Appendix: Glaciers

Cross-cutting theme in Collection 3.0 Version 1

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Summary

Wataniba (Socio-Environmental Working Group for the Amazon) is a Venezuelan civil society organization founded in 2005 that promotes sustainable land management processes in the Amazon. As a member of the Amazonian Network for Geo-Referenced Socio-Environmental Information (RAISG) since 2017, Wataniba actively participates in the generation of geospatial information for environmental monitoring in the Amazon basin.

Within the framework of MapBiomas Venezuela, an initiative co-created by Provita, Wataniba, LSIGMA-USB, and RAISG, Wataniba provides technical coordination for two fundamental components: MapBiomas Agua Venezuela and participates in adapting the tropical glacier mapping methodology to the Venezuelan context.

Since 2009, as part of the work with RAISG, the construction of deforestation maps of the Venezuelan Amazon began, applying increasingly advanced satellite data processing tools. In search of new alternatives for automating processes and generating timely information, in 2021 RAISG, in agreement with the General Coordination of MapBiomas Network, created the MapBiomas Venezuela initiative, of which Wataniba is a founding member.

MapBiomas Agua Venezuela maps and monitors water surfaces in Venezuela (rivers, lakes, lagoons, reservoirs, wetlands) from 1985 to 2024. The data reveal critical trends in water surface reduction, with a loss of 66,000 hectares between 2013 and 2021, forming part of a sustained regional water crisis lasting more than eight years. The glacier component documents a unique case in modern glaciological history: in 2024, Venezuela became the first Andean country to lose all its glaciers. The last glacier, located on Pico Humboldt (4,942 meters above sea level), shrank from 337.4 hectares (1910) to less than 2 hectares (2024), representing a loss of 99%. This retrospective mapping (1985-2024) is essential for preserving the historical record and providing evidence of climate change.

The objective of this Algorithms Theory Base Document (ATBD) is to provide users with an understanding of the methodological steps and computational algorithms used to produce Collection 3.0 of annual maps of water surface and glaciers in Venezuela between 1985 and 2024, using remote sensing techniques, machine learning, and automated processing on the Google Earth Engine platform.

1. Introduction

Glacier mapping is inherently difficult and dangerous due to the remoteness and inaccessibility of the terrain, as well as the challenges associated with conducting extensive fieldwork in high mountain environments. In the specific case of Venezuela, glaciers were mainly located in the Sierra Nevada de Mérida National Park between 4,700 and 4,978 meters above sea level, in areas that are difficult to access and have historically limited the frequency and spatial coverage of field studies. In addition, adverse weather conditions (sub-zero temperatures, strong winds, snowfall, intense solar radiation), the risk of crevasses hidden under the snow, the danger of avalanches, and the possibility of altitude sickness (soroche) make glaciological fieldwork a high-risk activity that requires strict safety protocols.

The precise delimitation of glacier edges using traditional field methods is also a complex and subjective task. The boundaries between glacial ice, seasonal snow, surface debris (moraines), and rock outcrops are often diffuse and variable over time, requiring consistent interpretation criteria and repeatable measurements. In very small glaciers such as those in Venezuela in their final decades of existence (<10 hectares after 2015), the identification of the boundary between permanent glacial ice and seasonal snow becomes particularly critical, especially considering that the formal definition of a glacier requires the ice mass to be thick and extensive enough to move under its own weight, a criterion that the remnant of Pico Humboldt ceased to meet around 2024, being reclassified as an "ice field."

In this context, remote sensing offers fundamental advantages: complete and systematic spatial coverage of all glaciers in a region, long and consistent time series (Landsat program since 1972), regular temporal revisit (every 16 days for Landsat), free access to historical and current data (USGS open data policy since 2008), automated processing using reproducible algorithms, and virtually zero marginal costs once the methodology has been developed. The judicious selection of spectral bands is essential in mapping glacial features: ice and snow have high reflectance in the visible spectrum and low reflectance in the shortwave infrared (SWIR)[1], a property that allows the NDSI (Normalized Difference Snow Index) to be calculated as (Green - SWIR1) / (Green + SWIR1), which maximizes the separability between snow/ice and other coverings such as clouds, rocks, or vegetation, under continuous training of the algorithm to adequately detect the ice surface[2].

However, remote sensing of glaciers also faces significant challenges. Cloud cover in tropical mountain regions can limit the availability of clear images, especially during the wet season. Differentiating between seasonal snow and permanent glacial ice requires careful multitemporal analysis, using dry season compositions (December-March in Venezuela) to minimize confusion with temporary snow. For very small glaciers such as those in Venezuela in recent decades (<5 hectares), Landsat's spatial resolution (30 meters) has limitations: a 4.5-hectare glacier (such as Humboldt in 2019) is equivalent to only ~50 pixels, where georeferencing errors of 1-2 pixels or classification errors can lead to significant uncertainties in area estimation.[3;4;5.]

In this context, MapBiomas Venezuela emerges as a collaborative initiative that seeks to generate robust, accessible, and up-to-date information on retrospective mapping of glacier surfaces as strategic components of the national hydrological cycle. This Algorithm Theory Base Document (ATBD) describes the methodology applied to generate the annual glacier surface maps corresponding to MapBiomas Agua - Venezuela Collection 3, covering the period 1985–2024. The purpose of this document is to provide users, researchers, and decision-makers with a clear and transparent understanding of the conceptual foundations, technical procedures, and computational algorithms used in the production of these maps, ensuring the replicability, traceability, and continuous

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[1] Dozier, J. (1989). Spectral signature of alpine snow cover from the Landsat Thematic Mapper. Remote Sensing of Environment, 28, 9-22

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[4] Rabatel, A., et al. (2013). Current state of glaciers in the tropical Andes: a multi-century perspective on glacier evolution and climate change. The Cryosphere, 7, 81-102.

[5] Braun, C., & Bezada, M. (2013). The history and disappearance of glaciers in Venezuela. Journal of Latin American Geography.

improvement of the products generated.

The methodology is based on the automated processing of Landsat satellite images using supervised classification algorithms implemented on the Google Earth Engine platform, taking advantage of the distinctive spectral properties of water and glacial ice in the electromagnetic spectrum. For surface water mapping, spectral indices such as NDWI and MNDWI are used, which exploit the high absorption of water in the infrared bands, while for glaciers, NDSI is used, which differentiates snow and ice from other coverages by combining visible-green and shortwave infrared bands.

1.1 Scope

The purpose of this document is to describe the theoretical basis, rationale, and methods applied to produce annual maps of solid water surface (glaciers) from 1985 to 2024 for Collection 3 of MapBiomas Venezuela. This document covers the methods for classifying Landsat images (L4, L5, L7, L8, L9), the image processing architecture in Google Earth Engine, and the approach for mapping critical components of the Andean territory's hydrological cycle. It also presents historical context and background information, as well as an overview of the satellite image dataset and the accuracy assessment method applied. The classification algorithms will be available in the MapBiomas Venezuela GitHub repository. The maps, statistics, and derivative products are available on the MapBiomas Venezuela web platform (https://venezuela.mapbiomas.org) for consultation and free download.

1.2 Diagnosis of the problem

El componente de glaciares documenta un caso único y emblemático: Venezuela se convirtió en 2024 en el primer país andino y tropical en perder todos sus glaciares. Una situación particularmente dramática, la Organización Meteorológica Mundial (OMM) confirmó que Venezuela, junto con Eslovenia, son los dos únicos países del mundo en perder todos sus glaciares en la época moderna. El último glaciar del Pico Humboldt se redujo de 337.4 hectáreas en 1910 a menos de 2 hectáreas en 2024, representando una pérdida del 99% documentada exhaustivamente mediante la aplicación de técnicas de teledetección satelital, algo que hubiera sido imposible de registrar con la misma precisión espacial y continuidad temporal mediante métodos tradicionales de campo.

The glacier component documents a unique and emblematic case: in 2024, Venezuela became the first Andean and tropical country to lose all its glaciers. A particularly dramatic situation, the World Meteorological Organization (WMO) confirmed that Venezuela, along with Slovenia, are the only two countries in the world to lose all their glaciers in modern times. The last glacier on Pico Humboldt shrank from 337.4 hectares in 1910 to less than 2 hectares in 2024, representing a 99% loss, which was thoroughly documented using satellite remote sensing techniques. This would have been impossible to record with the same spatial accuracy and temporal continuity using traditional field methods.

And why is it still important to study this area in Venezuela? Although Venezuelan glaciers have functionally disappeared, retrospective mapping is essential to preserve the historical record, generate evidence of climate change, warn other Andean countries where glaciers are also retreating rapidly, and understand the formation of new ecosystems in areas of glacial retreat.

The technical coordination of this glacier component within MapBiomas is part of its history as a member of the Amazonian Network for Geo-Referenced Socio-Environmental Information (RAISG) and its commitment to generating publicly accessible socio-environmental information that supports sustainable land management. The organization's technical team participates in adapting glacier mapping methodologies to the Venezuelan context.

1.3 Study Area

The working area for glacier mapping is limited exclusively to the Sierra Nevada de Mérida, located in the state of Mérida, in southwestern Venezuela, in the Andean region of the country. Geographically, the study area is roughly bounded by the coordinates 8°25'N - 8°33'N and 71°03'W - 71°31'W.

This region forms part of the Sierra Nevada National Park (created in 1952), covering the high mountain areas above 4,200 meters above sea level, where Venezuelan glaciers were historically located. The specific area of analysis includes:

- ✔ **Pico Humboldt** (4,942 msnm) and its surrounding areas
- ✔ **Pico Bolívar** (4,978 msnm, the highest peak in Venezuela)
- ✔ **Pico Bonpland** (4,883 msnm)
- ✔ **Pico La Concha** (4,922 msnm)
- ✔ **Pico El Toro** (4,758 msnm)

In addition, the study area includes a safety buffer of approximately 1.5 km around historic glacier areas to ensure complete capture of glacier retreat dynamics and primary succession zones (areas recently exposed by ice retreat). This buffer allows for the documentation of transitions between glacier coverage, newly exposed rock outcrops, and páramo vegetation colonizing post-glacial areas.

The analysis focuses on the altitudinal range between **4,200 y 4,978 msnm**, although with particular emphasis on areas above **4,700 msnm** where glaciers were located during the period 1985-2024.

1.4 Major glaciers and their chronology of disappearance

Venezuelan glaciers have experienced one of the fastest rates of retreat documented in the tropical Andes. Between 1910 and 2019, the glacial area shrank by 98.6%, from 337.4 hectares to just 4.54 hectares [4] [5]. The process has accelerated dramatically in recent decades: between 2016 and 2019, the average loss rate was 16.9% per year, equivalent to 23.3 meters per year of retreat of the glacier's terminal edge and 6.7 meters per year of retreat in elevation [4].

The Humboldt Glacier was the last to survive, partly due to its altitude and favorable topography. It sat on a gently sloping slope. (Below 15°) on the northwest slope of Humboldt Peak, where snow could accumulate and compact into glacial ice[6;7]. However, These characteristics were not sufficient to sustain it indefinitely in the face of accelerated climate change.

Table 1. Chronology of glacier disappearance in Venezuela..

Glaciar	*Altitud (msnm)*	*Location*	*Area 1910 (ha)*	*Area 1952 (ha)*	*Area 2009 (ha)*	*Year of disappearance*	*Current status*
Pico Humboldt	*4,942*	*8°33'10.6"N , 71°3'11.7"W*	*337.4**	*127.3*	*16.4*	*2024 (funcional)*	*Ice field <2 ha***
Pico Bolívar	*4,978*	*Near Pico Espejo*	*Part of continuous mass*	*60.1*	*11.0*	*2020*	*Completely disappeared*
Pico La Concha	*4,922*	*Sierra Nevada of Mérida*	*37.9*	*4.7*	*-*	*1990*	*Completely disappeared*

[6] Llambí, L.D., Melfo, A., & Santos, T. (2021). Los Andes Después del Hielo: El último Glaciar de Venezuela. Instituto de Ciencias Ambientales y Ecológicas - ICAE, Universidad de los Andes. Propuestas Andinas No. 17. CONDESAN.

[7] NASA Earth Observatory. (2024). Humboldt Glacier's Demise. https://earthobservatory.nasa.gov/images/152893/humboldt-glaciers-demise

Pico Bonpland	*4,883*	*North of Humboldt Peak*	*Conectado con Humboldt*	-	-	*~2009*	*Completely disappeared*
Pico El Toro	*4,758*	*Sierra Nevada de Mérida*	*Datos no disponible s*	-	-	*~1900-1910*	*Completely disappeared*

Source: *Llambí et al. 2021; Ramírez et al. 2020; NASA 2024; BBC Mundo 2024.*
Notes:*(*) Area of 1910 includes shared extension between Pico Humboldt and Pico Bonpland; (**) The glacier "La Corona" (Pico Humboldt) it was the last Venezuelan glacier, In 2024 was reclassified as "ice field" for failing to meet glaciological criteria (gravity movement)*

2. Methodology

The procedure is a standardized method developed for glacier mapping, a task that initially covered all areas connected to the Amazon region and was later expanded to other countries in the region. This methodology maintains technical procedures, classification algorithms, post-processing filters, and validation protocols that are applicable regardless of the size or current state of the glaciers.

However, it is essential to recognize that in the Venezuelan context:

1. The analysis focuses primarily on retrospective reconstruction (1985-2024)
2. Results for recent years (2020-2024) will show no or minimal glacier coverage.
3. The methodology allows us to document the transition from “active glacier” to “ice field” and finally to “absence of glacier.”

A pesar de la extinción de los glaciares venezolanos, mantener la metodología estándar es esencial para generar series temporales consistentes y comparables con otros países andinos; aplicar criterios homogéneos de clasificación en toda la región amazónica-andina; luego, permitir análisis comparativos de tasas de retroceso glaciar; y por último proveer datos históricos confiables para estudios de cambio climático.

2.1 Methodological flow

In this document, we present a description of the methodology applied for mapping solid water surfaces (glaciers) for MapBiomas Agua Venezuela Collection 3. To this end, we used the methodology applied by the MapBiomas network (Turpo Cayo et al., 2022) as a basis. The entire process was divided into six stages (Figure 1).

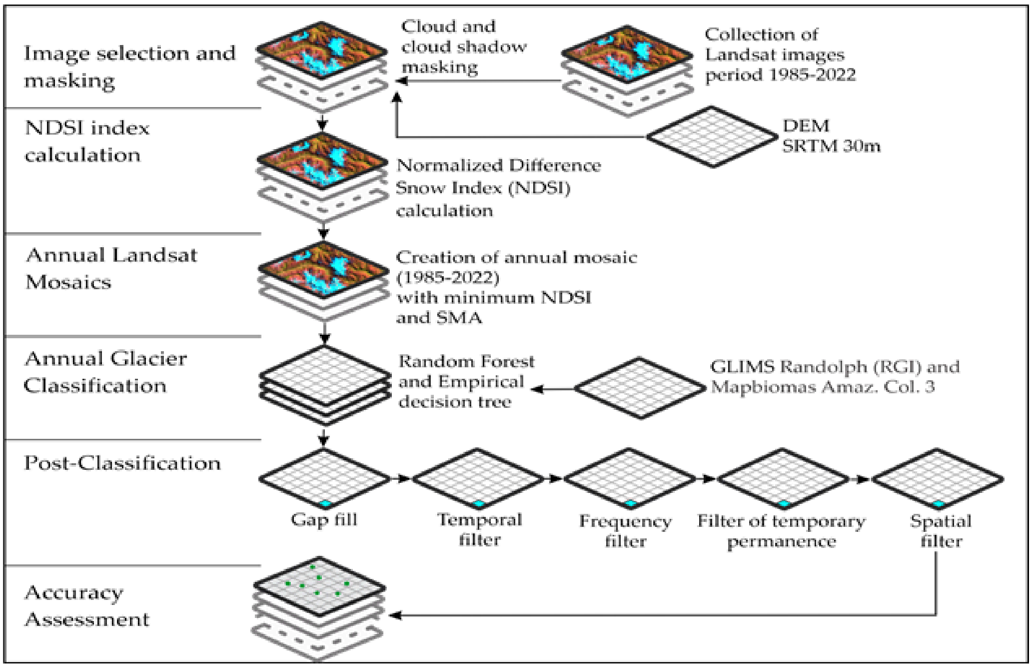

Figure 1 - Methodological flowchart for obtaining glacier coverage maps

2.2 Image mosaics

The classification of the cross-cutting theme “Glaciers” used Landsat image mosaics generated specifically for glacier mapping. These mosaics included images with minimum annual glacier area, based on the minimum NDSI quality pixel.

Image selection criteria:

- ✔ Use of Landsat 5 (TM), Landsat 7 (ETM+) y Landsat 8 (OLI) images.
- ✔ Selection based on NDSI index to identify snow and glacier coverage.
- ✔ Use of the 75th percentile and 25th percentile of the NDSI for wet and dry seasons, respectively Minimization of cloud cover using masking algorithms

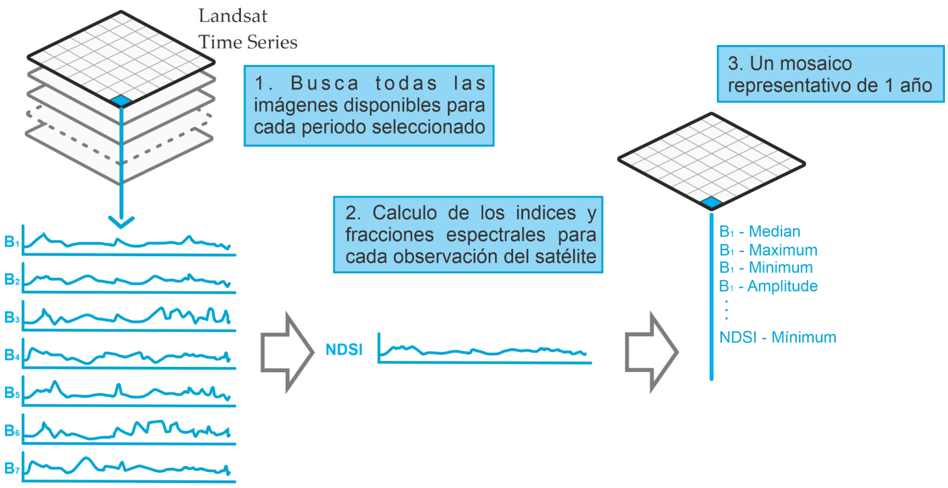

Figure 2 -Creation of annual mosaics for Glaciers

2.3 Classification

The classification of Landsat mosaics was carried out entirely on the Google Earth Engine platform, based on an empirical tree (Figure 3), where the median NIR reflectance values are close to 0.2114 in Landsat 5 and Landsat 7, while in Landsat 8 the values are close to 0.1730. In the case of RED median, values of 0.2497, 0.2497, and 0.2304 were used for Landsat 5, Landsat 7, and Landsat 8, respectively.

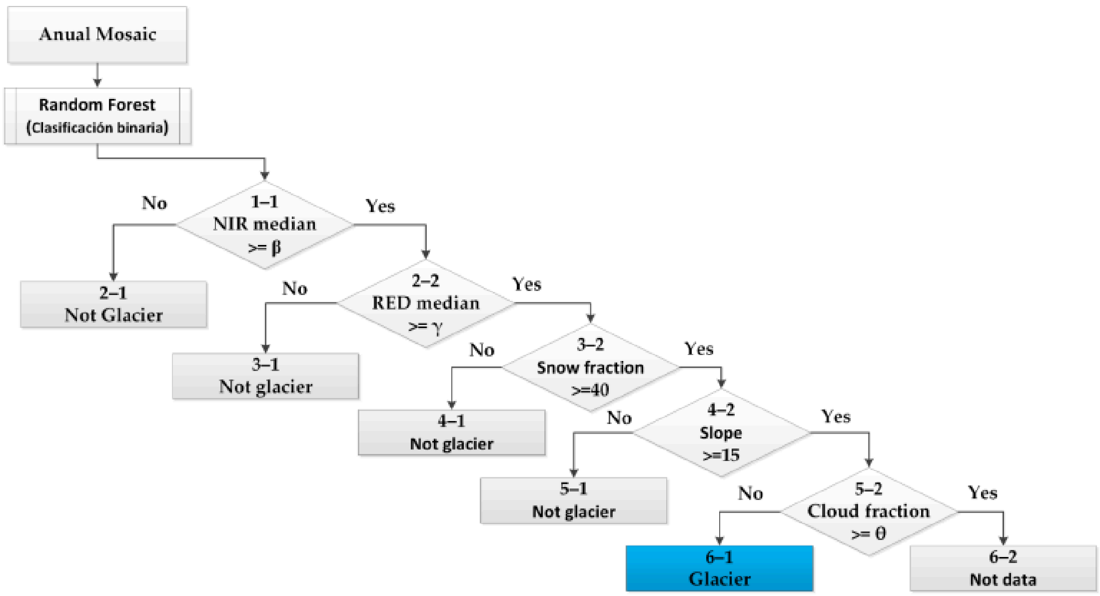

Figure 3 - Empirical tree combined with Random Forest for glacier classification

Classification thresholds

✔ NIR median: ~0.2114 (Landsat 5/7); ~0.1730 (Landsat 8)

✔ RED median: ~0.2497 (Landsat 5/7); ~0.2304 (Landsat 8)

2.3.1 Classification variables

Table 4. Spectral indices and bands used for classification.

Tipo	nombre	Fórmula	Descripción	Reductor				
				Media n	Median_ dry	Median_ wet	Mín	Max
Banda	blue	B1 (L5 y L7); B2 (L8)	Espectro visible azul		X			
	green	B2 (L5 y L7); B3 (L8)	Espectro visible verde		X			
	red	B3 (L5 y L7); B4 (L8)	Espectro visible rojo	X	X			
	nir	B4 (L5 y L7); B5 (L8	Infrarrojo cercano	X	X			
	swir1	B5 (L5 y L7); B6 (L8)	Infrarrojo de onda corta 1		X			
	swir2	B7 (L5); B8 (L7); B7(L8)	Infrarrojo de onda corta 2		X			
Índices	ndsi	(green-swir 1)/(green+s wi r1)	Índice Diferencial Normalizado de Nieve				X	
fracción es	cloud fracción	SMA	Fracción de nube		X			
	cloud Snow	SMA	Fracción de nieve		X			

2.3.2 Reference maps

The study area is defined based on the Global Land Ice Measurements from Space Glacier Inventory (2022), supplemented by visual inspection and the addition of missing glaciers documented in Venezuelan scientific literature, specifically:

- ✔ Historical maps by Alfredo Jahn (1910)
- ✔ Aerial photographs of 1952
- ✔ Studies at the University of Los Andes [1;2]
- ✔ Project "Last Glacier of Venezuela" (2019) [8;9]

[8] Llambí, L.D., et al. (2021). Vegetation Assembly, Adaptive Strategies and Positive Interactions During Primary Succession in the Forefield of the Last Venezuelan Glacier. *Frontiers in Ecology and Evolution*, 857755.
[9] Llambí, L.D., et al. (2024). Monitoreo de la Sucesión Primaria en el Último Glaciar de Venezuela. Proyecto Último Glaciar Venezuela, ICAE-ULA, National Geographic Society.

Figure 4 - Distribution of glaciers in South America, Source: (Global Land Ice Measurements from Space, 2022)

2.3.3 Reference maps

In the case of Venezuela, the training samples were collected with the intention of discriminating the spectral responses of ice masses from other nearby surfaces with similar reflectance. They should include:

✔ Glacier reference points in historical years (1985-2010)

✔ Seasonal glacier-snow transition points (2010-2020)

- ✔ Points of recent glacial retreat zones
- ✔ Negative validation points (exposed rock, high mountain vegetation)

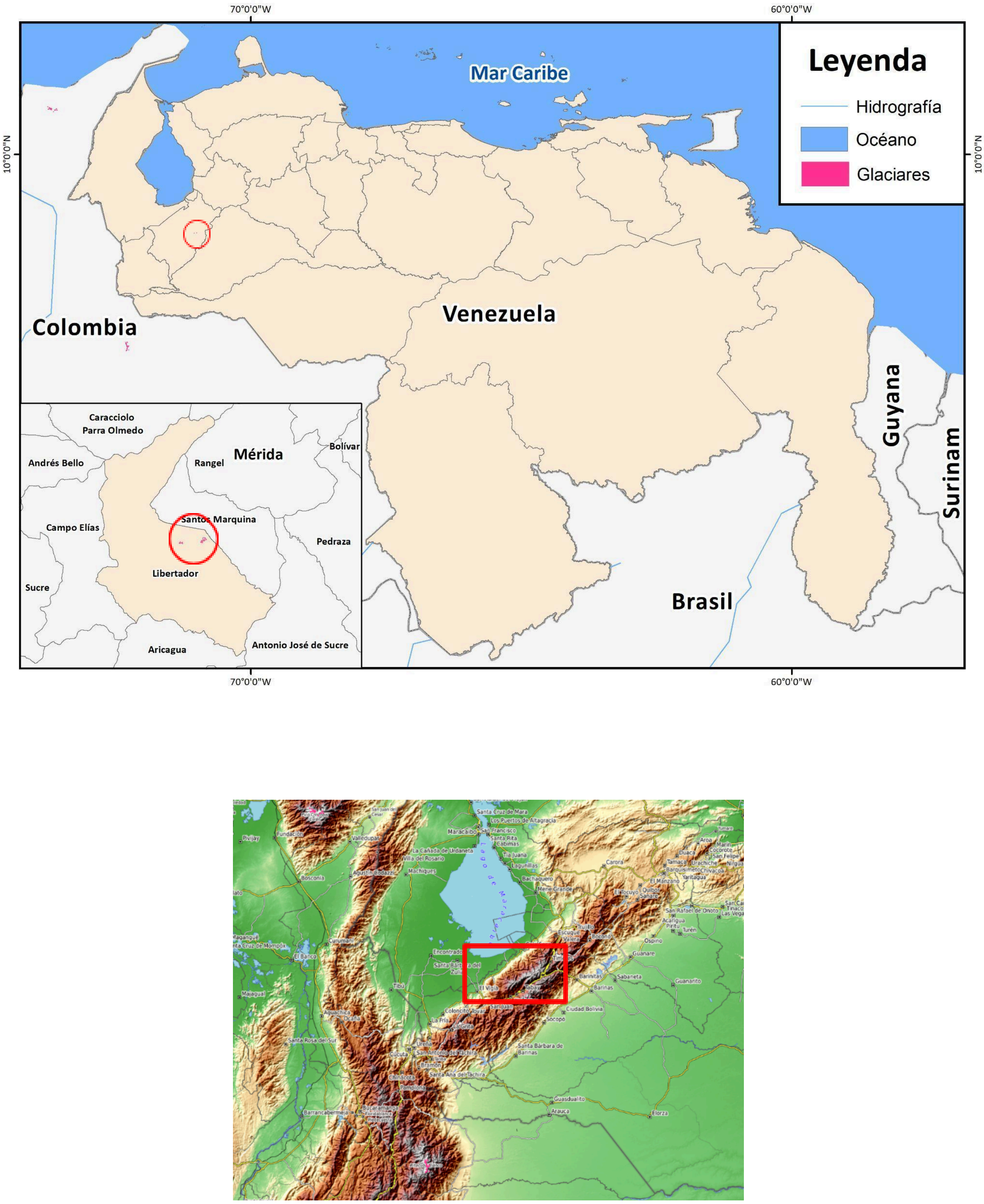

Figure 5 - Distribution of glaciers in the far west of the country, Source: [Visor de los Glaciares del Mundo | Visores Cartográficos | Meteosierra]

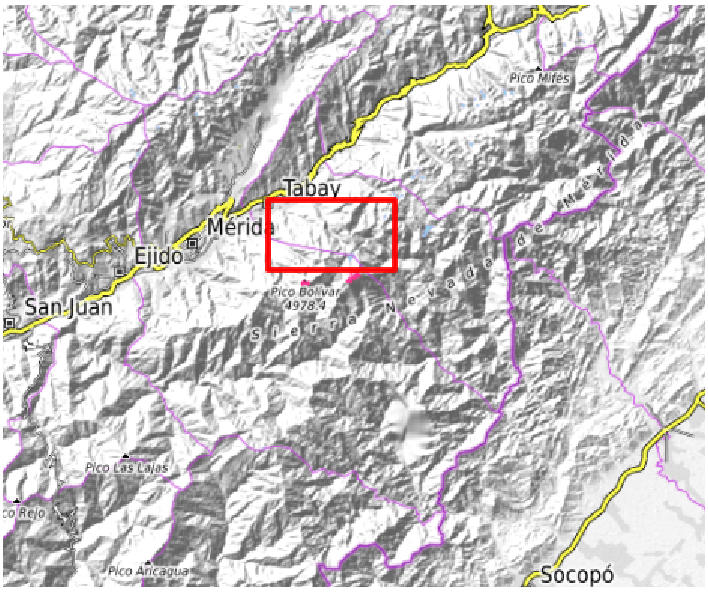

Figure 6 – Distribution of glaciers in the far west of the country, Source: [Visor de los Glaciares del Mundo | Visores Cartográficos | Meteosierra]()

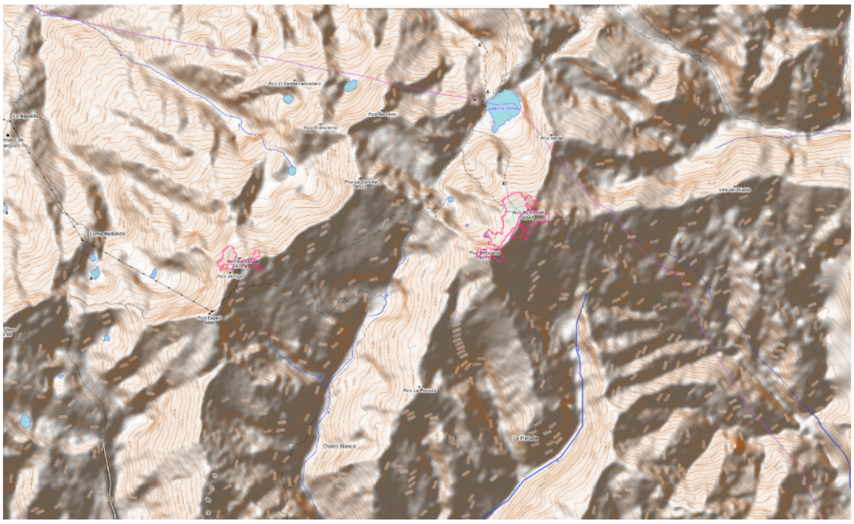

Figure 7 – Distribution of glaciers in Mérida, Source: [Visor de los Glaciares del Mundo | Visores Cartográficos | Meteosierra]()

2.4 Post-classification

Due to the pixel-based nature of the classification method and the work on an extensive time series, a chain of post-classification filters was applied. The post-classification process includes the application of fill, temporal, spatial, and frequency filters.

2.4.1 Filling in information gaps (Gap Fill)

In a long time series for regions severely affected by clouds, gaps may occur in the classification results. With Gap Fill, gaps are replaced by the closest temporal classification. If no value is available for the following year, the gap is replaced with the value from the preceding year.

This ensures that only pixels that have been classified as having no information in all years remain at the same value throughout the entire time period.

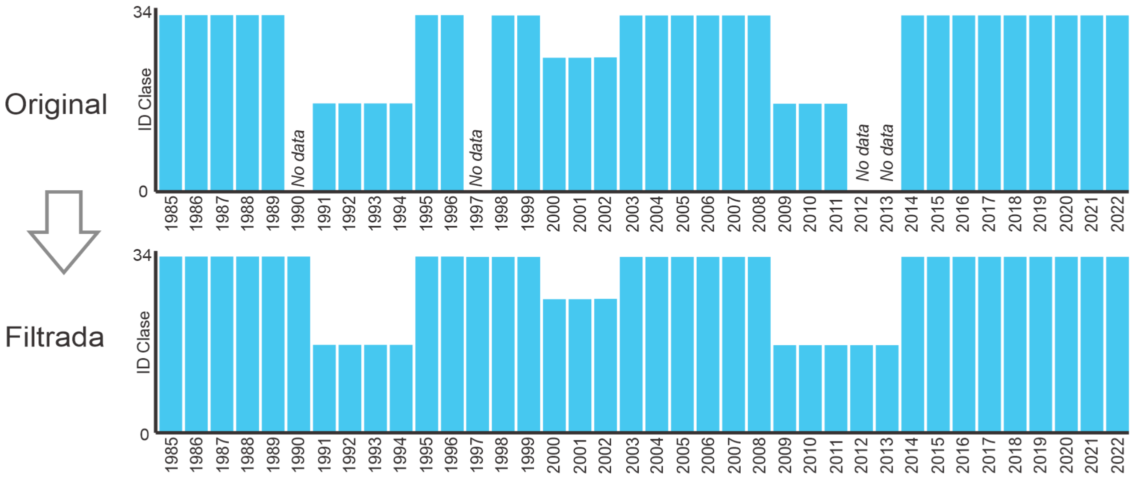

Figure 8 - Filtro Gap Fill

2.4.2 Temporary filter

Once Gap Fill has been applied, the temporal filter is executed, which uses sequential classifications in a unidirectional moving window of 3, 4, or 5 years to identify temporally inconsistent transitions, based on rules for: intermediate years, first and last year of the series.

Because there is missing data from previous years due to errors in data capture, it is important to use this filter, especially to smooth abrupt and unrealistic transitions in areas of glacier retreat.

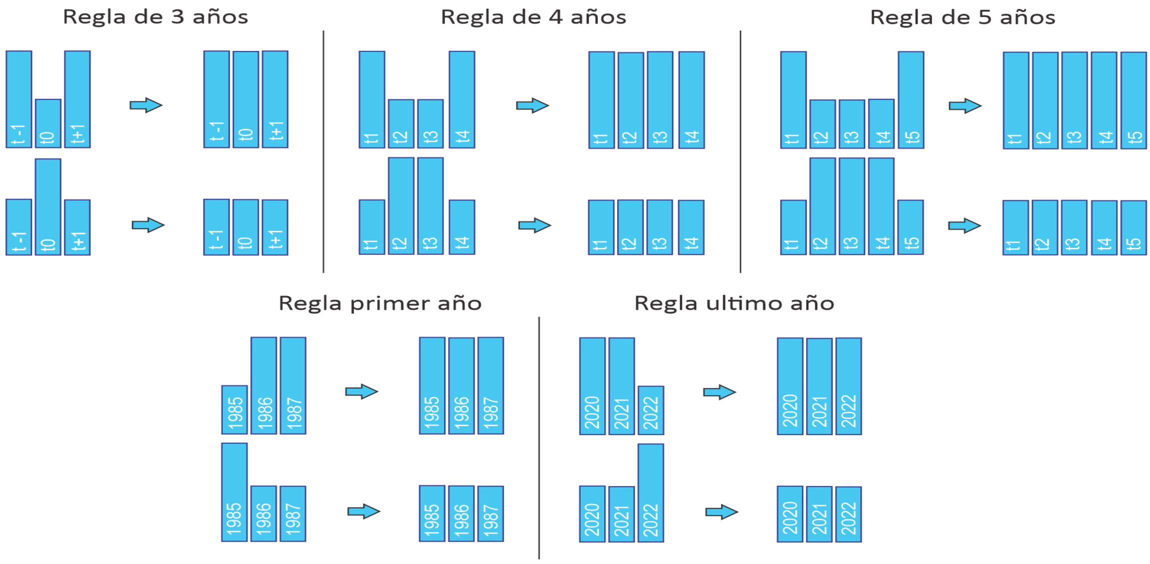

Figura 9- Filtro Temporal

2.4.3 Spatial filter

A spatial filter based on the “connectedPixelCount” function is applied, which identifies the set of pixels (neighborhoods) that share the same value. As a result, only pixels that are not connected, considering a predefined minimum number of identical pixels, are defined as isolated pixels and reclassified.

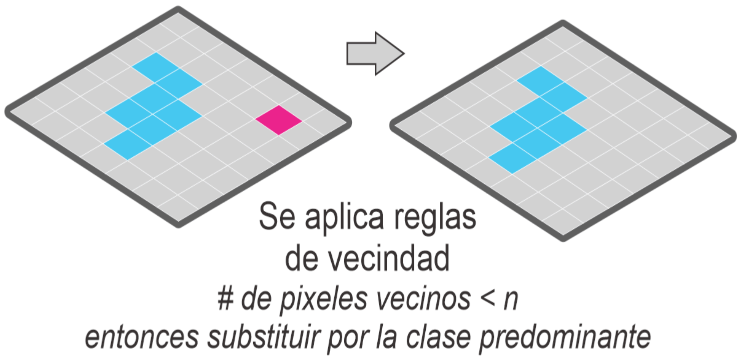

Figure 10 - Effect of applying the spatial filter

2.4.4 Frequency and time permanence filter

This filter considers the occurrence of the class throughout the time series to clean up the classification result, complemented by a temporary permanence rule.

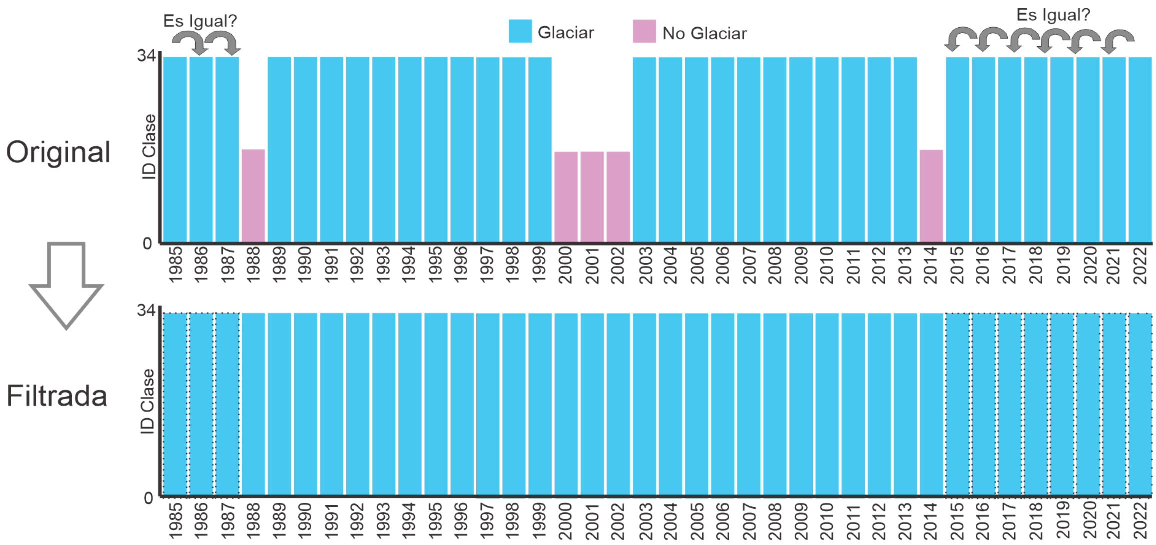

Figure 11 - Effect of applying the frequency filter

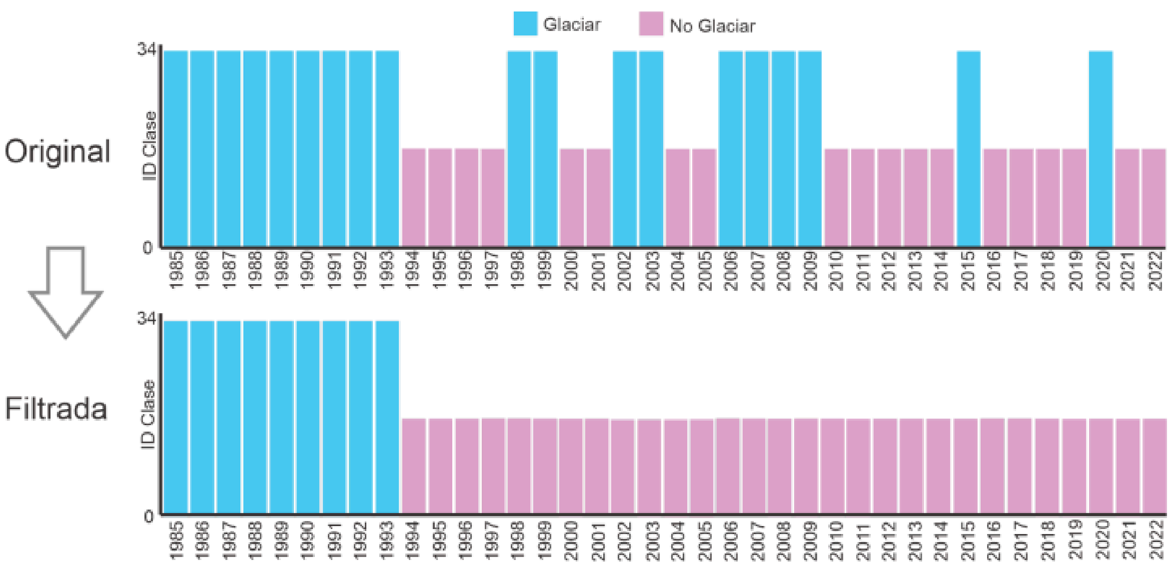

Figure 12 - Effect of applying the temporary permanence filter

2.5 Integration with other MapBiomes classes

After applying the filter sequence in the post-classification stage, the cross-cutting themes and general maps of each biome are integrated. This integration depends on a series of specific hierarchical rules that assign an order of prevalence to each class (Table 1). As a result of this integration, the detected solid water surface area can be observed in the annual land cover and land use maps of Venezuela.

In addition, the data is published in the Glaciers module of MapBiomas Agua Venezuela. It is important to note that for Venezuela, integration must consider the transition from “glacier” to “rock outcrop” and eventually to “high mountain vegetation (páramo)” in areas of glacial retreat.

2.6 Validation

2.6.1 Sampling design

Thematic accuracy analysis is the primary way to assess the quality of maps. Accuracy analysis considers stratified random sampling.

Sample size:

$$n = \frac{z_{\alpha/2}{}^{*}p^{*}q}{e^{2}}$$

Where:
$z_{\alpha/2}$ = Defined according to confidence level (Tabla Z)
p = Probability of success, or expected ratio
q = Probability of failure (100-p)
e = Accuracy (Maximum permissible error in terms of proportion)

For Venezuela: Taking a confidence level of 95% $(Z = 1.96); p = 95\%\ y\ e = 0.08$ it is recommended a minimum of 200 validation points strategically distributed in:

- ✔ Areas with historic glaciers (1985-2010)
- ✔ Accelerated rollover zones (2010-2020)
- ✔ Residual glacier areas (2020-2024)

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