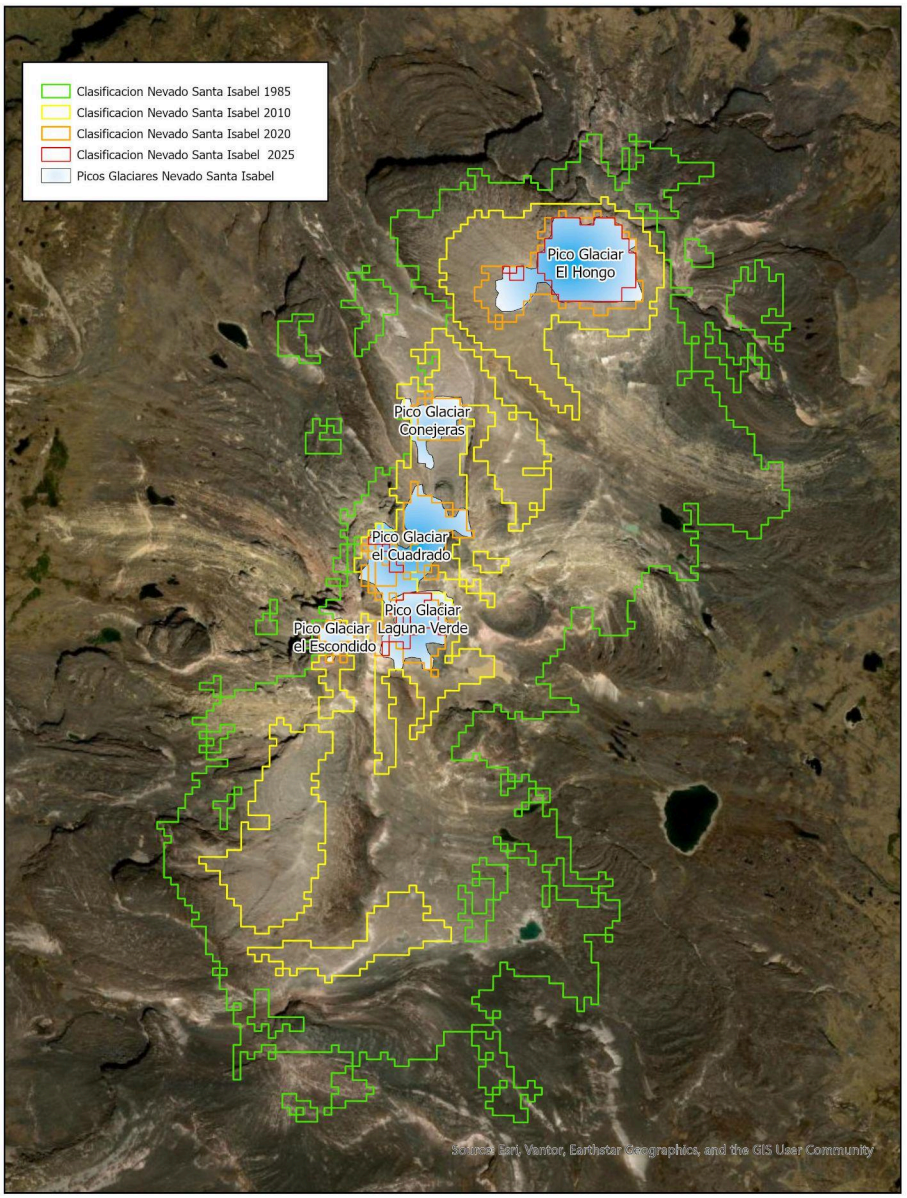

Figure 23. Delineation and assignment of the approximate location of glacier peaks through cartographic interpretation.

14. Generation of Glacier Information by Five-Year Periods and Analysis of Its Temporal Evolution

Based on the historical, cartographic, and geospatial information available for Colombia's glaciers, a complementary product was generated aimed at organizing and analyzing their temporal evolution through quinquennial intervals (five-year periods).

To this end, the available glacier cover information for each unit was compiled and organized by chronologically grouping the records into five-year periods. This structuring made it possible to consolidate a spatial and alphanumeric database that facilitates querying, visualizing, and comparing glacier extent across different time periods.

Subsequently, a multitemporal analysis was conducted to identify variations in the surface area of each glacier, recognize retreat trends, and compare their behavior over time. As a result, a geospatial product organized by five-year periods was obtained, enabling the analysis of the historical evolution of glaciers both individually and at a national scale.

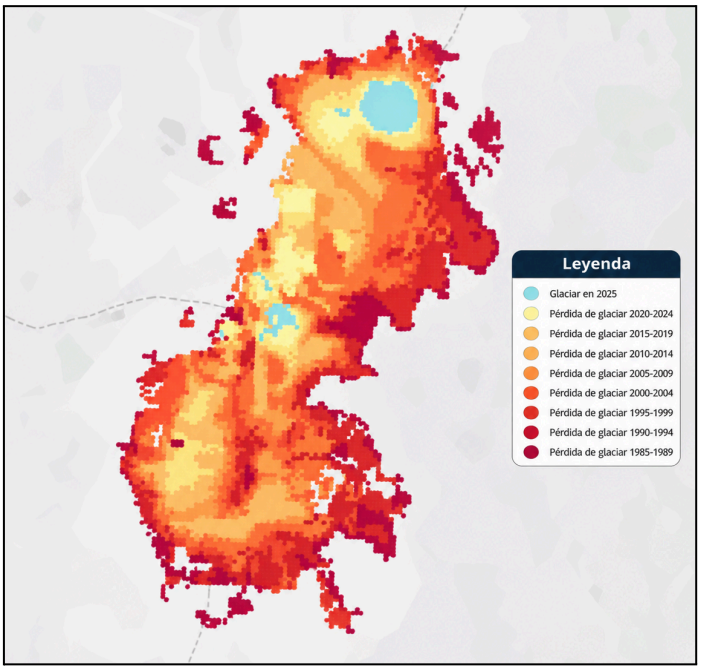

Figure 24. Organization of glacier information by five-year intervals.

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