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Inovações e Soluções Sustentáveis em Engenharia Ambiental

Temporal analysis of recurrence of flooded areas in Porto Alegre using Landsat and Sentinel-1 images

Análise temporal de recorrência de áreas inundadas em Porto Alegre utilizando imagens Landsat e Sentinel-1

Vinícius de Azevedo Silva[I], Rodrigo Bruno Zanin[II], André Luis Sotero Salustiano Martim[I], Cristiano Poleto[III], Francisco Lledo dos Santos[IV]

[I] Universidade Estadual de Campinas, Campinas, SP, Brasil
[II] Universidade do Estado de Mato Grosso, Sinop, MT, Brasil
[III] Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brasil
[IV] Universidade do Estado de Mato Grosso, Cáceres, MT, Brasil

ABSTRACT

This study uses the collection of Landsat images to analyze the recurrence of flooded areas in the Porto Alegre region, highlighting its entire temporal scale from 1984 to the present, analyzing the images with the highest index. Additionally, the use of Sentinel-1 data, despite its smaller temporal scale, is explored to complement the analysis of flooded areas. Using qualitative, quantitative and exploratory methodology, the research demonstrates that the joint use of technologies such as Landsat and Sentinel-1 significantly increases the potential for analysis and monitoring, providing a robust data set, which contributes to decision-making in the context of disaster mitigation and urban planning in vulnerable areas such as Porto Alegre.

Keywords: Flooded areas; MNDWI; Porto Alegre

RESUMO

Este estudo utiliza a coleção de imagens Landsat para analisar a recorrência de áreas inundadas na região de Porto Alegre, destacando sua vasta escala temporal inteira entre o ano de 1984 até o momento atual, analisando as imagens de maior índice. Adicionalmente, o uso de dados Sentinel-1, apesar de sua menor escala temporal, é explorado para complementar a análise de áreas inundadas. E sob metodologia qualitativa, quantitativa e exploratória, a pesquisa demonstra que a utilização conjunta de tecnologias como Landsat e sentinel-1 eleva significativamente o potencial de análise e monitoramento, disponibilizando um conjunto de dados robusto, o que contribui na tomada de decisões no contexto da mitigação de desastres e planejamento urbano em áreas vulneráveis como Porto Alegre.

Palavras-chave: Áreas inundadas; MNDWI; Porto Alegre

1 INTRODUCTION

The increase in the number of natural disasters such as floods is directly related to the increase in population in danger areas (Tucci, 2007).

Porto Alegre, the capital of Rio Grande do Sul, has faced recurring flooding events, amplified by heavy rains, climate change and the increase in the impermeability of urban soil. These events directly impact urban infrastructure and the quality of life of its inhabitants, affecting regions of high population density and commercial areas, in addition to interfering with essential services, such as transportation, energy supply and basic sanitation (Maddah; Mojaradi; Alizadeh, 2024; Declaro; Kanae, 2024).

Floods are caused by rivers overflowing, what submerges riverside areas that are particularly vulnerable due to their proximity to watercourses and the disorderly occupation of risk areas. The result shows significant economic damage, destruction of properties, public roads and infrastructure networks, in addition to risks to public health and the environment, favoring the proliferation of waterborne diseases and compromising sensitive ecosystems (Maddah; Mojaradi; Alizadeh, 2024; Declaro; Kanae, 2024).

The analysis and monitoring of flooded areas are essential for urban planning, aiming to prevent new events and mitigate their impacts. Advances in remote sensing technologies and access to large volumes of satellite data have provided a new dimension to the study of these hydrological phenomena, enabling a comprehensive and detailed view of the affected areas (Declaro; Kanae, 2024).

Among the various tools available, Google Earth Engine (GEE) has stood out for its ability to process and analyze vast collections of geospatial data in real time, aiding in quick and informed decision-making (Declaro; Kanae, 2024).

The use of images from the Landsat and Sentinel-1 satellites has been essential to identify and map flooded areas with high precision. Landsat, a multispectral optical satellite, captures information in several bands of the electromagnetic spectrum, allowing the detection of water bodies, vegetation, and urbanized areas. Its spatial resolution of 30 meters offers an adequate balance between detail and geographic coverage, making it ideal for large-scale studies, while its long time series, since 1984, provides a robust database for historical analyses (Maddah; Mojaradi; Alizadeh, 2024).

However, the use of optical data faces significant challenges, such as cloud contamination, especially during extreme events, when this cloud cover can compromise data accuracy (Declaro; Kanae, 2024).

The integration of data from Sentinel-1, equipped with Synthetic Aperture Radar (SAR), complements the limitations of Landsat by offering images that can be acquired in any weather condition, day or night. SAR is an active sensor that emits radar signals that penetrate clouds, allowing detailed images to be obtained, even in adverse conditions. This technology is particularly advantageous for detecting recent and ongoing floods (Declaro; Kanae, 2024).

The combination of data from multiple satellites, such as Landsat and Sentinel-1, allows not only greater accuracy in flood detection, but also a higher frequency of revisits, enabling more effective monitoring in vulnerable urban areas (Declaro; Kanae, 2024).

Recent studies highlight the effectiveness of this data fusion to improve temporal and spatial coverage, which is essential for monitoring flooded areas and formulating rapid and emergency responses (Declaro; Kanae, 2024).

The combined use of indices such as MNDWI and radar detection techniques allows for a robust and detailed approach, essential for urban planning and natural disaster mitigation. This advanced methodology offers a significant contribution to understanding flood patterns and formulating effective risk management strategies in urban areas (Declaro; Kanae, 2024).

Additionally, the GEE platform facilitates the integration and analysis of satellite data, allowing the efficient processing of large volumes of images, which is vital for the early detection of extreme events and the formulation of rapid responses.

This combination of multispectral and radar data offers a comprehensive perspective, covering both historical aspects of flooding and accurate detection in adverse meteorological conditions; this study therefore provides valuable data for disaster planning and management in urban areas vulnerable to flooding, contributing to the reduction of the socioeconomic and environmental impacts of these extreme events (Declaro; Kanae, 2024).

2 METHODOLOGY

2.1 Using Google Earth Engine (GEE) and Python

To perform the temporal analysis of the recurrence of flooded areas in the Porto Alegre region, a combined approach was adopted, using the Google Earth Engine (GEE) platform in conjunction with the Python programming language. GEE is an advanced platform designed for the massive processing and analysis of large volumes of geospatial data, offering a scalable computational infrastructure that enables the execution of computationally intensive operations on an efficient way.

The platform provides access to a vast collection of geospatial data, including high-resolution satellite images and other geographic data sources relevant to the temporal and spatial analysis of natural phenomena.

Integration with Python, in turn, enhances the automation of analytical workflows, while allowing greater flexibility in customizing analyses. This integration provides an efficient programmatic approach for managing large time series, allowing the repetition of analysis processes with consistency and high precision. This capability is especially critical in studies involving multiple temporal and spatial dimensions, ensuring reproducibility and scalability in the computational procedures required for the analysis of recurrences of flooded areas.

2.2 Landsat Collection and MNDWI

The Landsat imagery collection was chosen as the main data source for this study due to its wide availability and extensive temporal coverage, with images available from 1984 to the present - the entire temporal scale -, analyzing the images with the highest index. This allows for robust historical analyses of flood areas and the evolution of hydrological conditions in the region. It is important to note that Landsat is a multispectral optical satellite, which means that it captures information in several spectral bands of the electromagnetic spectrum, allowing the analysis of different features of the Earth's surface, including vegetation, exposed soil and, crucially, water bodies. The spatial resolution of Landsat imagery is 30 meters, which offers a balance between spatial detail and geographic coverage, making it suitable for both regional studies and more localized analyses.

The MNDWI (Modified Normalized Difference Water Index) is used to detect flooded areas, being calculated with the Green and SWIR bands of Landsat images; where the Green Band reflects vegetation and is sensitive to the presence of water bodies and the SWIR Band distinguishes between water and dry soil.

To ensure image quality, we applied a filter for cloud cover up to 20%. The threshold adopted for water detection was 0.4 – a value adjusted to minimize the inclusion of areas of waterlogged soil. Variations above this threshold indicate the presence of water, while values below it may include wet soil and vegetation.

2.3 Sentinel-1 data and water detection index

In addition to Landsat optical imagery (observed from 1985 to 2020), we incorporated data from Sentinel-1, a satellite equipped with a Synthetic Aperture Radar (SAR) sensor. Unlike optical sensors, SAR emits radar signals that penetrate clouds and can acquire images in any weather condition, day or night. The spatial resolution of SAR imagery is approximately 10 meters, providing greater spatial detail compared to Landsat.

For water detection in Sentinel-1 images, we used the intensity of the radar return in the VV band, from 2014 to 2024. Water surfaces tend to reflect less of the radar signal compared to solid surfaces, such as soil or vegetation, resulting in lower intensity values. The threshold used for water detection was -17 dB. Values below this threshold indicate the presence of water, while values above this threshold indicate dry surfaces or vegetation.

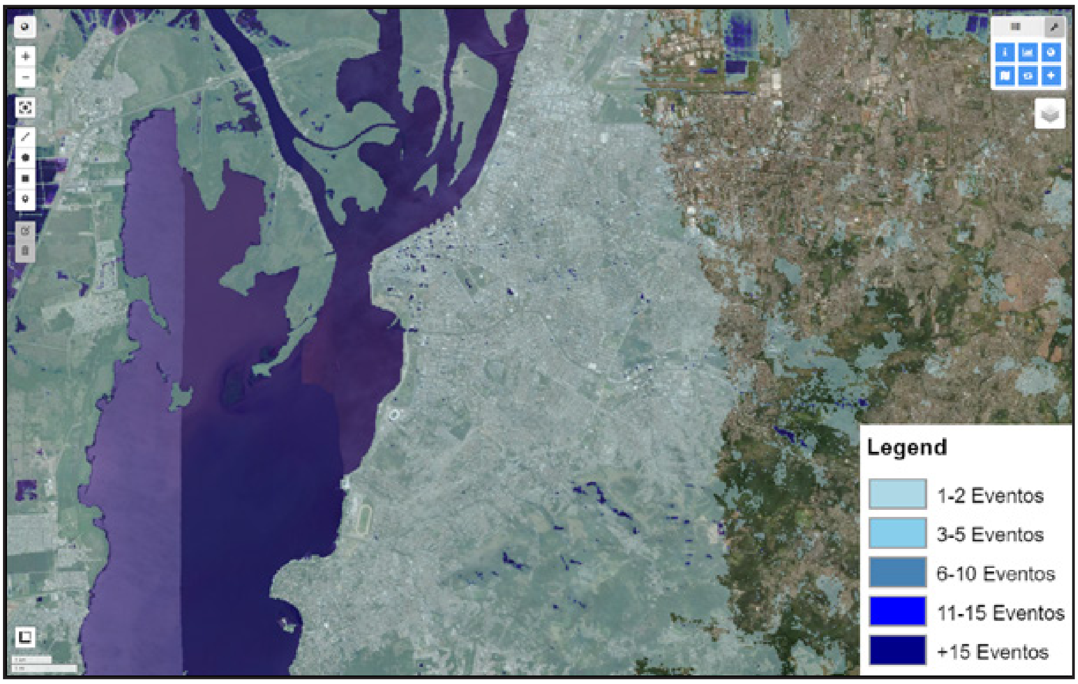
As in the case of Landsat images, the areas identified by Sentinel-1 were validated through comparisons with records of previous events, increasing the reliability of the results. In addition, the combination of Landsat and Sentinel-1 data allowed for a more comprehensive analysis, providing both a historical view and real-time detection of floods. The use of both types of satellites offers a complementary approach, where optical images provide a detailed history and SAR images ensure continuity of monitoring in adverse weather conditions.

3 RESULTS

The analysis of the results, obtained from Landsat images (Figure 1), shows a significant recurrence of flooded areas in the Porto Alegre region over the last few decades, revealing patterns that are repeated especially in areas of greater vulnerability, such as areas close to rivers and regions with low soil permeability.

The use of MNDWI allowed the identification of large urban areas that were flooded, demonstrating the effectiveness of this index in detecting locations with the presence of water, even in densely built areas or in regions of difficult access. However, detection can be affected by cloud cover, which justifies the use of a filter for images with up to 20% cloud cover in order to guarantee the quality and accuracy of the data used in the analyses. It is important to note, therefore, that even with the use of a filter, some images containing clouds may have remained, generating the detected result.

Figure 1 – Recurrence of flooded areas with Landsat



Source: Authors’ private collection (May 2024)

In contrast, Sentinel-1 data, although with less temporal availability, provide continuous detection of flooded areas due to the ability of SAR to overcome cloud cover and operate independently of solar lighting conditions. The results showed that Sentinel-1 was able to detect recent flooded areas (Figure 2) with high accuracy.

Figure 2 – Recurrence of flooded areas with Sentinel-1

Source: Authors’ private collection (May 2024)

However, the smaller amount of images available in recent years, when compared to Landsat, may have influenced the identification of flooded areas in the urban region in a less continuous manner, especially in periods with less frequent satellite passage. This limitation, however, does not reduce the importance of the data provided by Sentinel-1, but highlights the need to combine both sources for a more complete and integrated analysis.

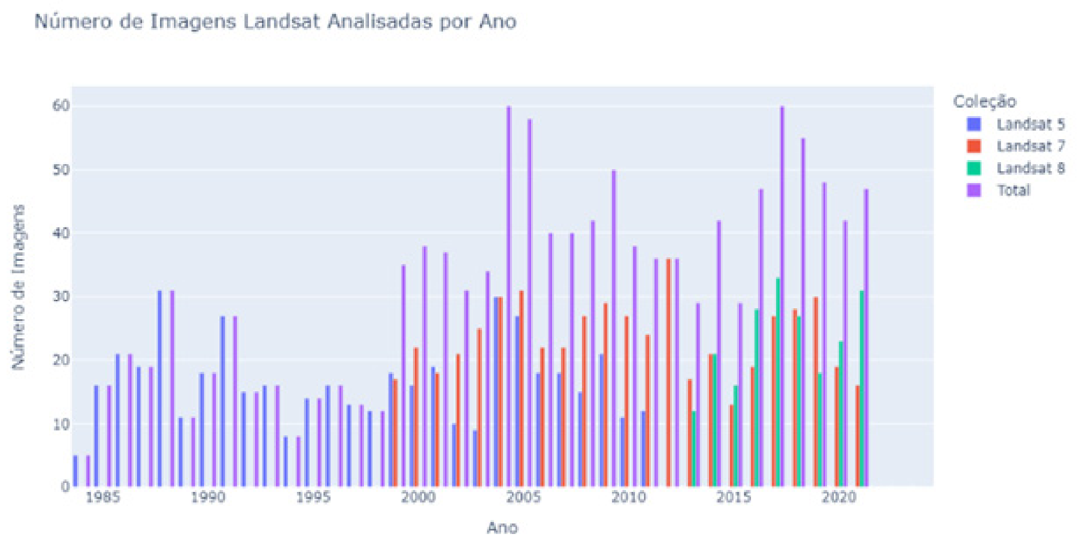
The graphs (Figure 3) showing the number of images analyzed per year for Landsat and Sentinel-1 highlight the variable availability of data over time, reflecting the differences in mission frequency. Landsat's most extensive time series, since 1984, offers a robust database for long-term historical analyses, enabling a broad view of flooding trends in the region. In downtown Porto Alegre, significant flooding was recorded in 1941, 1967, and more recently in May 2024, when the water level reached 535 cm, surpassing the historic mark of 1941 (Allasia *et al*., 2015; Sexton, 2024). These events allow the correlation of flood patterns with climatic and anthropogenic factors, such as the waterproofing of urban soil.

The long duration of this time series allows us to identify changes in flood dynamics associated with increasing urbanization and changing hydrological patterns in the basin, while the shorter Sentinel-1 series, since 2014, still provides valuable data for detecting flooded areas under adverse weather conditions.

However, the availability of Sentinel-1 images has been reduced in recent years due to the critical failure of the Sentinel-1B satellite in December 2021, which affected the power supply to the radar. After several recovery attempts, the European Space Agency (ESA) officially declared the end of the mission in August 2022. This resulted in a lower frequency of images between 2022 and 2024, as only Sentinel-1A remained operational. The launch of the replacement, Sentinel-1C, is scheduled for late 2024. During this period, ESA adjusted the observation plans for Sentinel-1A and used data from other collaborative missions, such as Radarsat-2 and TerraSAR-X, to minimize the gaps left by the absence of Sentinel-1B (Mission ends for Copernicus Sentinel-1b Satellite, 2022; Mission ends for Copernicus Sentinel-1b Satellite | Copernicus, 2022).

Figure 3 – Landsat and Sentinel-1 – variable data availability over time

Number of Landsat Images analyzed per year



Number of SAR Sentinel-1 Images analyzed per year

Source: Authors' private collection (May 2024)

The level of detail provided by radar images compensates for the smaller temporal coverage, allowing flood detection with greater spatial precision and in conditions where optical sensors would fail. The combination of both data sources offers a complementary approach, maximizing the potential for monitoring and analyzing flood risk areas in Porto Alegre, in addition to providing essential support for urban planning and the formulation of public policies aimed at disaster mitigation and climate adaptation.

4 DISCUSSION

The use of remote sensing data, such as those provided by the Landsat and Sentinel-1 missions, has proven to be extremely advantageous for studying flooding in urban and rural areas, especially in the context of Porto Alegre, where the combination of increasing urbanization and extreme weather events has made continuous monitoring a necessity. The integration of these two data sources allows for robust analysis, covering both historical aspects and real-time detection of flooding events, based on the satellite's passage and its availability of the collected data. The main advantages and limitations associated with each of these technologies are discussed below.

4.1 Advantages of Using Landsat

The extensive temporal coverage of the Landsat mission, which dates back to 1984, is one of the main advantages of this satellite for long-term studies. The historical series of images provides a reliable and continuous database, allowing the analysis of flood trends over several decades. This is especially important in studies of environmental and climate change, where understanding the evolution of flood patterns over time can reveal the cumulative effects of urbanization, infrastructure construction and changes in land use. The regularity of image acquisitions – usually at 16-day intervals – ensures data consistency, facilitating the comparison of past and present events, as well as allowing detailed temporal analyses. The spatial resolution of 30 meters, although not the highest available, offers an excellent balance between the level of detail and the breadth of the area covered, making Landsat ideal for regional-scale analyses. This balance is especially relevant in studies that aim both at identifying specific flood areas and at a broader view of the hydrological dynamics of entire river basins.

4.2 Limitations of Landsat Usage

Despite its many advantages, Landsat has some important limitations, especially in terms of its sensitivity to weather conditions. As an optical sensing satellite, the quality of its images can be compromised by the presence of clouds, which is particularly challenging during periods of heavy rainfall when flooding is more likely. In such conditions, images captured by Landsat often require filtering for cloud cover in order to ensure the accuracy of the analyses.

This filtering process, although effective, can reduce the amount of usable imagery, making it difficult to detect floods that occur during periods of prolonged bad weather. Furthermore, in flash flood events, the dependence on favorable atmospheric conditions for image capture can result in a time gap that compromises the immediate identification of these affected areas.

4.3 Advantages of Using Sentinel-1

In contrast, Sentinel-1 offers a number of complementary advantages to Landsat, especially with regard to its ability to acquire data in any weather condition. Equipped with a SAR (Synthetic Aperture Radar) sensor, Sentinel-1 can penetrate clouds, vegetation and even in total darkness, allowing it to obtain high-quality images regardless of weather conditions, a significant factor in regions such as Porto Alegre, where flooding events often coincide with periods of prolonged rain and dense cloud cover, rendering optical sensors ineffective.

The ability to perform continuous acquisitions, without being affected by adverse weather conditions, makes Sentinel-1 an essential tool for real-time detection of flooded areas. Another notable aspect is the high accuracy of Sentinel-1 in detecting recently flooded areas. Its 10-meter spatial resolution offers a higher level of detail than Landsat, allowing for greater accuracy in delineating affected areas, especially in densely built urban environments.

This greater spatial precision is particularly valuable in studies seeking to assess the impacts of flooding on critical infrastructure and residential areas, where small details can make a big difference in resource allocation and evacuation planning.

4.4 Limitations of Using Sentinel-1:

Sentinel-1 also has its limitations. The main one is its more restricted temporal coverage, since the mission only began in 2014, which limits the historical analysis of flood events compared to Landsat.

Although Sentinel-1 offers high-quality data for detecting recent floods, the lack of a more extensive time series makes it difficult to conduct long-term studies, which are crucial for understanding changes in flood patterns over the last few decades. Furthermore, the reduced availability of images in some periods can influence the detection of flooded areas, especially in regions where the satellite passes less frequently. In dynamic urban areas such as Porto Alegre, where floods can occur quickly and unpredictably, the limited availability of images at certain times can impact the ability to respond immediately, resulting in possible gaps in event detection.

Previous studies corroborate the relevance of flood monitoring in Porto Alegre. For example, the research by Altafini *et al*. (2023) mapped flood-prone areas in the Porto Alegre Metropolitan Region, using network techniques to understand changes in these areas over time.

This work provides a broad view of the impacts of flooding on road infrastructure and suggests mitigation measures at the regional level, which can be integrated into their analysis to expand the focus beyond directly flooded areas (Altafini; Claudio, 2023).

Furthermore, the work of Allasia *et al*. (2015) highlighted how the perception of flood risk in Porto Alegre has changed over the years, especially after the construction of barriers and pumping stations in the 1960s and 1970s. Although these structures prevented major flooding for many years, they also created a false sense of security among residents, leading to criticism about the maintenance of the protection system.

This study can contribute to enrich the discussion on public perception and the impact of flood control infrastructures on water resource management in the city (Allasia *et al*, 2015).

In addition, the analysis by Silveira *et al*. (2024) revealed how the backwash effect in choked sections of the Jacuí River intensified recent flooding in Porto Alegre, exacerbating the impacts in dense urban areas. This study uses satellite altimetry to analyze distinct flooding patterns and can provide additional insights into the need for adaptation of flood control infrastructures (Silveira *et al*, 2024).

Combining different data sources and developing new forecasting models can significantly contribute to the creation of more robust public policies capable of mitigating the impacts of flooding and swamping, especially in densely urbanized areas such as Porto Alegre. By including both flooded and swamped areas, it is possible to provide a more complete view of the risks and measures needed to increase urban resilience in the face of extreme events.

5 CONCLUSIONS

Given the above, it is clear that the combination of Landsat and Sentinel-1 data offers a complementary and synergistic approach to flood monitoring. While Landsat provides a broad historical view, essential for identifying long-term patterns, Sentinel-1 offers an indispensable tool for the immediate detection of events under adverse atmospheric conditions. The joint use of these technologies maximizes the potential for analysis and monitoring, offering a robust data set to support decision-making in the context of disaster mitigation and urban planning in vulnerable areas, such as Porto Alegre.

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Authorship contributions

1 – Vinícius de Azevedo Silva

Professional Master's Degree in Water Resources Management and Regulation from the State University of Rio de Janeiro
https://orcid.org/0009-0009-9008-4095 • vinicius@azevedoambiental.com
Contribution: Data analysis and methodology application

2 – Rodrigo Bruno Zanin

PhD in Cartographic Sciences from the São Paulo State University Júlio de Mesquita Filho
https://orcid.org/0000-0002-4990-0056 • rodrigo.zanin@unemat.br
Contribution: Conceptualization

3 – André Luis Sotero Salustiano Martim

PhD in Civil Engineering from the State University of Campinas
https://orcid.org/0000-0002-3578-0719 • asmartim@unicamp.br
Contribution: Review

4 – Cristiano Poleto

PhD in Water Resources and Environmental Sanitation from the Federal University of Rio Grande do Sul
https://orcid.org/0000-0001-7376-1634 • cristiano.poleto@ufrgs.br
Contribution: Validation

5 – Francisco Lledo dos Santos

PhD in Electrical Engineering from the São Paulo State University Júlio de Mesquita Filho
https://orcid.org/0000-0002-7718-8203 • franciscolledo@unemat.br
Contribution: Validation and Conceptualization

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