Flood Mapping Caused by Hurricane Melissa in the Middle-Lower Section of the Cauto River Using Sentinel-1 SAR Imagery

Cartografía de las inundaciones provocadas por el huracán Melissa en el tramo medio-bajo del río Cauto mediante imágenes SAR Sentinel-1

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Abstract: This study aims to map floods and temporarily induced morphological changes caused by Hurricane Melissa through the processing of Sentinel-1 SAR imagery in a remote sensing and geographic information system environment. The analyzed area encompassed the municipalities of Río Cauto, Yara, Bayamo, and Cauto Cristo (Granma Province). Two Sentinel-1A images (pre-event and post-event) were processed using SNAP software. A false-color composite was generated, applying supervised (Random Forest) and unsupervised classifications, and flooded areas were delineated using a -15 dB threshold in the VV band. Final processing was carried out in QGIS. Results showed that surface waters increased from 34.474 km² (3.23%) before the hurricane to 107.333 km² (10.07%) after the event. Flooded areas specifically attributable to Melissa reached 72.859 km², equivalent to 6.84% of the study area. The main impacts were concentrated in abandoned meanders, paleo channels, and rice cultivation zones, while the city of Río Cauto and the surroundings of the Tasajera dam recorded minimal impacts. The results reveal that the integration of Sentinel-1 imagery with open-source tools (SNAP-QGIS) represents an efficient, accurate, and low-cost methodology for rapid flood assessment in tropical contexts.

Keywords: floods, natural hazards, risk management

Resumen: El presente estudio tuvo como objetivo cartografiar las inundaciones y los cambios morfológicos inducidos temporalmente por el huracán Melissa mediante el procesamiento de imágenes SAR Sentinel-1 en un entorno de teledetección y sistemas de información geográfica. Se analizó un área comprendida entre los municipios Río Cauto, Yara, Bayamo y Cauto Cristo (provincia Granma). Se utilizaron dos imágenes Sentinel-1A (pre-evento, y post-evento) procesadas con el software SNAP. Se generó un compuesto de falso color, aplicándose clasificaciones supervisada (Random Forest) y no supervisada, y se delimitaron las áreas inundadas mediante umbral de -15 dB en la banda VV. El procesamiento final se realizó en QGIS. Los resultados indicaron que las aguas superficiales aumentaron de 34,474 km² (3,23 %) antes del huracán a 107,333 km² (10,07 %) después del evento. Las áreas inundadas específicamente por Melissa alcanzaron 72,859 km², equivalentes al 6,84 % del área de estudio. Las principales afectaciones se concentraron en meandros abandonados, paleocauces y zonas de cultivo de arroz, mientras que la ciudad de Río Cauto y las inmediaciones de la presa Tasajera registraron impactos mínimos. Se concluye que la integración de imágenes Sentinel-1 con herramientas de código abierto (SNAP-QGIS) constituye una metodología eficiente, precisa y de bajo costo para la evaluación rápida de inundaciones en contextos tropicales.

Palabras clave: inundación, amenaza natural, gestión de riesgos

1. Introduction

Climate change has increased the frequency and intensity of extreme hydrometeorological events, among which floods are one of the most devastating hazards for Caribbean's riverside communities (Cred, 2020; Sandoval-Díaz *et al.,* 2023; Donatti *et al.*, 2024; Suazo-Muñoz *et al.,* 2025; Galbán & Pérez, 2026). In this context, tropical hurricanes generate not only economic losses and infrastructure damage, but also profound alterations to fluvial dynamics, such as bank erosion, sedimentation, and lateral channel migration (Ibarra & Rodríguez, 2023; Blanco & Salvia, 2024; Wohl *et al.,* 2024; Ollero, 2025).

Due to its geographical position in the Antillean archipelago, Cuba is recurrently affected by tropical cyclones (Pérez Rodríguez *et al*., 2024; Ramos, 2025; Ruiz-Siles, 2025). Between 1851 and 2023, more than 160 cyclonic events directly impacting the national territory have been recorded (Cruz Torres *et al.,* 2025).

Although the Cuban State has developed an internationally acknowledged civil defense system, the material and environmental damage resulting from intense hurricanes continues to represent a significant challenge, particularly in Cauto River basin, the largest in the country (8,928 km²). It has historically been one of the most affected by floods because of its flat topography, alluvial soils, and the convergence of runoffs coming from Sierra Maestra (Ramón Puebla *et al.*, 2011; Sánchez *et al.*, 2013). In spite of this, previous studies in Cuba have basically used data from hydrometric stations and aerial photographs, having limitations in the spatial quantification of floods as constant tropical cloud cover prevents optical sensor's optimal use.

Hurricane Melissa, October 2025, constitutes one of the most intense cyclonic events hitting eastern Cuba in recent decades, with an accumulated rainfall exceeding 600 mm in 48 hours and flows reaching up to 1,200 m³/s in Cauto River. However, the assessments carried out to date have been fundamentally qualitative and have not managed to exactly quantify the floods' spatial extent nor the morphological changes induced in the river channel. This lack of comprehensive and quantitative studies limits the effectiveness of mitigation strategies and risk zoning in one of the country's most vulnerable basins.

The use of satellite imagery, especially from Sentinel missions of the European Space Agency's Copernicus program, has revolutionized the capacity to monitor and assess natural disasters on a global scale (Ab-Rahman *et al*., 2023; Santana-Castro *et al.,* 2025; Pech-May *et al.,* 2025). The combination of optical sensors (Sentinel-2) and synthetic aperture radar (Sentinel-1) enables to overcome the limitation posed by cloud cover, since radars operate in all weather and lighting conditions.

Several studies have demonstrated these images high precision for delineating water bodies and detecting morphological changes in river channels (Sánchez Hernández *et al.,* 2021; Sevillano Rodríguez *et al*., 2020; Blanco & Salvia, 2024). Tiampo *et al.* (2022) achieved accuracies higher than 90 % using Sentinel-1 when mapping floods caused by Hurricane Harvey, while Konapala *et al.* (2021) obtained F1-scores higher than 0.90 by combining Sentinel-1 and Sentinel-2. The quality of the information generated from these satellite sources has been widely validated, justifying its application to the Cuban context.

Furthermore, the freely distributed software SNAP (Sentinel Application Platform), developed by the European Space Agency, provides an intuitive and powerful environment for Sentinel images preprocessing (atmospheric correction with Sen2Cor, band resampling, speckle noise filtering) and supervised classification, achieving overall accuracies higher than 86% in land cover classification (Casella *et al.,* 2018; Fragoso-Campón & Quirós, 2019). Integrating SNAP with geographic information systems (GIS) provides an efficient geospatial information analysis and visualization that generate vulnerability and risk maps integrating multiple factors (Burrough & McDonnell, 2015).

The integration of these images, processed with SNAP and analyzed in a GIS setting, will allow for precise quantification of flood extent and main morphological changes, identification of geo-environmental vulnerability factors and proposition of mitigation measures based on natural solutions.

This work is aimed at analyzing Hurricane Melissa geo-environmental impact on the fluvial dynamics and flooded areas at Cauto River through the above-mentioned integration, in order to quantify the morphological changes in the channel and the floods extent, and to identify vulnerability factors that allow proposing mitigation measures in the highest-risk areas. This study addresses an immediate scientific gap and establishes a replicable methodological framework for geo-environmental risk management in other vulnerable Caribbean basins, contributing to territorial resilience in the face of climate change. In addition, it applies an affordable and low-cost procedure for rapid disaster assessment in Cuba and the Caribbean, generating updated geo-environmental risk cartography for one of the country's most vulnerable basins, and offering concrete recommendations for risk zoning and future territorial planning, particularly on paleochannels protection and productive activities regulation in low-lying areas.

2. Materials and methods

2.1. Study area

An area of 1065 km², encompassing Granma’s Río Cauto, Yara, Bayamo, and Cauto Cristo municipalities (Figure 1), was chosen to carry out the comparative analysis. This area was selected since it includes prominent anthropogenic structures: Río Cauto city, Cauto Embarcadero and Guamo Embarcadero population settlements, Tasajera dam, and Calisur shrimp farm —important areas from a social and economic perspective included within the area covered by the satellite images to be processed.

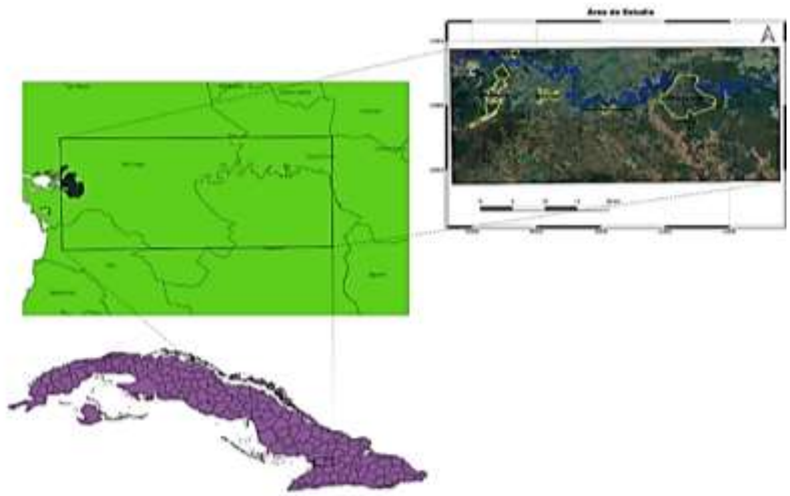

Figure 1. Geographic location map of the study area.

The research determines the flooded areas following Hurricane Melissa. For this purpose, Sentinel-1 imagery was used as they are efficient for comparative analyses of areas covered by water. The methodology employed was based on downloading and processing one image before and one after the meteorological phenomenon’s strike, offering a perspective of the areas covered by water that are perceptible with satellite images. It must be clarified that it is not possible to define with total accuracy all the flooded areas through the satellite image analysis, since there are flooded areas where water cannot be detected by the satellite (building's partial flooding and others).

Hurricane Melissa affected the study area between October 28 and 31, 2025. Therefore, images from October 27 (before) and November 2 (after) were used to carry out the comparison. These dates were chosen as they are the closest to the impact of the hurricane. Before it struck, the hydrological conditions in the region can be considered normal for that time of the year. It is not advisable to use images from later days, since surface waters are draining and the flooded areas gradually decrease.

2.2. Satellite imagery and software used

Synthetic aperture radar (SAR) images from Sentinel-1A sensor in Interferometric Wide swath (IW) mode, Ground Range Detected (GRD) product, VV and VH polarizations were used. Two scenes were selected:

- Pre-hurricane image: October 27, 2025.
(S1A_IW_GRDH_1SDV_20251027T110342_20251027T110407_061610_07B233_99BF)

-Post-hurricane image: November 2, 2025. (S1A_IW_GRDH_1SDV_20260107T110336_20260107T110401_062660_07DB12_CF41)

Both images were downloaded from Sentinel Hub platform (https://browser.dataspace.copernicus.eu/). Preprocessing, calibration, and classification were performed with SNAP software (version 10.0 from the European Space Agency, ESA). Subsequent spatial analysis, mask generation, and final mapping were carried out in QGIS 3.34.

2.3. Image preprocessing

The following processing workflow was applied in SNAP, which was developed for this study with the necessary corrections to obtain reliable data:

1. Scene cropping to the area of interest.
2. Radiometric calibration (calibration to σ^0 backscatter values).
3. Speckle noise removal using the Lee filter (5×5).
4. Geometric correction (Range-Doppler terrain correction) with the SRTM 1 arc-second digital elevation model.
5. Conversion from linear values to decibels (dB).
6. Thermal Noise Correction (to reduce discontinuities between sub-swath for multiple-swath scenes).
7. Generation of a multiband stack with the VV and VH polarizations from both dates.
8. Export of the corrected images in GeoTIFF format for analysis in QGIS (Maps and schemes were created with UTM projection zone 17N \[WGS 84]).

2.4. Methods used for flooded areas delineation

2.4.1 False Color Analysis

A false-color map was created, combining the VV bands from October 27 for red and VV from November 2 for green and blue. This combination allows for visualizing in red the areas where decibel values are high in October 27 and low in November 2 (Figure 2). Areas where values are low in both cases remain in dark color, while greenish colors are associated to areas where values are higher in November 2 image.

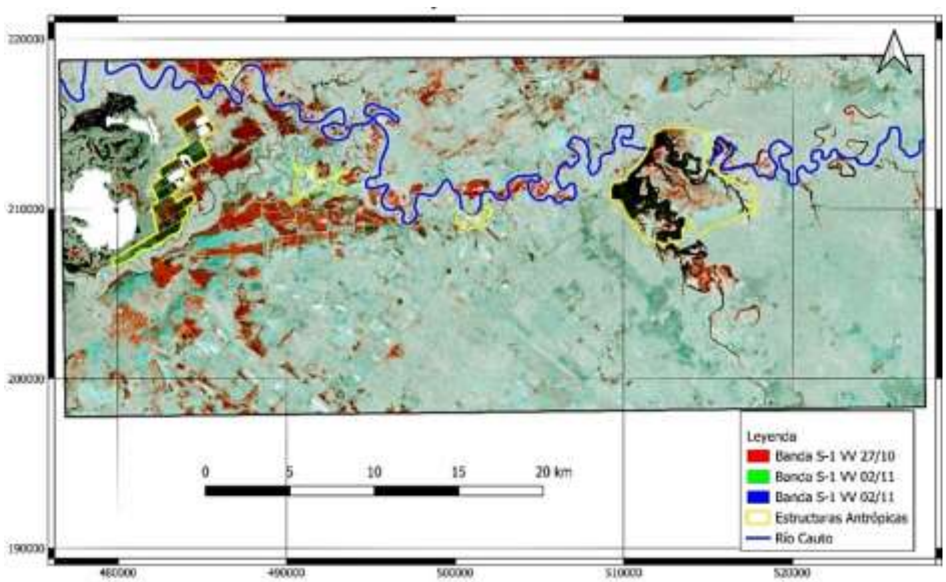

Figure 2. False Color map with bands before and after Hurricane Melissa struck.

2.4.2. Supervised and Unsupervised Classifications

A band package (VV images from both days are indistinctly combined to create a single image in an RGB composition) and a false-color scheme were created, therefore the Unsupervised Classification methods (k-means, with 5 classes)—where the SNAP software itself creates a set of differentiated classes— as well as a Supervised Classification with the Random Forest method (number of trees: 10; number of training samples: 5000) could be applied, specifically to the combination used for the false-color image creation (R: VV October 27; G: November 2; B: November 2). Some areas as croplands, surface waters, anthropogenic infrastructure, bare soils, and natural vegetation zones were manually defined (5 defined vectors, to match the quantity established for the Unsupervised Classification, with 10 samples for each type of vector).

2.4.3. Threshold segmentation

During the processing of images exported from SNAP in QGIS, three masks associated with surface waters were created from the VV bands used in the research. The first one contains the areas with surface water from October 27, the second contains the surface water from November 2, and the last one shows the difference between the previous two, therefore, it visualizes separately the areas of normal surface waters and flooded areas.

When processing S-1 VV images, the limit values range between -10 dB and -23 dB. According to Sevillano Rodríguez *et al.* (2020); Sánchez Hernández *et al.* (2021) and Blanco & Salvia (2024), the limit value to be used depends on multiple factors and varies greatly among groups of researchers. For the specific analysis, -15 dB was chosen as threshold value because it is the most suitable for the areas indicated by the Supervised Classification for zones with surface waters.

2.4.4. Flooded areas quantification

Using the area calculation tools from Zonal Statistics and Field Calculator in QGIS, the different category's extent was determined. These methods were used for quantitative determinations because the Unsupervised Classification did not provide an appropriate flooded-area differentiation. In turn, although the Supervised Classification allowed for a better classification, a sufficient number of sample zones was not available, nor was there better clarity in their definition, therefore, the margin of error is greater when focusing the procedure on threshold segmentation.

3. Analysis of results

3.1. False color analysis and classification

Figure 3 shows a close-up view of the described false-color combination for the areas of Tasajera dam and Río Cauto city, along with the Shrimp Farm. The areas linked to surface waters, after Hurricane Melissa hit the area, are highlighted in red.

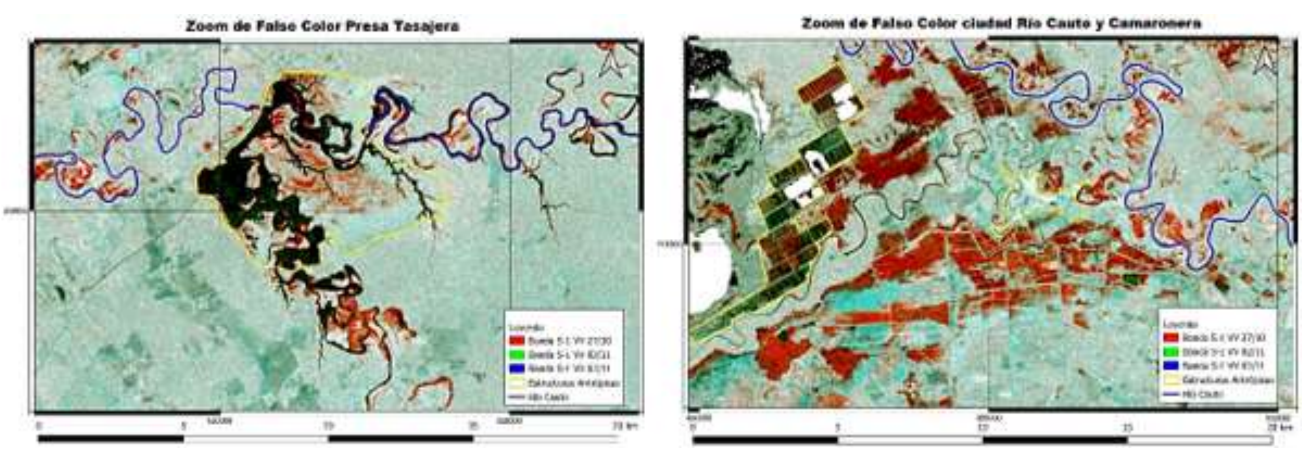

Figure 3. Zoom of the False Color for the areas of Tasajera dam and Río Cauto city.

Figure 4 shows the results obtained from the Supervised Classification — in more detail than those generated by the Unsupervised Classification. Though the Unsupervised Classification (Figure 4c) generates a class that includes possible surface water areas, the Supervised Classification generates a division of classes within the surface waters themselves (Figure 4d), defining lower values, with a smoother surface, from other possible surface waters with low but higher values than those mentioned, possibly associated to waters with a less smooth dispersion surface, probably linked to runoff waters still active days after the hurricane.

Figure 4 shows a flooded area in the zone of an abandoned meander—dry before the cyclone (Figure 4a) and with accumulated water after it (Figure 4b)— at Cauto River. There is also observed the differentiation between the Unsupervised Classification (Figure 4c), where surface water areas are shown in red; and the Supervised Classification (Figure 4d), where there is a distinction between blue surface waters and other zones associated with them, which are possibly runoff waters, but have different characteristics and behaviors (red color) also due to their shallowness.

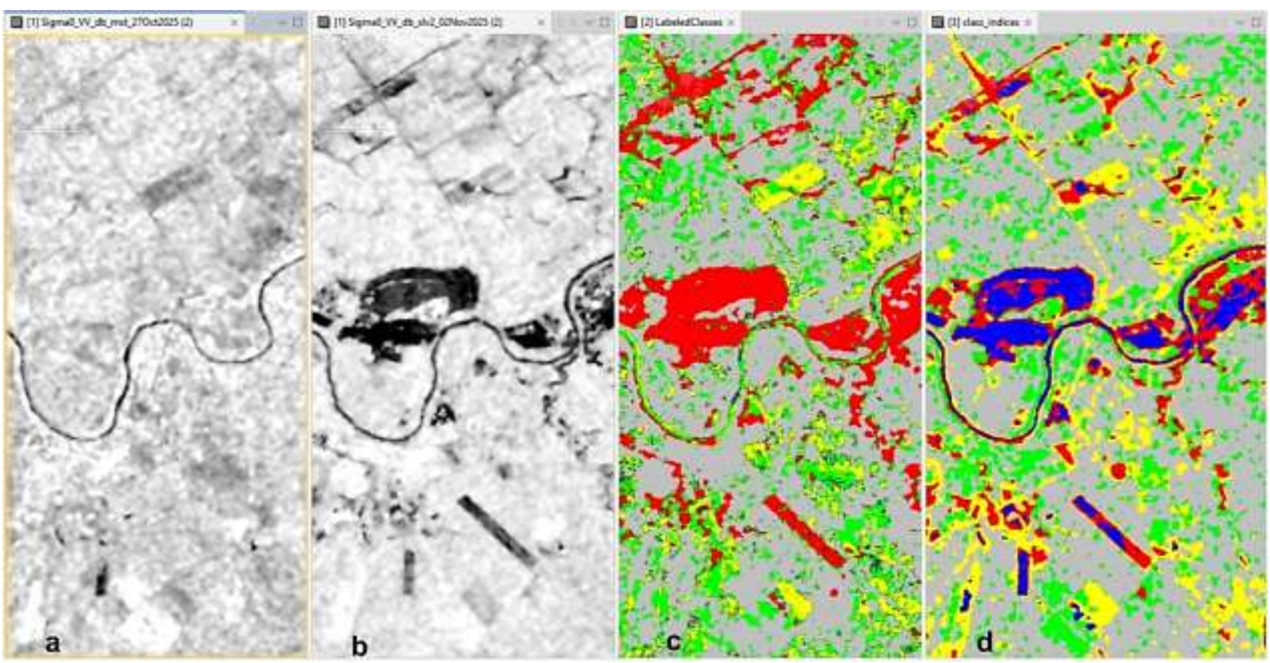

Figure 4. Images comparison in SNAP with classifications for an abandoned meander. a) Before the hurricane (VV October 27). b) After the hurricane (VV November 2). c) Unsupervised Classification. d) Supervised Classification.

Figure 5 shows an analysis for zones around Tasajera dam. Areas with surface waters before the hurricane (Figure 5a), areas with surface waters after it (Figure 5b), as well as the Unsupervised Classification image (Figure 5c) and Supervised Classification with Random Forest (Figure 5d) are visualized.

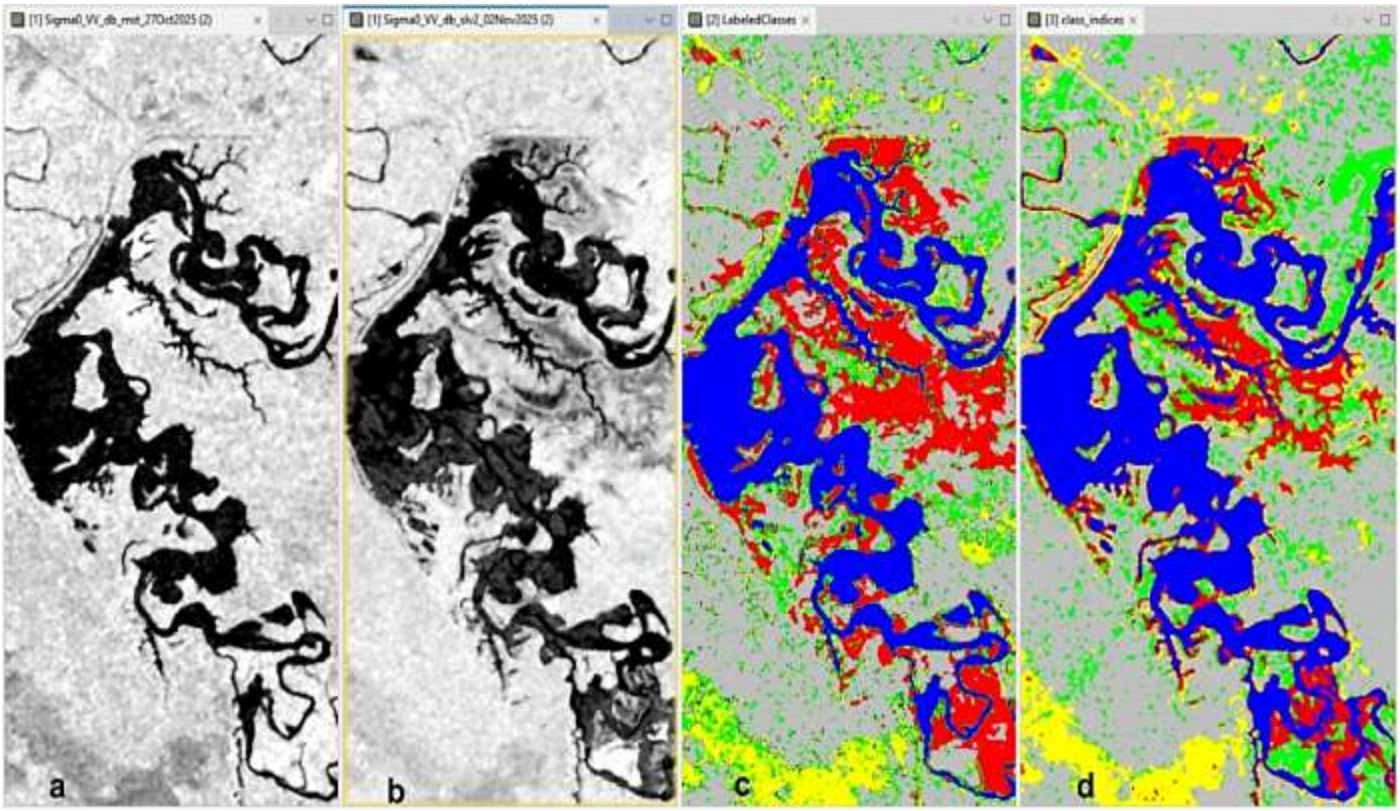

Figure 5. Comparison of images in SNAP with classifications for Tasajera dam. a) Before the hurricane (VV October 27). b) After the hurricane (VV November 2). c) Unsupervised Classification. d) Supervised Classification.

Figure 5 highlights the areas where the Unsupervised Classification only generates one class (red color), while the Supervised Classification does discriminate at least two different classes by their characteristics (blue and red). In this case, it can be appreciated there are zones considered as surface water areas by Supervised Classification but not by the Unsupervised Classification, allowing for a more precise delineation of flooded areas.

3.2. Flooded area delineation

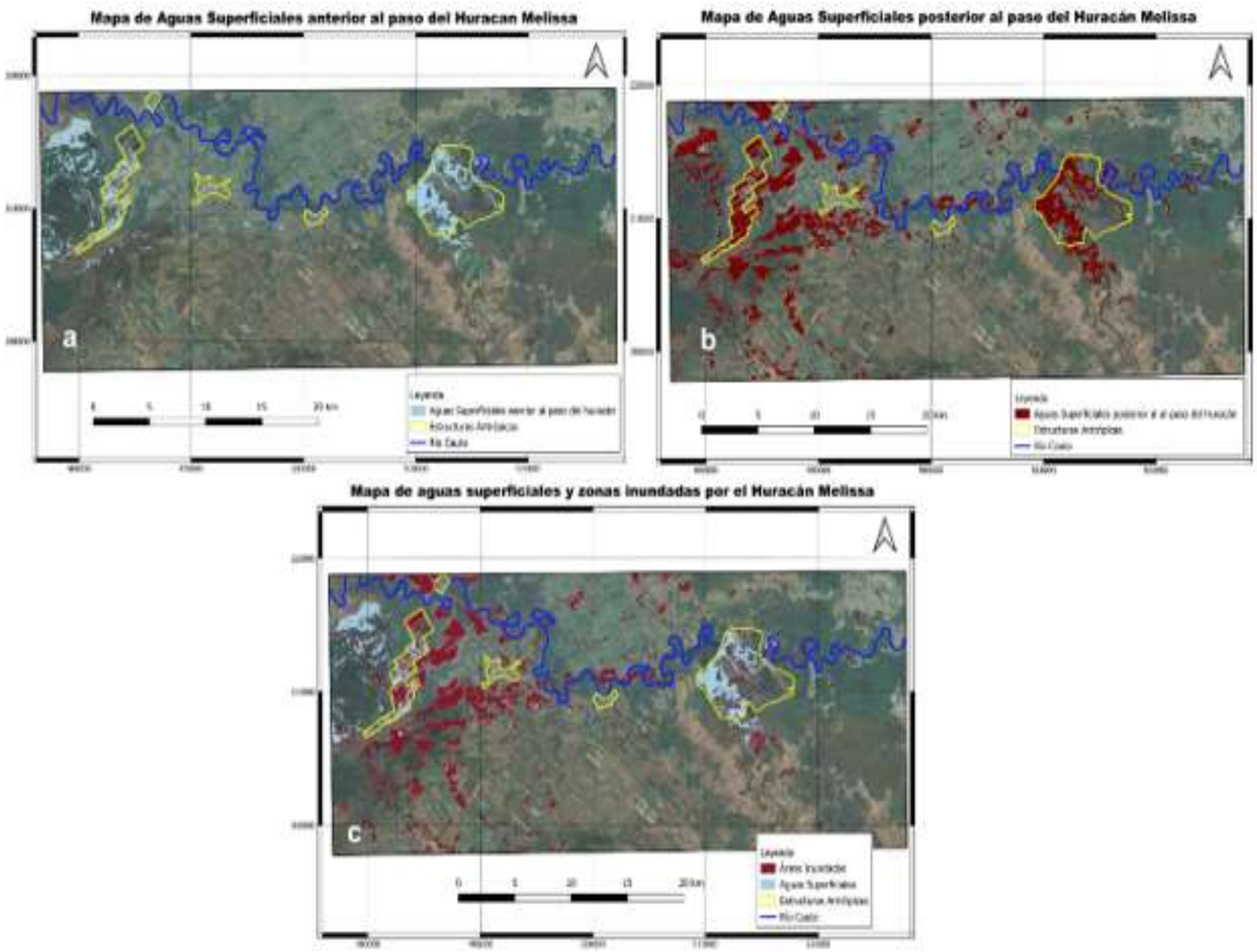

Figure 6. Surface water maps in the study area. a) Surface waters before the hurricane. b) Surface waters after the hurricane. c) Surface waters and floodwaters.

Figure 6 shows the areas where surface waters coincide before and after Hurricane Melissa. Those where there was no water before and accumulations occurred, after the intense rains, are observed.

The mask showing surface waters and floodwaters was reclassified to generate a new mask showing only the areas flooded by Hurricane Melissa (Figure 7).

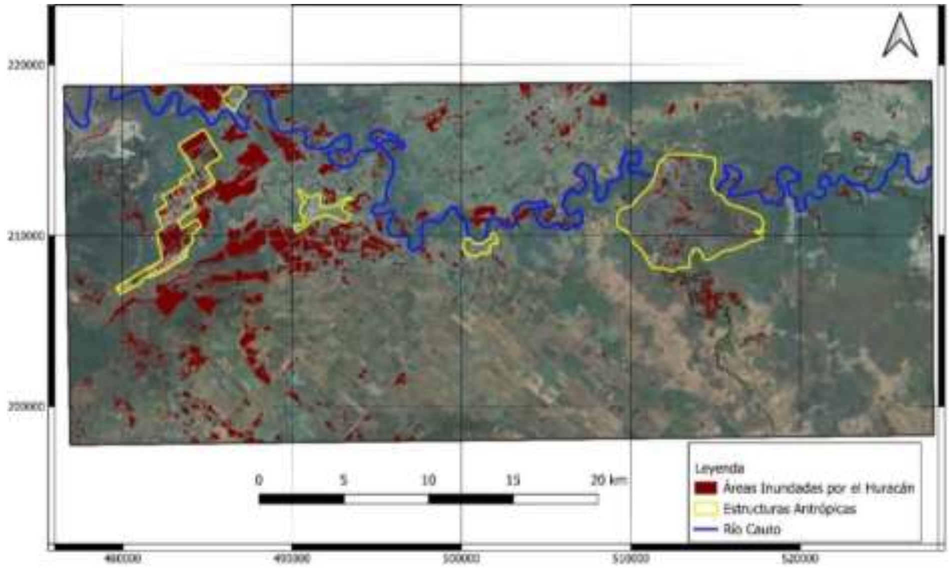

Figure 7. Maps of flooded areas after Hurricane Melissa.

Once a map showing the flooded areas has been created, it is possible to zoom in on the areas of greatest interest in order to show the most significant flood impacts (Figure 8).

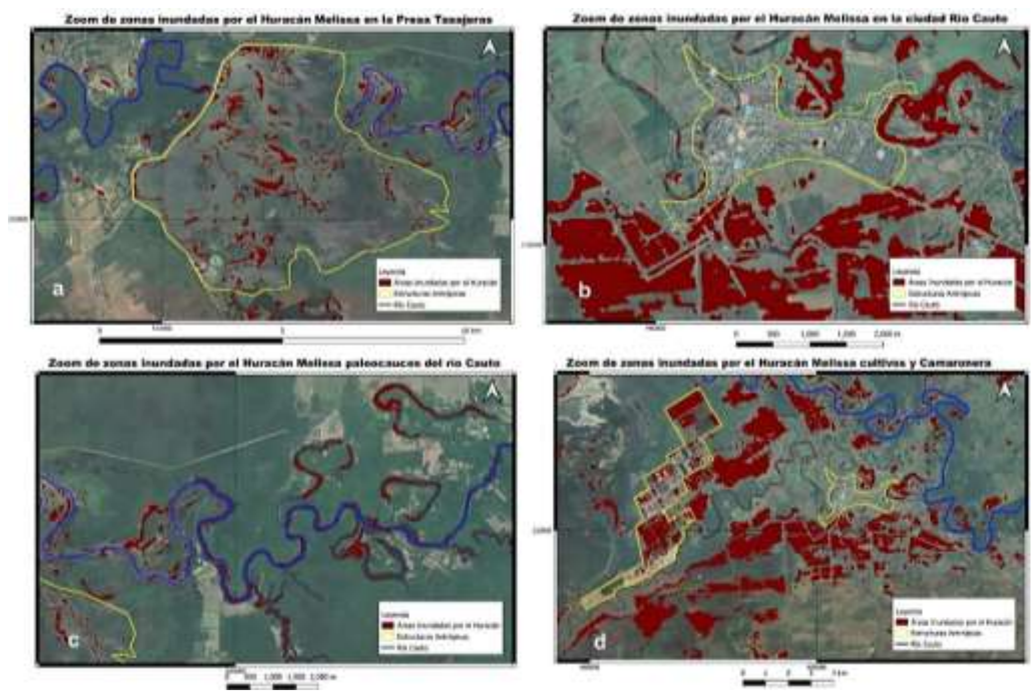

Figure 8. Zoom of areas linked to flooding. a) Tasajera dam. b) Río Cauto city. c) Abandoned meanders. d) City, Calisur shrimp farm, and rice cultivation areas.

Tasajera dam surrounding area does not show considerable floods (Figure 8a), which is evidence of the correct work carried out by the operating personnel, who had defined the amounts of water the dam could contain and, therefore, were prepared to face the strike of the hurricane.

Figure 8b shows how Río Cauto city did not suffer too many impacts in terms of flooding associated to the hurricane’s intense rain. The surroundings of the city do show large extensions of flooded areas, essentially crop fields and abandoned meanders at the former Cauto River channel.

In Figure 8c, an area with a predominance of abandoned meanders from Cauto River that accumulated water again is observed. However, the floods did not extend too far outside these old channels, hence the simple delineation of the flooded areas.

Figure 8d shows a wider view of Río Cauto city, Calisur shrimp farm, and the south of both rice cultivation areas. These latter tend to be low and, in many times of the year, are covered by water. Therefore, they are favorable areas for flooding with not too negative impact, depending on the stages of the crop. Anthropogenic activity is noted in these flooded zones, where straight linear patterns and regular areas are evident in the flooded zones, associated with crop fields boundaries and the shrimp farm. However, in the central and the southwestern part of this area more irregular areas appear in the flooded zones.

Attention should be paid to the areas near the Shrimp farm, as they are more prone to flooding. It is vital to map Cauto River’s abandoned meanders and paleochannels, since they are flood-prone areas. These are aspects to consider in future construction projects in pursuit of anthropogenic activity growth in the region.

3.3. Flooded areas quantification

As shown in table 1, only the 6,84 % of the total area was affected by floods resulting from Hurricane Melissa.

Table 1. Surface Waters extent in the study area

Elements	Area (Km^2)	Percentage (%)
Study area	1065.89	100
Surface waters before the hurricane	34.47	3.23
Surface waters after the hurricane	107.33	10.07
Floodwaters	72.86	6.84

In spite of the intense rains associated to this hurricane's magnitude, the main socio-economic affectations declared by the authorities the territory were not directly related to floods but to other factors such as landslides, high winds and runoff waters.

4. Conclusions

The integration of Sentinel-1 SAR imagery, processed with SNAP software and analyzed in QGIS, was proven effective for quantitative and spatial assessment of floods caused by Hurricane Melissa in Cauto River's medium-lower section (October 2025). The applied methodology coped with traditional limitations associated to tropical cloud cover and generated highly reliable information in a reduced amount of time.

Within the 1 065,893 km² study area, it was quantified an increase of surface waters from 34.474 km² (3.23 %) before the hurricane to 107.333 km² (10.07 %) after it. Flooded areas specifically due to the impact of Melissa reached 72.859 km², equivalent to 6.84 % of the whole analyzed area. These results confirm the stated hypothesis and validate the usability of Sentine-1 images for flooded area precise delineation and morphological change identification in fluvial channels.

The main impacts were concentrated in abandoned meanders, paleochannels form the former Cauto River, as well as low-lying zones used for rice cultivation and Calisur Shrimp farm's surroundings. Meanwhile, Río Cauto city and Tasajera dam's surroundings recorded minimal impacts, demonstrating the effectiveness of the hydraulic managing measures implemented at the dam. The Supervised Classification with Random Forest evidenced a greater precision and detail than the Unsupervised Classification, making possible to discriminate among different types of water bodies and to refine flooded area mapping.

From the geo-environmental point of view, the results demonstrate the high vulnerability of the paleochannels and the flood plains from Cauto River basin in front of extreme hydrometeorological events, which intensifies with climate change. Anthropogenic activity (straight linear patterns in crop fields and shrimp farms) models floods distribution, generating risks as well as management opportunities.

The integration of SAR remote sensing and open-source tools (SNAP-QGIS) consolidates as a powerful and reliable tool for geo-environmental risk management in tropical contexts. The results obtained strengthen the county’s capacity to respond to climate change and proves Geological Engineering ‘s relevance for building more resilient territories.

5. Recommendations

To incorporate food maps within territorial land development and civil defense plans in the involved municipalities, as well as to keep the systematical monitoring through Sentinel-1 to update risk mapping in the face of future weather events.

To implement continuous monitoring systems based on SAR imagery that enable the detection, in real time, of flooded area's expansion and to support decision making in emergency situations, especially during the hurricane period.

To strengthen risk management in agricultural zones by planning flood-resistant crops in low terraces and paleochannels, and adopting sustainable management practices in flood-prone areas.

To develop community contingency plans that include evacuation and infrastructure protection protocols, especially in localities near Cauto River and Tasajera dam, as well as areas identified as highly vulnerable.

To update flood risk maps from the National Hydraulic Resources Institute, incorporating detailed mapping of paleochannels and abandoned meanders (scale1:25 000 or higher), because these geomorphologic elements proved to be the first ones reactivated during Melissa.

To assess the impacts of existing dams and hydraulic works on floods dynamics, considering the possibility of creating areas for controlled overflooding in order to reduce pressure on the main channel during extreme weather events.

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