Lessonia-1 SAR time-series for identifying flooded areas

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Abstract

The catastrophic floods that hit Rio Grande do Sul, Brazil, in May 2024 underscored the urgent necessity for sophisticated flood monitoring and management methods. Notably, Synthetic Aperture Radar (SAR) satellite imagery has proven to be an essential resource for detecting flooded regions and evaluating the extent of flooding, even in challenging weather conditions. The Lessonia-1 SAR project represents a significant advancement in Brazil’s technological capabilities, particularly in enhancing flood management. By providing continuous and precise imagery monitoring, it plays a crucial role in mitigating flood risks. During heavy rains in the southern Brazilian State of Rio Grande do Sul, the Space Operations Center (COPE) was tasked to acquire imagery from Lessonia-1 SAR to support operations aimed at mitigating the impact on residents' lives. The purpose of this study is to assess the feasibility of utilizing Lessonia-1 SAR imagery, operating at X band with VV polarization, using a time-series approach for identifying flooded areas. The results demonstrate that utilizing imagery from October 2022 (before) and May 2024 (after) with normalization between both images enables the identification of flooded areas of interest. Additionally, the study employs false-color composition (R:after, G:before and B:normalization) to visualize the flooding curve in blue.

1. INTRODUCTION

The devastating floods that struck the State of Rio Grande do Sul, Brazil, in May 2024 underscored the urgent need for advanced flood monitoring and management techniques. This necessity is further emphasized by the recurrence of such events, as seen with the floods that occurred in September 2023 (Alvalá et al., 2024).

Among these, the use of Synthetic Aperture Radar (SAR) satellite imagery has emerged as a crucial tool for identifying flooded areas and assessing the extent of inundation, even under adverse weather conditions (Zhao et al., 2022).

In the context of these floods, Brazilian SAR satellites, launched under the Strategic Space Systems Program (PESE) and known as Lessonia, have played a key role (Defesa, 2018). These satellites allow for the precise mapping of flooded areas, enabling rapid and effective assessments of the impacts of flooding, particularly in critical regions, such as those around the city of Porto Alegre, in the state of Rio Grande do Sul, where flooding caused significant socioeconomic disruption.

The use of SAR radar imagery can help researchers and disaster management authorities better understand flood dynamics, improve predictive models and implement more effective mitigation strategies. This technological advancement represents a milestone in environmental monitoring in Brazil, while also strengthening the country’s ability to respond to natural disasters (Mason et al., 2015; Mehravar et al., 2023; Riyanto et al., 2022).

1.1 The Lessônia-1 SAR Project

The Lessonia satellite family is part of the PESE and includes radar remote sensing satellites (SAR) designed for various civil and military applications such as: border monitoring, drug trafficking, mining and burning, deforestation, illegal fishing, among other national security activities. The first satellites launched under this project, Carcará I and Carcará II, were developed by the Finnish company Iceye (Ignatenko et al., 2020). These satellites were launched by SpaceX using the Falcon 9 rocket from the Kennedy Space Center in Cape Canaveral, Florida, USA.

Designed to provide high-resolution images under any weather condition, day or night, they are crucial for monitoring natural disasters, environmental surveillance, and public safety. The satellites are particularly useful for observing areas such as the Amazon, where cloud cover can hinder observation with optical satellites.

They support different imaging modes, such as Spot, StripMap, and Scan, each tailored to specific observation needs. The satellite is in low orbit, operating in the X-band, with VV polarization, the Lessonia satellites offer high-resolution images, with a spatial resolution of up to 1 meter in Spot mode, 3 meter in Strip mode and 15 meter in Scam mode. With a temporal resolution of 3 days with two satellites, Lessonia can frequently revisit and monitor areas of interest. Having its performance verified through the Iceye company in the report calibration (Lamentowski et al., 2022).

1.2 The Flood Event

In May 2024, the State of Rio Grande do Sul faced catastrophic floods due to relentless rainfall that began in late April. The Guaíba River, surrounding Porto Alegre, reached historic levels, causing widespread destruction and affecting over 2 million people. The floods resulted in significant infrastructure damage, including the destruction of bridges, roads, and buildings, and with 149 deaths and 108 missing people as of May 15, 2024. Over 870 municipalities are identified as risk zones, with approximately 18% of the population in these areas (Martins-Filho et al., 2024).

According to the EMATER report (Leite et al., 2024), 456 municipalities were affected, with 78 in a state of public calamity and 340 in a state of emergency. The heavy rains caused significant damage to rural infrastructure, including roads, buildings and water supplies, in addition to substantial losses in agricultural production, such as grains, fruits and vegetables. Livestock production was also severely impacted, with the death of thousands of animals and losses in dairy production. In addition to the immediate damage, the report highlights soil erosion and contamination of water sources, affecting the fertility and quality of water resources.

The use of SAR satellite systems proved crucial in these efforts, as they provided high-resolution images regardless of weather conditions, enabling the mapping of flooded areas and aiding in resource allocation. These events underscored the urgent need for improved flood management and preparedness strategies to mitigate the impact of such extreme weather events in the future (Júnior et al., 2021; Mehravar et al., 2023).

2. METHODOLOGY

Two SAR radar images from the Lessônia satellite were used to analyze the flooded area. The images, captured at different times, allowed the detection of the flooded area that occurred after the heavy rains that began between May 10 and 11, 2024. The methodology employed involved pre-processing the images for geometric correction and attenuation of the speckle effect, followed by the application of supervised classification techniques to identify and quantify the changes that occurred.

2.1 Study Area

This work utilized imagery from October 11, 2022 (before of the flood event) and May 18, 2024 (after of the flood event), made in Scam SAR mode and its position can be seen on the situation map shown in Figure 01, at a scale of 1:25,000,000. These images were obtained around the city of Porto Alegre, state of Rio Grande do Sul, which was severely hit by the floods.

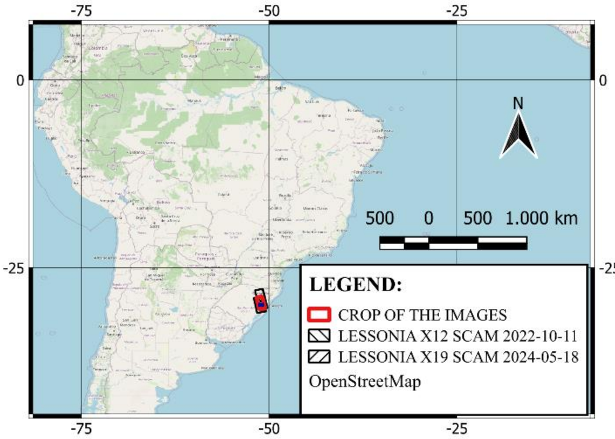

Figure 1. Situation map of the Lessônia images in Scam SAR mode at a scale of 1:25,000,000.

To enable identification of the flooded areas of interest, the study uses false-color composition. To do this, it was necessary to construct a third band with a normalization between these two images and place it in the blue band (R: after, G: before and B: normalization) to highlight the flooded area, as can be seen in the legend of Figure 2. In band 1 the before image was placed, in band 2 the after image and in band 3 the normalized image.

Figure 2 shows a situation map with the position of the two images of Lessônia. The situation map shows the overlap between these two images, which is highlighted in red. Both images were cropped and, finally, the image of the area of interest was cropped again, forming the image that was used in this work, as can be seen in the situation map, at a scale of 1:5,000,000.

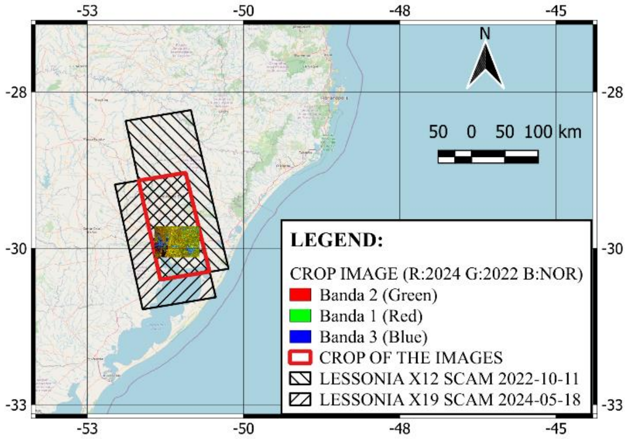

Figure 2. Situation map with Crop of the Lessônia images in the study area in Scam SAR mode at a scale of 1:5,000,000.

2.2 Data Source

Figure 3 shows a section of the image taken before the event, obtained on October 11, 2022. In this radar image, it can be seen that the areas where the surface is water, i.e. rivers and lakes, the image appears black. This occurs because in these areas there is low roughness in relation to the radar wavelength, resulting in a specular reflection, not returning electromagnetic energy to the sensor.

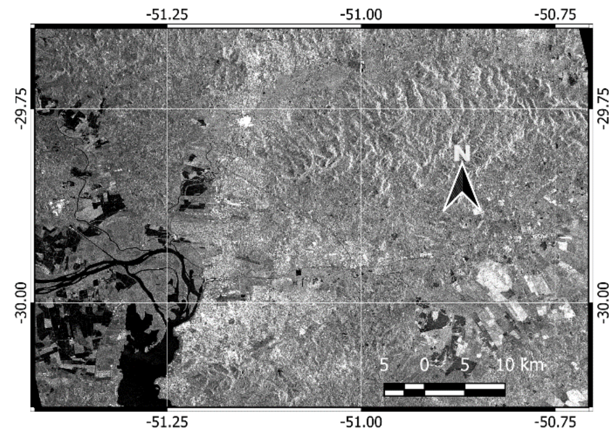

Figure 3. Crop of the Lessônia image obtained on October 11, 2022, in Scam SAR mode, at a scale of 1:400,000.

Similarly, the areas where there was flooding can be seen in black in the image obtained on May 18, 2024, as shown in Figure 04. In this image, it is possible to observe the overflow of the Jacuí River in the lower left corner, the Caí River towards the upper left corner, the Sinos River towards the upper right corner, flooding of the Salgado Filho International Airport near the city of Porto Alegre and some plantation areas in the lower right corner.

In Figure 04, it can be observed that no dark areas are observed in urban spots; on the contrary, flooded urban areas appear in the image in light tones. This is due to corner reflection, which occurs when the signal encounters water near walls and roofs, and is reflected and returned with great intensity in the direction of the sensor, also known as "double bounce" (Zhao et al., 2022).

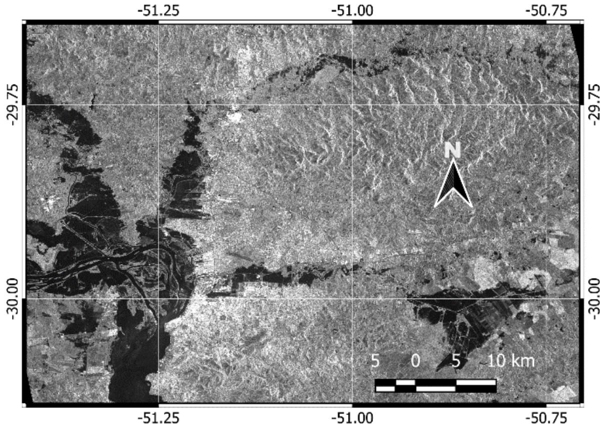

Figure 4. Crop of the Lessônia image obtained on May 18, 2024, in Scam SAR mode, at a scale of 1:400,000.

2.3 Softwares

To carry out the work, specialized software was used for the different stages of data processing and analysis. First, the SNAP software was used for radiometric calibration of the images, ensuring the accuracy of the backscatter values. In addition, SNAP was used to remove speckle using specific filters, orthorectify the images for geometric correction, co-register the images for precise alignment, crop the area of interest and apply band mathematics to generate a normalized band.

Next, the ENVI software was used to classify the flood area. This software allowed the application of advanced supervised classification algorithms, facilitating the identification and delimitation of the areas affected by the floods. ENVI's ability to handle large volumes of data and its intuitive interface were essential for analyzing the images.

Finally, QGIS was used to edit and analyze the resulting geospatial data. This open-source software provided robust tools for data visualization, manipulation and analysis, allowing the creation of thematic maps and spatial analyses. The integration of the results obtained with other software in QGIS enabled an efficient approach to data interpretation and the generation of final products presented in this article.

3. RESULTS

The results section will present the findings obtained from the analysis of SAR radar images from the Lessônia satellite. First, band mathematics was used to perform normalization between the images captured before and after the flood event. This process allowed for direct comparison of the images, highlighting the changes that occurred in the study area and facilitating the identification of the regions affected by the flood.

Next, the bands were stacked to compose a false-color image. This image was composed of the bands from the previous and subsequent images and the normalized band, providing a clear and intuitive visualization of the changes in land cover. The use of false-color composition was essential to highlight the flooded areas and other significant changes in the terrain.

Finally, the extraction of flood area vectors was performed to obtain an accurate and detailed representation of the affected regions. This process involved the application of classification and segmentation techniques to the false-color images, resulting in vectors that delineate the flooded areas. These vectors were subsequently analyzed and integrated into geographic information systems (GIS) for a better understanding and management of the impacts of the flood.

3.1 Normalization by band mathematics

To highlight the flooded areas, a third band was created using the normalized difference between two images captured before and after the flood event. This process is similar to that used to calculate indexes such as the Normalized Difference Scattering Index (NDSI) and the Normalized Difference Vegetation Index (NDVI), where the difference and sum of the two images are used to generate a new image. The mathematical formula used for this calculation is presented in Formula 1 (Bayma and Sano, 2015; Ulloa et al., 2020).

$$X_{(l,c)} = \frac{B_{(l,c)} - A_{(l,c)}}{B_{(l,c)} + A_{(l,c)}}, \quad (1)$$

where $B_{(l,c)}$ = Before Image
$A_{(l,c)}$ = After Image
$X_{(l,c)}$ = Normalized Image

This formula allows the detection of changes between the two images. The image resulting from this process, which highlights the areas affected by the flood, is illustrated in Figure 05. However, the image generated from the normalized difference may contain noise that makes it difficult to accurately identify the flooded areas.

To improve the image quality and better highlight the flooded areas, a filter was applied to the histogram of the resulting image. This filter adjusted the range of values of the image, using a minimum threshold of 0.4 and a maximum threshold of 0.65, which helped to reduce noise and highlight the flood curve in the areas of interest.

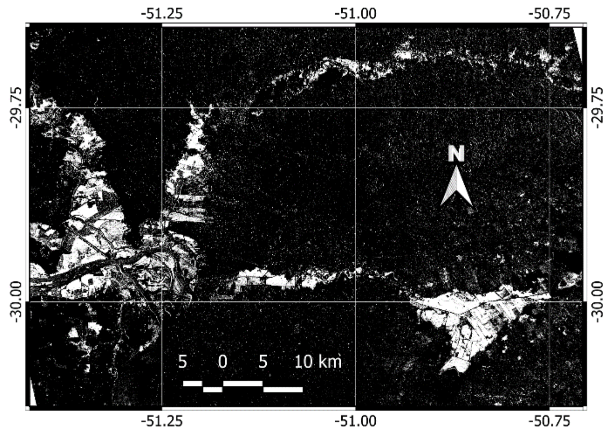

Figure 5. Normalization between the Images of October 11, 2022 and May 18, 2024.

3.2 False-color composition of the bands

To provide false-color composition of the bands, the three images were radiometrically calibrated, subjected to Speckle filtering, coregistered, and geometrically corrected for terrain using the free software SNAP from the European Space Agency (ESA). These steps ensure the accuracy and quality of the data, allowing for more reliable and detailed analyses.

To highlight the flooded areas, the false-color image was stacked by placing the image after the flood event in the red band; the image before the flood event in the green band; and the normalized image in the blue band (R:after, G:before and B:normalization). This resulted in the image shown in Figure 6, where the flooded areas can be seen in shades of blue.

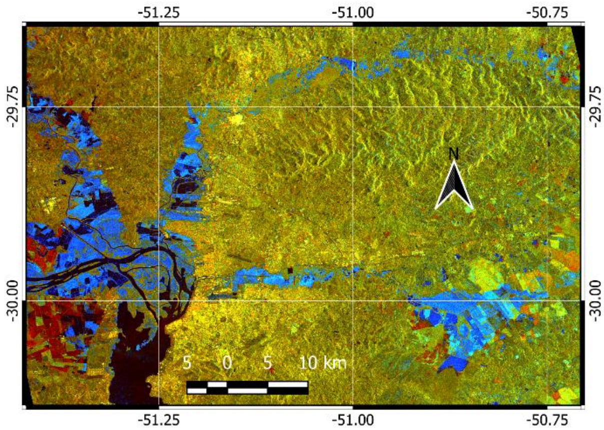

Figure 6. False-color composition (R:after, G:before and B:normalization).

It can be seen that some areas of this image have a reddish colour, this occurred in areas that were flooded before the flood event and after the flood event were no longer flooded. This probably occurred because this area is usually used for planting rice, where at the beginning of the planting it is necessary to flood the region where this crop is planted and probably after the flood these areas were not at the beginning of the planting of this crop.

3.3 Flood Curve Classification

The polygons of affected areas were obtained through supervised classification using the parallelepiped method of the ENVI software. For this classification, four distinct classes were created: "flooded area", "City", "previous rice plantation area not flooded" and "Vegetation".

The image used for this analysis was a false-color composite, generated with the three bands previously described. For the purposes of this work, only the flooded area class was used in contrast to the unaffected areas, as can be seen in Figure 7.

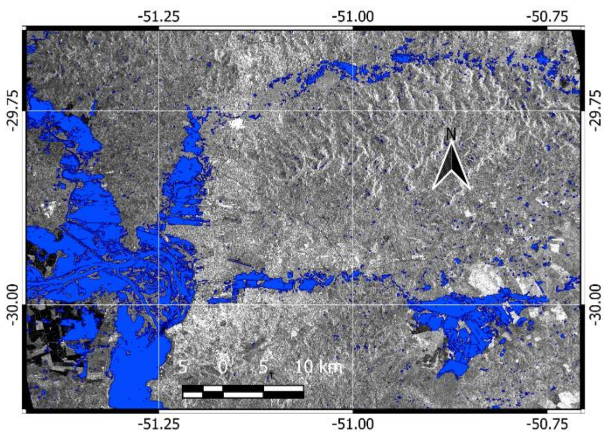

Figure 7. Flood curve classification map shown in blue, with the Lessônia SAR radar image in the background.

To facilitate visual identification of the affected areas, Figure 8 shows a specific section of the Salgado Filho International Airport area. In this section, it is possible to clearly see the region that was covered by water during the flood event. The use of the OpenStreetMap map in the background allows the areas affected by the flood to be highlighted in blue, providing a detailed analysis of the extent of the flooding in this critical region.

In addition, this map background serves as a spatial reference, allowing a better understanding of the location and extent of the areas affected by the flood in relation to the urban context. Using OpenStreetMap as a base facilitates the visualization and interpretation of the classification results.

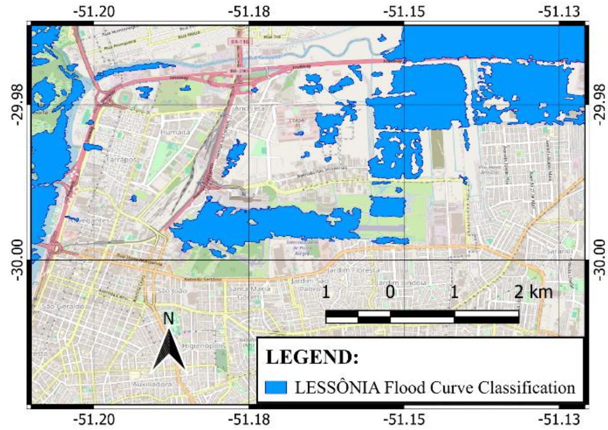

Figure 8. Map with flood curve classification in the Salgado Filho International Airport near the city of Porto Alegre-RS.

The integration of flood information with the OpenStreetMap base not only helps in visualizing the data, but also in making decisions in emergency situations more accurate. This combination of data allows for the rapid identification of areas at greatest risk and can assist in response and damage mitigation actions, highlighting the importance of geoprocessing tools in the monitoring and management of natural disasters.

3.4 Qualitative Assessment with Google Earth Engine (GEE)

To evaluate the proposed approach, it will be used Google Earth Engine (GEE). GEE is a powerful cloud-based platform designed for planetary-scale analysis of Earth science data. It combines a vast catalog of satellite imagery and geospatial datasets with advanced computational capabilities, enabling scientists, researchers, and developers to detect changes, map trends, and quantify differences on the Earth's surface, Figure 9 shows the Google Earth Engine interface (Gorelick et al., 2017; Liang et al., 2023; Mullissa et al., 2021).

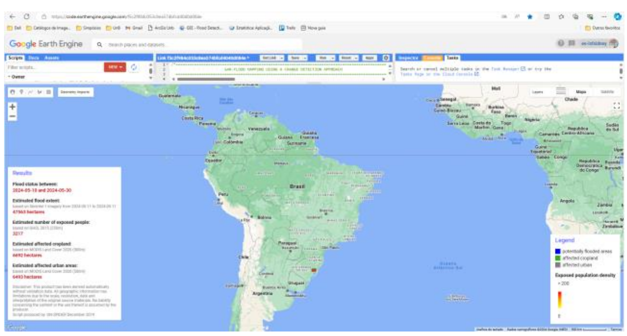

Figure 9. Interface of Google Earth Engine (GEE).

Google Earth Engine supports a wide range of applications, from environmental monitoring and disaster response to urban planning and climate change studies. Its user-friendly interface and robust API make it accessible for both beginners and experienced users, facilitating the rapid development and deployment of geospatial analysis workflows (Gorelick et al., 2017; Liang et al., 2023; Mullissa et al., 2021).

The script titled "SAR-flood mapping using a change detection approach" utilizes Sentinel-1 SAR imagery to generate a flood extent map. This approach involves comparing images captured before and after a flood event to detect changes. The Sentinel-1 GRD (Ground Range Detected) imagery undergoes several preprocessing steps, including thermal-noise removal, radiometric calibration, and terrain correction (Ali et al., 2018; Notti et al., 2018; Soille and Marchetti, 2017).

Following these steps, a speckle filter is applied to reduce noise and enhance image quality. This method allows for precise identification of flooded areas, providing valuable data for disaster management and mitigation efforts, Figure 10 shows the result of this script (Ali et al., 2018; Notti et al., 2018; Soille and Marchetti, 2017).

As can be seen in Figure 10, the algorithm presents the flood curve for the May 2024 flood period, with an approximate indication of the affected urban population and the affected plantation area. This visualization allows a clear understanding of the impact of the flood event, highlighting the most severely affected regions and facilitating decision-making for mitigation and recovery actions.

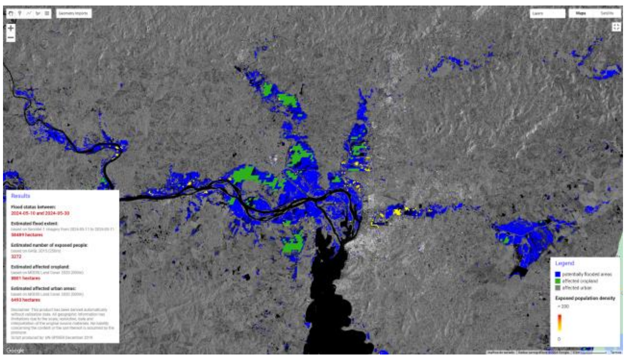

Figure 10. Interface of the script titled "SAR-flood mapping using a change detection approach" that use Sentinel-1 SAR imagery to generate a flood extent map.

The Landsat 8 satellite, equipped with the OLI (Operational Land Imager) sensor, is an advanced Earth observation platform that captures high-resolution images in several spectral bands, from visible to infrared. Launched in 2013, OLI allows the monitoring of several features of the Earth's surface, such as bodies of water, urban areas and environmental changes. Its images are essential for studies on land use and occupation, and for monitoring natural disasters such as the one that occurred in Rio Grande do Sul.

Figure 11 shows the image captured by the OLI (Operational Land Imager) on board the Landsat 8 satellite, dated May 8, 2024. In this image, it is possible to visualize the extent of the area affected by the flooding, clearly highlighting the submerged regions. The image provides a detailed view of the extent of the impact of the floods, highlighting the flooded areas and allowing a precise analysis of the affected regions. This image can be obtained from the NASA website (Levy and Przyborski, 2024).

Figure 11. Image from the OLI (Operational Land Imager) aboard the Landsat 8 satellite, dated May 8, 2024.

Figure 12 shows a Google Earth Pro image from June 2024, which shows the scar left by the flood in the region. Through this image and the Landsat 8 image, it is possible to observe in detail the extent of the affected area, which reached the Salgado Filho airport, one of the critical infrastructures in the Porto Alegre region.

Using the tools available in Google Earth Pro, it was possible to calculate the total area of the flood that hit the airport, estimating that approximately 2.7 km² were covered by the waters. This calculation is essential to assess the dimensions of the damage caused and to compare the flood area estimated by the Google EAR Engine (GEE) and the area calculated from the Lessônia images using the ENVI image processing software.

Figure 12. Approximate area of Salgado Filho Airport affected by flooding.

The analysis of the images obtained by the Lessonia satellite, processed and classified using the ENVI software, allowed us to calculate the area affected by the flooding at Salgado Filho airport, totaling 1.41 km². This process involved the application of advanced image classification techniques to accurately identify the flooded areas, providing a detailed view of the damage to the airport infrastructure. However, when comparing this value with the approximate estimate of 2.7 km² for the affected area, it was observed that the classification using the Lessonia images was closer to reality.

On the other hand, the verification carried out with Google Earth Engine indicated that the area of the airport affected was only 0.17 km². This estimate was significantly smaller than the approximate value of 2.7 km². Thus, the classification based on the Lessonia images proved to be more accurate than that carried out with Google Earth Engine for this specific case. The two classified areas can be seen in Figure 13, where the differences in the delimitations of the flooded areas are clearly shown.

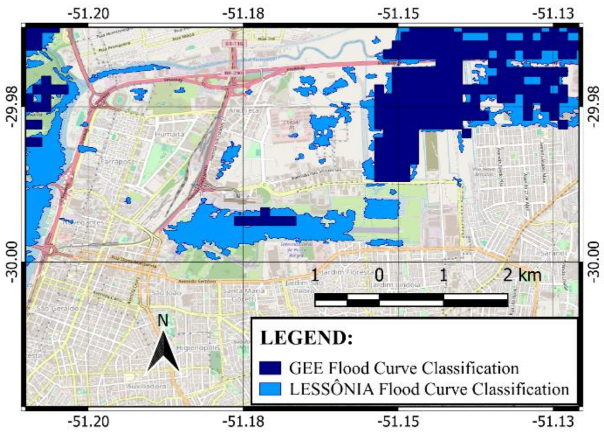

Figure 13. Comparison between the flood curves generated by Google Earth Engine (GGE) and the flood curve generated by ENVI with the Lessônia images.

Considering the flood area in the airport using the optical images from Landsat 8 and Google Earth Pro, shown in Figures 11 and 12, as ground truth, the analysis revealed that the classification performed with the Lessonia images, processed in the ENVI software, achieved an accuracy of 52%. In contrast, the classification performed in Google Earth Engine using the Sentinel-1 images had a significantly lower accuracy, with only 6% accuracy.

These results highlight the superiority of the classification based on the Lessonia images, using a resolution compatible with the ENVI software, for identifying the flooded areas in the case in question.

4. DISCUSSIONS

In urban areas, verifying the flood curve faces significant challenges due to the "double bounce" effect. This phenomenon occurs when the radar signal is reflected both by water and by urban structures, such as walls and roofs that remain above the water level. Both the Lessônia and Sentinel-1 satellites are affected by this effect, making it difficult to accurately identify flooded areas.

The presence of multiple reflections can lead to erroneous interpretations, underestimating the extent of the flood. This fact can be mitigated by accessing Digital Terrain Models to predict flood areas and better estimate the affected areas through geoprocessing tools.

Since the Lessônia satellite has only one polarization, an effective solution for presenting the flood curve, which is essentially a change detection, involves the use of images captured before and after the event, in addition to the normalization of these images.

This method allows the identification of flooded areas by comparing the differences between the pre- and post-flood periods. Normalizing the images helps minimize variations unrelated to the flood, highlighting significant changes in the terrain.

To remove noise, it was necessary to initially apply the speckle filter and then classification and filtering techniques by area. This process aimed to eliminate the large number of polygons created due to noise or classification errors. Filtering by area helped to refine the results, removing small areas that did not represent real floods. This procedure, although performed a posteriori, can be automated through algorithms, increasing the efficiency and accuracy of the analysis.

It is important to note that the peak of the flood event occurred on May 11, 2024, but the closest satellite image of Lessônia to that date was obtained on May 18, 2024. In that interval, the waters could have receded, resulting in an underestimation of the maximum extent of the flood. This highlights the importance of good temporal resolution, requiring the use of dedicated satellites with continuous and emergency imaging plans to optimize decision-making support processes and provide more accurate data in the shortest possible time.

Standardizing and storing SAR radar image data from the Lessônia satellite family in a data repository with previously defined algorithms is essential to optimize processes and accelerate decision-making. A system similar to Google Earth Engine, which offers an integrated platform for analysing and processing geospatial data, could be extremely beneficial.

This would allow the reuse of validated algorithms and the rapid implementation of analyses in emergency situations. Another option is to enter into cooperation agreements, like Brazilian Federal Data Processing Service (SERPRO), and use this tool, both for data repository and for processing on servers and also for cooperation in the development of algorithms.

Google Earth Engine, together with the “SAR-flood mapping using a change detection approach” algorithm, is an excellent tool for detecting flood curves. It provides free online geoprocessing tools, supported by robust servers, and uses SAR radar images from Sentinel-1, also free of charge. This combination allows for the rapid and accurate identification of flooded areas, as long as the images are available on the servers, facilitating disaster response.

Brazil should take inspiration from this success story to develop decision-support tools in situations where the population is at risk due to natural disasters, such as the one that occurred in May 2024 in Rio Grande do Sul.

This will only be possible with investments in hardware, software and personnel training (peopleware), aiming to increase interoperability and streamline decision-making processes in support of the competent authorities. The implementation of such systems can significantly improve disaster response and risk management in the country.

The classification performed using the ENVI software with Lessonia satellite images in SCAM mode, which has a spatial resolution of 15 meters, was adjusted to use a compatible resolution, that is, the same 15 meters, allowing a more detailed and accurate analysis of the flooded areas. In contrast, the classification performed in Google Earth Engine, which used Sentinel-1 images, which have a spatial resolution of 18 meters, was adjusted to use a classification resolution of approximately 150 meters.

This significant difference in the spatial resolution of the classification may have contributed to the discrepancy in the calculation of the area affected by the flooding at the airport, resulting in an underestimation in the Google Earth Engine analysis compared to the Lessonia classification.

5. CONCLUSIONS

The catastrophic floods in Rio Grande do Sul in May 2024 underscored the importance of advanced flood monitoring systems, particularly the use of SAR satellite imagery. The Lessonia satellites, operating within the Strategic Space Systems Program (PESE), proved to be invaluable assets in assessing flood impacts and guiding disaster response efforts. Their ability to capture high-resolution images under any weather condition allowed for timely identification of flooded areas, which was crucial for effective resource allocation and mitigation strategies.

Through the analysis of pre- and post-flood images, this study demonstrated how SAR technology could accurately detect inundated regions, even in challenging environments. The use of normalization techniques and false-color compositions further enhanced the visualization of affected areas, providing clear insights into the extent of the flooding and its aftermath.

This research not only highlights the technical capabilities of the Lessonia satellites but also emphasizes the broader need for continued investment in space-based technologies for disaster management. As climate change increases the frequency and severity of extreme weather events, the ability to monitor and respond to such events will become even more critical. The integration of SAR satellite data into disaster response frameworks can significantly enhance preparedness, reduce damage, and save lives, ensuring that Brazil is better equipped to handle future natural disasters. Future researchs will focus on the utilization of a SAR processor system integrated with AI to enhance production efficiency.

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