ATBD

Algorithm Theoretical Base Document

MapBiomas Chile

Water — Collection 1

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I. Introduction

1.1 Scope and Content of the Document

The main objective of MapBiomas Agua is to map surface water dynamics in mainland Chile on a monthly and annual basis from 1998 to 2025. Additionally, the module includes a section identifying Chile's Andean glaciers, covering the same time series. One of the main outcomes is a set of maps containing annual water surface area data, partially incorporated as a cross-cutting theme in the future MapBiomas Land Cover Chile Collection 3 to strengthen the integration of land cover and land use maps. Beyond integration with Collection 3 on land cover and land use, other outputs produced by the MapBiomas Agua initiative include the publication of the dataset, which is publicly available on a web platform to improve the management and use of water resources in the country.

MapBiomas Water Chile Collection 1 represents the first national effort to generate a consistent, spatially explicit, and open-access time series on the distribution and dynamics of the surface water of the country. This collection characterizes the spatial and temporal variability of lakes, lagoons, rivers, reservoirs, flooded salt flats, and other surface water bodies in mainland Chile, providing continuous data to support scientific research, water resource management, land-use planning, and the conservation of aquatic ecosystems.

The purpose of this Algorithm Theoretical Basis Document (ATBD) is to provide users with a detailed guide on the methodological steps, zoning context, and justification of thresholds used in the generation of water surface maps for mainland Chile, which are part of Collection 1 of the MapBiomas Water Chile initiative. Finally, this document presents an overview of the MapBiomas Water initiative, a historical context of the influence of climate change on water resource dynamics, and background information on the detection of water bodies.

1.2 Overview

MapBiomas Water is an initiative of the MapBiomas network, whose main objective is to map surface water bodies throughout mainland Chile on a monthly and annual basis, from 1998 through 2025. This initiative stems from a previous study conducted by Imazon and WWF-Brazil in the Brazilian Amazon biome, which was expanded to include the Upper Paraguay Basin in the Chaco biome and published before (Souza et al. 2019). This former study demonstrated the potential to enhance the capacity of the MapBiomas Land Cover and Land Use Initiative to detect and monitor surface water dynamics across all Brazilian biomes. Building on this foundation, the MapBiomas Water working group expanded the same approach and methodology to the entire Brazilian territory. Subsequently, in 2022, through a partnership between MapBiomas and the Amazonian Network for

Georeferenced Socio-Environmental Information (RAISG), it was decided to adapt, extend, and apply the MapBiomas Water methodology to the entire territories of the Amazonian countries in order to capture and understand water dynamics across the various biomes throughout the region. In 2025, the MapBiomas Water initiative expanded to the Andean-Patagonian countries, such as Chile and Argentina, with the first survey of their freshwater bodies using satellite imagery.

The methodology for mapping and monitoring surface water is based on subpixel-level classification of Landsat 5, 7, 8, and 9 images, along with spatial analysis of surface water bodies to identify anthropogenic impacts and the potential effects of climate change. All data processing was performed on the Google Earth Engine cloud platform. As a result of this initiative, a collection of maps was produced that includes data on: water surface area on a monthly and annual basis, as well as changes and trends. In addition, these results will be incorporated into the third collection of MapBiomas Chile land-use and land-cover maps. All data is published in the Water module of the MapBiomas Chile web platform which is freely accessible to the public.

MapBiomas Water Chile aims to provide a public, transparent, and reproducible database that makes it possible to quantify the historical evolution of the surface water of the country. The availability of consistent spatial information facilitates trend analysis, the assessment of processes leading to the loss or expansion of water bodies, the identification of changes associated with climate variability and human activities, and support for public policies aimed at the sustainable management of water resources.

1.3 Science and Key Applications

The dataset on the dynamics of surface water bodies helps us understand aquatic systems and their interaction with other components of the environment; it is crucial for decision-making and contributes to water resource management with a focus on sustainable development. Information on surface water mapping can support: integrated land-use planning; monitoring of the Sustainable Development Goals; sustainable water management initiatives; monitoring of water concessions and small dams; assessment of the quality of freshwater ecosystems; research and evaluation of changes in water bodies; and ecosystem services and their relationship to climate change.

II. General Information and Background

2.1 Context and Key Information

The conditions of many freshwater ecosystems have deteriorated due to human activities in recent decades. Drastic changes in land use and land cover (Martinez-Rutureta et al. 2020), the construction of hydroelectric dams, non-point source pollution (Rodríguez-López et al. 2025), and the excessive use of water resources for the production of goods and services have altered water quality and availability worldwide. Recent evidence shows that freshwater species have extinction rates twice as high as those of terrestrial species (WWF, 2020). Furthermore, extreme droughts and floods linked to climate change have increased pressure on water reservoirs and aquatic ecosystems. This situation is likely to worsen further, given the growth of the world's population—which surpassed 8 billion in 2022—and the increasing use of resources; unless integrated water management strategies are developed, it will be impossible to achieve global sustainable development goals. From this perspective, continuously and historically assessing changes in water surface dynamics on a continental scale is one of the main challenges in decision-making regarding this valuable resource (Oliveira et al., 2019).

In Chile, the marked climatic and physiographic heterogeneity gives rise to a wide variety of aquatic systems that perform essential functions for biodiversity conservation, drinking water supply, agricultural production, hydroelectric power generation, mining, tourism, and numerous ecosystem services. At the same time, these systems face increasing pressures stemming from climate change (Boisier et al. 2025), declining precipitation across much of the country, glacial retreat, more severe droughts, the expansion of economic activities, and changes in land use.

The information generated by MapBiomas Water Chile helps strengthen integrated water resources management by providing consistent spatial indicators on changes in surface water. Its main applications include:

- Assessment of long-term trends in surface water availability;
- Monitoring of lakes, lagoons, rivers, and reservoirs;
- Support for aquatic ecosystem conservation strategies;
- Monitoring the effects of climate variability and climate change;
- evaluation of the effectiveness of public policies related to water resource protection;
- Support for land-use planning and watershed management;
- Development of indicators for national and international commitments related to biodiversity, climate change, and sustainable development;
- Conducting scientific research in hydrology, ecology, geomorphology, and environmental sciences.

The open nature of the project also promotes scientific reproducibility, transparency in the generation of environmental information, and equitable access to high-quality spatial data by public institutions, nongovernmental organizations, universities, businesses, and the general public.

2.2 Historical Perspective: Existing Maps and Cartographic Initiatives

The use of satellite data revolutionized humanity's ability to map inland surface waters and their dynamics. The combination of free access to Landsat data and cloud-based processing capabilities enabled the release of a global dataset spanning several decades on surface waters:

The Global Surface Water (GSW) initiative (Donchyts et al. 2016, Pekel et al. 2016) provides information on the extent and dynamics of surface water across the Earth's surface, based on an analysis of more than 30 years of pixel-level Landsat imagery for various scientific and management applications. However, the direct use of GSW at the national level remains a challenge due to methodological limitations in detecting water in floodplains, wetlands, and small bodies of water.

MapBiomas Water seeks to overcome some of these limitations by adopting the same general approach of combining Landsat data with cloud computing capabilities, but by incorporating several methodological innovations to improve the detection and mapping of surface water. In particular, the initiative employs a subpixel-level surface water classifier (SWSC), initially applied to the Brazilian Amazon biome (Souza et al. 2019). Details of this methodology are presented in the following sections.

III. Methodology

The combination of the Landsat historical archive and the cloud-processing capabilities provided by Google Earth Engine allowed MapBiomas Agua Chile to produce a monthly and annual surface-water dataset for the entire Chilean territory between 1998 and 2025. The methodological workflow follows the general MapBiomas Agua approach based on sub-pixel water detection using Spectral Mixture Analysis (SMA), temporal consistency rules and post-classification procedures. However, the Chilean implementation required specific adaptations due to the country's strong latitudinal, climatic, topographic and spectral heterogeneity.

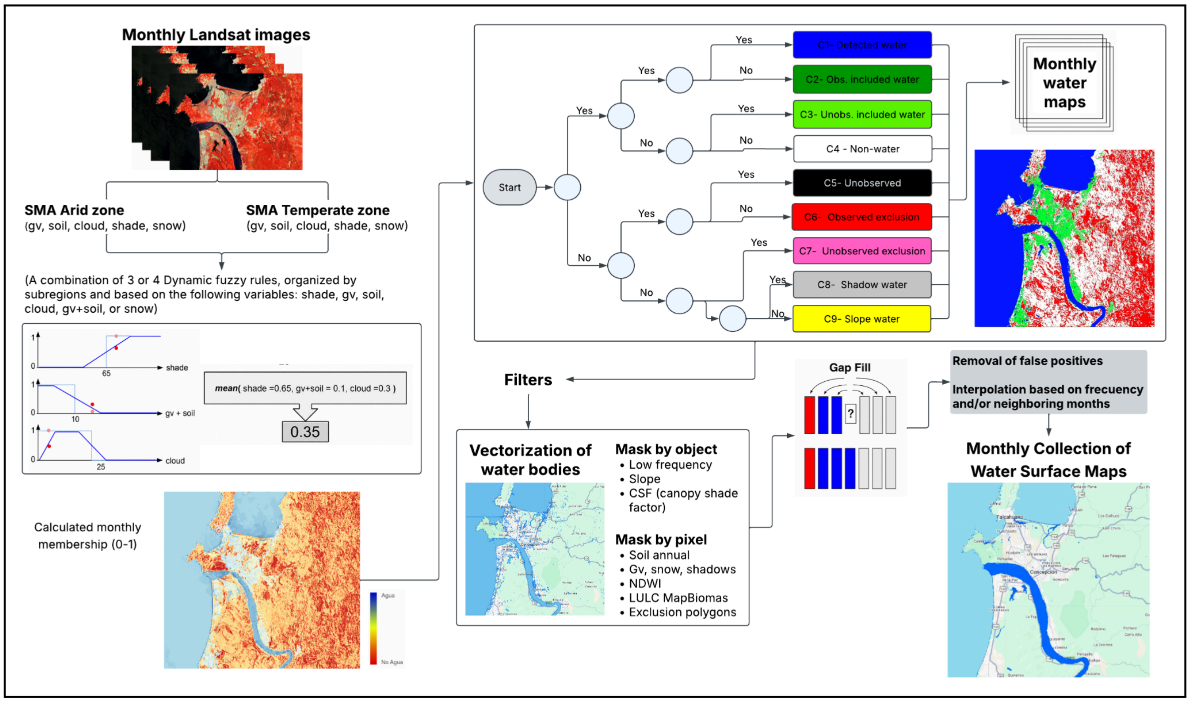

Figure 1. Methodology workflow.

The methodological process was organized into four main stages: **preliminary classification**, **vectorization**, **false-positive masking** and **gap filling**. Each stage was designed to progressively refine the monthly water classification, moving from a preliminary spectral detection to a final product corrected by temporal, topographic, seasonal and object-based criteria.

3.1 Landsat imagery

The project used Landsat Collection 2 imagery available in Google Earth Engine, including Landsat 5 TM, Landsat 7 ETM+, Landsat 8 OLI and Landsat 9 OLI-2. These sensors provide a 30 m spatial resolution. The original spectral bands were harmonized into a common structure composed of blue, green, red, near infrared, short-wave infrared 1 and short-wave infrared 2 bands.

Images were filtered by date, processing grid and cloud-cover criteria. Cloud and snow contamination were reduced through cloud-screening procedures and auxiliary spectral filters. Monthly image collections were then used to generate the spectral and temporal metrics required for water detection, including monthly water membership, annual water probability and monthly temporal consistency indicators.

3.2 Regionalization and threshold definition

Given the environmental heterogeneity of Chile, the preliminary classification was calibrated separately for arid and temperate/wet zones. The transition zone was treated as an intermediate area, where either the arid or the temperate/wet model was applied according to classification performance.

All methodological steps were implemented at the grid level (see Figure 2). Each grid, or mapping tile, was processed independently throughout the workflow, including preliminary classification, vectorization, seasonal masking and gap filling. This grid-based approach allowed the methodology to adjust spectral thresholds, hydroclimatic conditions and post-classification rules to local environmental characteristics, while maintaining a consistent national processing structure.

In addition to this first classification regionalization, a second level of regionalization was incorporated during the post-classification masking stage. For this purpose, each grid was assigned to one of four macrozones: North, Central, South and Austral. Within each macrozone, monthly thresholds were adjusted according to the seasonal condition of the month, classified as dry, neutral or wet based on the climatological behavior of the dominant hydroclimatic forcing variable, either precipitation or streamflow (Figure 2).

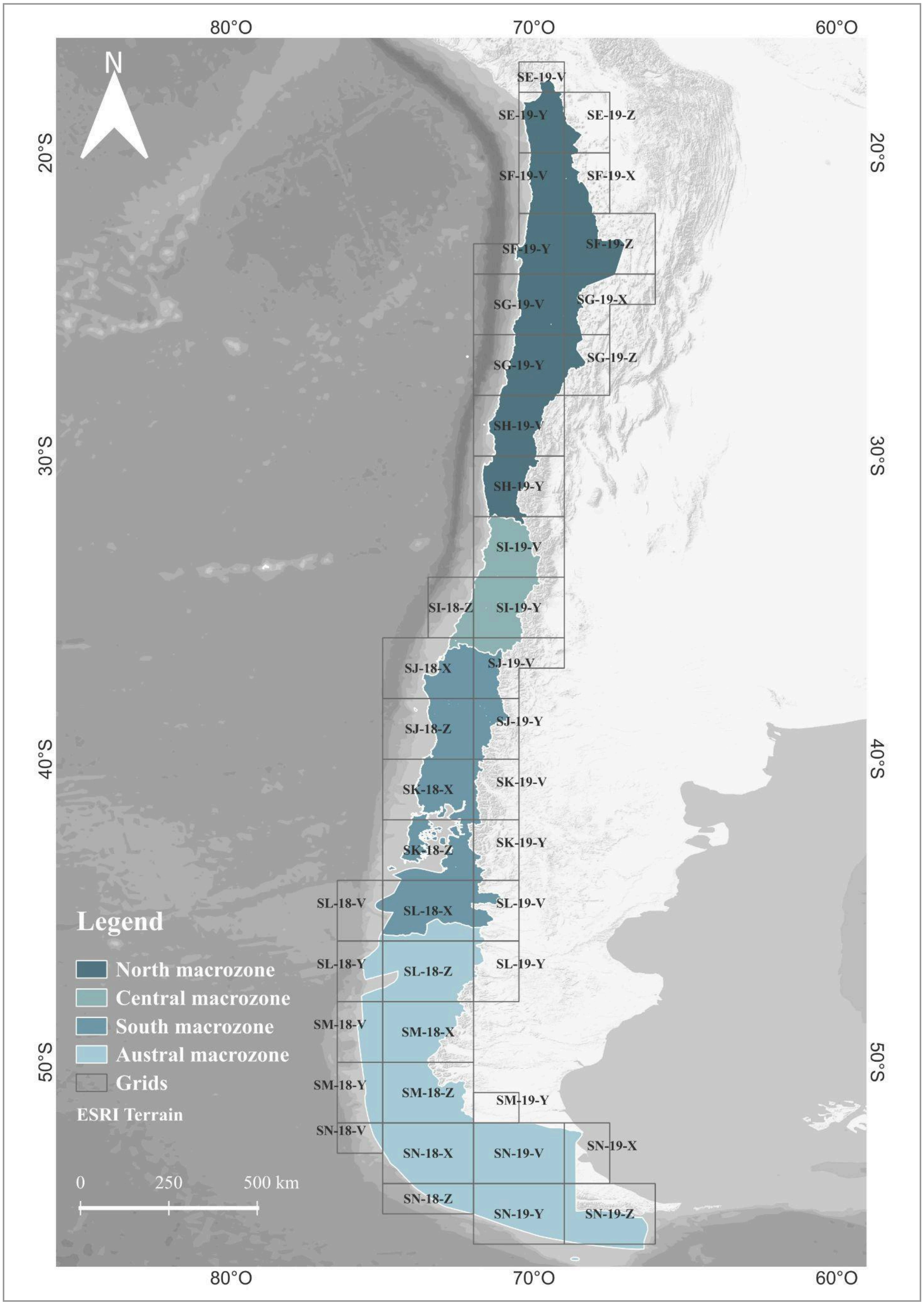

Figure 2. Grids distribution and macrozones.

This two-level approach is a specific adaptation of the Chilean methodology. The first level defines the spectral thresholds used to generate preliminary water detections, while the second level supports the seasonal removal of false positives according to macrozone-specific hydroclimatic conditions.

3.3 Algorithm description

3.3.1 Spectral Mixture Analysis

Spectral Mixture Analysis (SMA) was used as the basis for the preliminary detection of surface water. This technique estimates the fractional composition of each pixel from a set of pure spectral components, or endmembers. In the MapBiomas Agua Chile workflow, the main endmembers were: i) Shade, which represents dark surfaces and is strongly associated with water; ii) Green Vegetation (GV), which represents photosynthetically active vegetation; iii) Soil, associated with bare ground or exposed sediment; iv) Cloud, used to identify atmospheric contamination or bright cloud-related responses; v) Snow was also incorporated as an additional endmember/control variable to reduce confusion with snow patches and other high-reflectance surfaces. This SMA approach allowed the identification of sub-pixel spectral responses associated with water and with other surfaces that may generate confusion, such as vegetation, bare soil, clouds, snow in arid areas, shadows and high-reflectance surfaces.

The SMA-based classification was adapted to the country's environmental heterogeneity through two preliminary configurations: an **arid model** and a **temperate/wet model**. This regional adaptation allowed the same sub-pixel classification logic to be applied under different spectral and hydroclimatic conditions, while adjusting the role of each endmember according to the main sources of confusion in each zone.

In the arid model, the main endmembers were Shade, Green Vegetation (GV) and Soil, while Cloud was calculated as a diagnostic component and Snow was incorporated as an additional exclusion control. This configuration was designed to reduce confusion with bare soil, salt flats, snow patches, bright surfaces and intermittent wetlands. In this model, pixels with spectral responses more consistent with exposed soil or snow were forced to zero water probability during the preliminary stage.

In the temperate/wet model, the classification was based on Shade, the combined GV + Soil fraction, and Cloud endmembers. These variables were used to estimate the degree of membership to the water class under humid, vegetated and topographically complex conditions. Unlike the arid model, snow was not parameterized as an SMA endmember threshold in the preliminary classifier; instead, snow-related confusion was addressed through the wet mosaic configuration and later post-classification masking procedures.

The SMA fractions were transformed into fuzzy membership values ranging from 0 to 1. These membership values represent the degree to which each pixel matches the expected spectral behavior of surface water. Instead of applying a single binary threshold directly to the Landsat bands, the classifier used these continuous membership values to estimate monthly water probability.

3.3.2. Subpixel Water Surface Classifier

The Subpixel Water Surface Classifier used the SMA-derived membership values to generate monthly preliminary water maps for each processing grid and year. Following the general MapBiomas Water approach, the classifier was implemented as a rule-based decision tree that combines monthly water probability, annual water probability and temporal consistency indicators.

For Chile, the classifier was applied separately through the arid and temperate/wet models. Both models followed the same general logic, but used different threshold values and control rules. The arid model applied a more conservative decision rule for direct water detection, including additional controls based on Soil, Snow and MNDWI. The temperate/wet model used a more flexible monthly detection threshold to retain water candidates in cloudy, humid and topographically complex areas, while controlling bright false positives in specific manually defined areas.

The decision flow was structured in four main steps. First, direct water detections were identified when the monthly water probability exceeded the model-specific threshold. Second, pixels not directly detected as water, but supported by monthly recurrence and annual probability, were classified as water inclusions. Third, pixels with low annual probability were flagged as exclusions. Finally, pixels without valid monthly information were assigned as not observed, while the remaining pixels were classified as non-water.

The preliminary classification produced a multi-class monthly raster, with one band per month from w_1 to w_12. The classes were:

Table 1: Classes.

Class	Label	Interpretation
C1	Detected water	Direct monthly water detection
C2	Included water, observed	Temporal water inclusion with valid monthly observation
C3	Included water, not observed	Temporal water inclusion without valid monthly observation
C4	Non-water	Pixel not classified as water

C5	Not observed	No valid monthly observation
C6	Observed exclusion	Low-confidence exclusion with valid observation
C7	Non-observed exclusion	Low-confidence exclusion without valid observation
C8	Water in shadow	Water candidate affected by topographic shadow
C9	Water in slope	Water candidate located on steep terrain

Classes C1, C2 and C3 were considered preliminary water candidates for the following processing stages. Classes C8 and C9 retained information on potential water detections affected by terrain conditions and were treated as quality-control classes for later post-classification review.

3.3.3 Vectorization of preliminary water objects

After the preliminary classification, annual water candidates were converted from raster to vector objects. This step was implemented to incorporate object-level information into the post-classification process. For each year and processing grid, pixels classified as water candidates were grouped into polygons, and attributes such as annual water frequency and mean slope were calculated for each object.

A specific operational adaptation of the Chilean workflow was implemented for computationally demanding grids. Processing grids were subdivided into smaller cells or quadrants, allowing the vectorization to be exported by cell rather than as a single national or grid-level task. In highly saturated grids, where this subdivision was not sufficient to complete the process in Google Earth Engine, the vectorization was processed using the National Laboratory for High Performance Computing Chile (NLHPC) cluster, hosted by Universidad de Chile. This strategy improved processing stability while preserving the same object-based information required for the subsequent masking stage.

3.3.4 Seasonal false-positive masking

After obtaining the preliminary monthly water classification, a set of masks and post-classification rules was applied to reduce false positives and improve the spatial consistency of the monthly maps. These adjustments were especially important in Chile due to the diversity of spectral confusion sources, including topographic shadows, steep slopes, snow, bare soil, bright surfaces, vegetation, wetlands, salt flats and seasonally variable water bodies.

Unlike a fixed national mask, the Chilean workflow incorporated a seasonal adjustment of thresholds. Each processing grid was assigned to one macrozone —North, Central, South or Austral— and to a dominant hydroclimatic forcing variable, either precipitation or streamflow. Monthly climatological values of this variable were used to classify each month as dry, neutral or wet, based on the 33^{th} and 67^{th} percentiles of the seasonal curve. The masking thresholds were then adjusted according to the macrozone and seasonal condition of each month.

■ Seasonal frequency thresholds: For each macrozone and seasonal state, different thresholds were applied to evaluate whether a preliminary water detection had enough temporal consistency to be retained. These thresholds considered both the annual water frequency at the pixel level and the mean water frequency of the vectorized water object. This allowed the classification to be more conservative in arid and bright environments, while preserving recurrent detections in humid, cloudy or snow-affected areas.

■ Topographic slope and shadow: Topographic information was used to reduce false positives associated with terrain effects. The mean slope of vectorized water objects was used as part of the masking decision, while topographic shadow was incorporated as a hard exclusion criterion. An additional pixel-level slope mask derived from FABDEM could also be activated to remove detections located in steep terrain.

■ HAND mask: The Height Above Nearest Drainage (HAND) layer was used as an ancillary topographic mask to provide hydrological context during the water-mapping workflow. The layer used in this workflow corresponds to the NASA Global 30-m HAND dataset, generated by the Alaska Satellite Facility (ASF) using the Copernicus GLO-30 Public DEM. The Global 30-m HAND dataset represents the vertical distance, in meters, between each pixel and the nearest drainage network, providing near-global land coverage at 30-m spatial resolution (Donchyts et al., 2016). In the masking procedure, high HAND values were used as a strict topographic filter to remove water detections located in areas that were hydrologically unlikely to contain surface water, particularly far above the drainage network. Conversely, low HAND values were used to retain uncertain detections in low-lying areas where water occurrence was considered more plausible. This criterion was especially relevant during winter, when lower solar elevation angles increase topographic shadows, which can be spectrally confused with water.

■ Snow, brightness and soil masks: Snow was treated as a hard mask, since high snow values can be spectrally confused with water but should not be rescued by contextual rules. Brightness was included as an optional hard filter to remove bright false positives, while soil response was considered as a soft filter when activated, mainly to control confusion with bare soil or sediment-rich surfaces.

■ CSF and MNDWI: CSF and MNDWI were used to identify uncertain water detections. Low CSF consistency or low MNDWI values suggested that a preliminary water pixel could correspond to vegetation, shadow or another non-water surface. These filters were treated as soft masks, meaning that detections could still be retained when other evidence, such as HAND position or temporal frequency, supported the presence of water. Monthly values were calculated with annual fallback values in months or pixels with limited Landsat observations.

- Land-cover masks: The MapBiomas land-cover classification was used to remove detections occurring in classes with high probability of false positives, such as urban areas, non-water barren surfaces, glaciers or shrublands. At the same time, specific rescue rules were applied for classes associated with wetlands or water, avoiding the removal of valid detections in areas where the spectral response of water may be ambiguous, such as wetlands, mineral-rich water bodies or recurrent water pixels.

The masking decision followed a hierarchical logic. First, preliminary water pixels that failed hard-filter conditions were reclassified as non-water. Second, pixels affected only by soft-filter conditions were temporarily removed but could be recovered through HAND, land-cover or frequency-based rescue rules. Finally, accepted detections were preserved and exported as annual raster assets with twelve monthly bands, maintaining the monthly structure required for the subsequent gap-filling stage.

3.3.5 Gap filling and final post-processing

After the seasonal masking stage, a gap-filling procedure was applied to reduce NO-DATA areas and remaining unfilled gap classes in the monthly water series. This process used the masked annual products as input and was implemented independently for each processing grid and year.

For each target year, a five-year temporal stack was constructed using the two years before and the two years after the year of interest, with adjustments at the beginning and end of the 1998–2025 time series. Each target month was compared with neighboring monthly observations, and pixels classified as not observed or as unfilled gaps were replaced using the closest valid observations. Pixels belonging to the unfilled-gap class were not used as valid sources, avoiding the propagation of missing information.

After gap filling, additional filters were applied. A long-term water-frequency filter was calculated for the complete 1998–2025 period to remove pixels classified as water only sporadically across the time series. Manual polygons were used to eliminate known false-positive areas, while other polygons were used to protect areas where automatic filters could incorrectly remove valid water detections.

A final water-recovery step was applied in selected grids to correct remaining omissions. Two methods were implemented depending on regional conditions. The frequency-based method was used mainly in southern and austral areas with persistent cloud cover, filling non-water gaps where historical water frequency indicated permanent or highly recurrent water. The temporal-neighbor method was used mainly in central areas, filling short non-water gaps only when they were flanked by water observations on both sides of the continuous monthly series. This helped correct cloud-related gaps while preserving real drying events.

3.4 Monthly and Annual Surface Water Maps

After the gap-filling and final post-processing stages, the monthly classifications generated for each processing grid were converted into national products for publication on the MapBiomas platform. The final grid-level assets were selected according to the best available version for each grid. These grid products were then mosaicked to generate national monthly and annual maps.

For the monthly product, each year and month was processed independently. For each grid, the corresponding monthly band (w_1 to w_12) was selected, and pixels classified as water classes C1, C2 or C3 were retained as water. These grid-level detections were mosaicked into a national image. The monthly output was exported as one single-band image per month, where the pixel value corresponds to the month of detection, from 1 for January to 12 for December, while non-water areas remain masked.

For the annual product, the twelve monthly national water maps were summarized for each year. A pixel was classified as annual water when it was detected as water in at least six months of the year, equivalent to 50% of the annual monthly observations. The annual product was exported as a single multiband national image, with one band per year named classification_1998 to classification_2025. In this product, water presence is coded as value 1, while non-water areas remain masked.

Both monthly and annual products were clipped using a national land mask. An additional coastal anti-buffer was applied through a morphological erosion of the Chile land raster, reducing coastal edge artifacts caused by the interaction between land, ocean and mixed pixels. To avoid removing valid inland or transboundary water bodies, the erosion was not applied along protected terrestrial border areas with neighboring countries.

The final platform-ready products therefore consist of: monthly single-band images for the 1998–2025 period and one annual multiband image covering the same period.

4. Practical Considerations

The first collection of MapBiomas Agua Chile represents an important step toward the continuous mapping of surface-water bodies across mainland Chile. The product provides monthly and annual information for the 1998–2025 period and supports open access to spatial data for water-resource monitoring, environmental assessment, territorial planning and public decision-making.

This collection should be understood as a national-scale and dynamic product. The methodology integrates Landsat imagery, Spectral Mixture Analysis, regional classification models, seasonal masking, object-level vector information, temporal gap filling and final post-processing. However, its use must consider the limitations associated with satellite resolution, data availability and Chile’s environmental complexity.

One of the main limitations is the 30 m spatial resolution of Landsat imagery. Small ponds, narrow rivers, irrigation canals, wetland margins and mixed pixels may be underestimated or inconsistently detected. In arid zones, confusion may occur with bare soil, bright surfaces and wet sediments. In southern and austral zones, persistent cloud cover, snow, topographic shadows and steep terrain may still generate omissions or false detections.

Regional thresholds and seasonal rules improved national consistency, but they may not fully capture local variability, especially in transition areas or highly dynamic hydrological systems. Similarly, gap-filling and final water-recovery procedures improved temporal continuity, but conservative rules were applied to avoid artificially filling real drying events. As a result, short-term hydrological changes may not always be fully represented.

Future collections should focus on improving the detection of small and narrow water bodies, refining thresholds in transition zones, strengthening the treatment of snow, shadows and bright arid surfaces and reducing dependence on manual correction.

It is important for users to recognize that the application of the quantitative data presented must be accompanied by a rigorous review of accuracy levels and associated uncertainty metrics. This will allow for a more robust interpretation and an appropriate assessment of its applicability in different contexts.

All generated data are publicly available, promoting transparency and open access. This approach makes it easier for users to review the content, identify strengths, and suggest necessary adjustments. User contributions and feedback are essential to ensuring that future versions follow an iterative process of refinement and that the product remains up-to-date and relevant.

This approach to continuous improvement reinforces the developers' commitment to the quality and usefulness of the product, fostering collaboration between the scientific community and other users to maximize the positive impact of the dataset.

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