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Papers

Application of the Roughness Concentration Index (RCI) in the Assessment of the Flood Extent of the 2024 Flood Event in the Municipality of Pelotas-RS

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Abstract

The present study investigates the increasing recurrence of catastrophic events, particularly urban flooding, and their associated social and economic impacts. The research underscores the role of precipitation intensity and spatial-temporal patterns as critical drivers exacerbating flood events, especially in socially and geographically vulnerable urban areas. The main objective is to assess the flood extent generated by the 2024 flood event in Pelotas, Rio Grande do Sul, through the application of the Rugosity Concentration Index (RCI). The RCI is a geomorphological technique used to analyze the Earth's surface, identifying areas with homogeneous terrain characteristics, particularly regarding surface roughness distribution. Specific objectives include the identification and characterization of zones with varying degrees of rugosity within the flood extent, correlating these patterns with spatial coverage and water depth. The methodological framework employed advanced Geographic Information System (GIS) techniques for spatial data processing, including the development of a detailed cartographic base and the extraction of elevation data from municipal altimetry datasets. The results demonstrate the effectiveness of the RCI in detecting morphometric patterns and quantifying terrain roughness, contributing to a better understanding of hydrological redistribution processes during extreme events. Critical areas were identified where terrain roughness significantly influenced both the spatial extent and depth of floodwaters. The study concludes that the integration of the RCI into flood risk assessments can offer strategic insights for urban planning and disaster risk reduction, supporting the implementation of Sustainable Development Goals (SDGs) 1, 11, and 13, and promoting the development of resilient and sustainable urban environments.

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INTRODUCTION

According to the Center for Research on the Epidemiology of Disasters (CRED), the frequency of catastrophic events recorded in 2022 exceeded the average identified between 2002 and 2021 (CRED, 2023). In addition to direct damage, urban floods lead to significant social and economic impacts, such as population-wide impoverishment, degradation of the urban environment, and income losses. The situation is made worse by failures in critical infrastructure, such as energy supply, compromising the recovery of affected populations (Guimarães *et al.*, 2021).

The intensification and variability of rainfall both extend the impacts of extreme events, with precipitation peaks being associated with more severe damage and shorter response times (MEI *et al.*, 2020). Low-income urban populations are particularly vulnerable, being more susceptible to post-flood comorbidities and prolonged effects on physical and mental health (Escobar Carías *et al.*, 2022). Urban flooding also poses a risk to public and environmental health due to the spread of pathogens and the collapse of sewage systems (Kim *et al.*, 2022).

The floods between April and May 2024, caused by a migratory anticyclone over the South Atlantic that pushed warm and humid air masses into the continental land mass resulted in extreme rainfall in the state of Rio Grande do Sul- Brazil. The event affected over 9,000 locations, notably the municipalities of Pelotas, São José do Norte, Rio Grande, and São Lourenço do Sul, which declared a state of emergency due to severe damages to urban, agricultural, and road infrastructure (BBC, 2024; Azevedo, 2024).

Given the pressing need to improve urban planning and risk management, flood susceptibility maps have become a strategic tool. The integration of geomorphological metrics allows for the identification and prioritization of critical areas, supporting preventive and mitigation actions (Pace, 2022). The Roughness Concentration Index (RCI) stands out among said metrics, being relevant in geomorphological analysis when assessing the homogeneity of the terrain based on slope variation. The index contributes to the definition of morphometric units, helping ascertain surface dynamics and their relationship with hydrological processes (Paz; Sampaio, 2016). However, there is a gap in the literature regarding how the RCI can be applied to flood susceptibility studies, which underscores the relevance of the proposed approach.

Studies such as those by Flores and Oliveira (2016) demonstrate that the RCI is an effective metric in identifying relief fragmentation and in mapping soil and vegetation slopes (Araújo *et al.*, 2022). Its application also helps identify regions with different degrees of tectonic influence, being useful to prevent environmental disasters (Morais; Fernandes, 2023). By analyzing lineaments, the RCI highlights areas with different levels of fluvial incision, favoring the interpretation of geomorphological dynamics, especially in fault and fracture zones (Flores; Oliveira, 2016).

This approach is essential for geomorphological studies, as it offers a detailed read of the physical characteristics of the terrain, helping when it comes to differentiating global and local relief patterns (Sousa *et al.*, 2016; Fan, 2022). It is, therefore, a tool of high morphometric relevance, effective in environmental analyses and mapping (Navarro, 2023).

Considering the analytical potential of the RCI, the general objective of this work is to evaluate the flood extent caused by the 2024 flood in the municipality of Pelotas, Rio Grande do Sul - Brazil. The RCI is used as a central tool to identify terrain roughness patterns that may influence the extent and depth of flooded areas. The specific objectives involve the analysis of areas with higher and lower roughness within the flood extent, correlating these variables with surface runoff dynamics.

This study is also in alignment with the Sustainable Development Goals (SDGs), with an emphasis on goals 1 (No Poverty), 11 (Sustainable Cities and Communities), and 13 (Climate Action), since it provides technical grounds for public policies involving urban resilience and the reduction of vulnerability to environmental disasters (ONU Brasil, 2024; Governo Federal; Silva, 2018).

With a critical analysis of the relationship between extreme events and urban geomorphological characteristics, focusing on the 2024 flood in Pelotas- RS, this research contributes to the understanding of the spatial determinants of floods and to the improvement of mitigation strategies given the intensification of climate impacts on Brazilian urban centers.

MATERIALS AND METHODS

Bibliometric Analysis

In order to ground the theoretical discussion and highlight the relevance of the topic, this study conducted a bibliometric analysis on the applicability of the Roughness Concentration Index (RCI). Five keywords were selected: Roughness Concentration Index (RCI), Urban flood, Digital Elevation Models (DEM), Flood damage assessment, and Relief Dissection.

Keywords were chosen based on methodological aspects and practical research applications. Roughness Concentration Index (RCI) directed the search towards studies on the central metric, while Urban flood and Flood damage assessment expanded the investigation towards floods in urban areas. Digital Elevation Models (DEM) represented the terrain and enabled the calculation of the RCI. Relief Dissection contributed to the analysis of the morphological compartmentalization of the terrain and its influence on flood susceptibility. The selection of descriptors ensured a comprehensive and integrated approach to the topic.

However, the investigation presented limitations regarding the availability of data in consolidated databases, such as Scopus. A significant scarcity of articles was noted, in both English and Portuguese, specifically on the use of RCI in flood analysis and terrain morphometry. Although this limitation represents a methodological obstacle, it also sheds light on the novel and innovative nature of the approach, highlighting the originality of the research.

The bibliographic data were organized and analyzed using the VOSviewer software (available for free under a public license) (Van Eck; Waltman, 2025), which allows the creation of Co-occurrence Maps. These maps are visual representations that highlight the frequency with which terms or authors appear together in scientific publications, allowing for the identification of thematic patterns, collaboration networks, and gaps in the literature (Luiz *et al.*, 2023). VOSviewer stands out for its intuitive interface and the ability to export data to other platforms, enhancing its applicability in systematic reviews and exploratory studies.

In addition to bibliographic limitations, the study faced methodological constraints related to the resolution and accuracy of the Digital Terrain Models (DTMs) used. The USE of RCI requires high-quality data, with compromised reliability in urban areas with dense vegetation or buildings. The precision of the DEMs directly influences slope calculations and index results, underscoring the importance of considering the uncertainties associated with input data at the final interpretation stage.

Automated Mapping

In order to achieve the proposed objective, the first step consisted of defining the study area. The city of Pelotas, located around the Lagoa dos Patos coastal lagoon, was selected due to the significant impact of the May 2024 floods. As one of the most affected bodies of water in the region, it has become a site of interest for investigating the effects of floods and applying analysis indices, such as the Roughness Concentration Index (RCI), in the assessment of flood extent and dynamics. This selection attempts to better understand the dynamics associated with floods and contribute to the improvement of natural disaster mitigation strategies.

Digital Terrain Models (DTMs) are versatile tools in geographical analysis, applicable to vulnerability mapping, topographic attribute classification, and the identification of areas susceptible to anthropogenic impacts (Paz; Sampaio, 2017). Understanding the physical aspects of the landscape on a watershed scale, such as relief, morphometry, and water dynamics, is fundamental. Drainage distribution and density are mainly controlled by the topographic gradient and the hydrographic network, which support the analysis of susceptibilities and environmental planning (Simonetti *et al.*, 2022).

The integration between remote sensing, GIS, and mathematical models has expanded geomorphological analysis. DTMs include information on soil, drainage, and slope, providing an integrated reading of the landscape, while Digital Elevation Models (DEMs) prioritize topographic representation. The application of these models favors the formulation of preventive scenarios and the improvement of environmental and territorial management.

The methodology employed by Sampaio (2008) for the identification of homogeneous relief units uses the mathematical processing of pixels in DEMs, enabling the quantitative analysis of the shape of slopes and the dissection of the relief. The technique is based on the evaluation of vertical and horizontal curvatures, allowing for an accurate classification of the relief in terms of morphometric terms (Júnior *et al.,* 2015; Sampaio, 2017).

The study area is part of the hydrographic region of the coastal basins, delineated by the Mirim-São Gonçalo basin, one of the three major hydrographic regions of the state of Rio Grande do Sul (Neves, 2012). With 28,499 km², the basin had, in 2020, a population of 770,308, with 684,202 urban and 86,106 rural inhabitants (Rio Grande do Sul, 2020). The proportion of the area attributed to Pelotas in the basin is 90%.

After defining the study area, the data analysis was carried out with the aid of a Geographic Information System (GIS). The cartographic base was organized with altimetric data obtained through the Geomorphometric Database of Brazil - TOPODATA. From these data, a series of necessary procedures for calculating the ICR was initiated, ensuring an appropriate methodological approach.

The TOPODATA data were processed in QGIS 3.16 software (QGIS Development Team, 2025), with the insertion of images and projection defined in SIRGAS 2000/UTM zone 22S, where the study area is determined. Subsequently, the elevations were extracted and the slope data obtained, categorized according to the guidelines of the Brazilian Geography and Statistics Institute (IBGE, 2015). After defining the classes, the analysis was conducted using the same software, resulting in the slope expressed as a percentage.

The development of the Roughness Concentration Index (RCI) then began, a technique that allows the identification of homogeneous geomorphological units based on morphometric patterns of dissection and slope (Sampaio; Augostin, 2014). Since this index uses slope as a fundamental parameter, the first step was the conversion of raster data into vector points.

Next, the kernel density estimation was applied using the "Kernel Density" tool of the ArcGIS 10.2 software (ESRI, 2025). This technique calculates the concentration of point events, generating a continuous surface that represents the spatial distribution of the data (Costa *et al.*, 2019). It is especially useful for identifying clustering patterns and critical areas. Okabe, Satoh, and Sugihara (2009) highlight its application in spatial networks, such as urban roads and riverbanks, even in the face of technical limitations. By smoothing the data on a two- dimensional plane, this technique favors more accurate spatial analyses, contributing to diagnostics and planning.

In the "Search radius" configuration, 282 meter-radii were adopted for the calculation of the Local Roughness Concentration Index and 564 meters for the Global Roughness Concentration Index. The choice was based on Sampaio's methodology, which recommends the 1:25,000 scale for morphometric analyses. This scale is suitable for the urban area of Pelotas, considering its territorial extension and the need to detail the variations in relief that directly influence the dynamics of rainwater and the areas susceptible to flooding.

After this stage, the indices were classified where the Local ICR was subdivided into five classes, determined from the quartiles, and the Global ICR into six classes, according to the methodology of Sampaio and Augostin (2014). This categorization allows for a detailed analysis of the variability of roughness at different spatial scales.

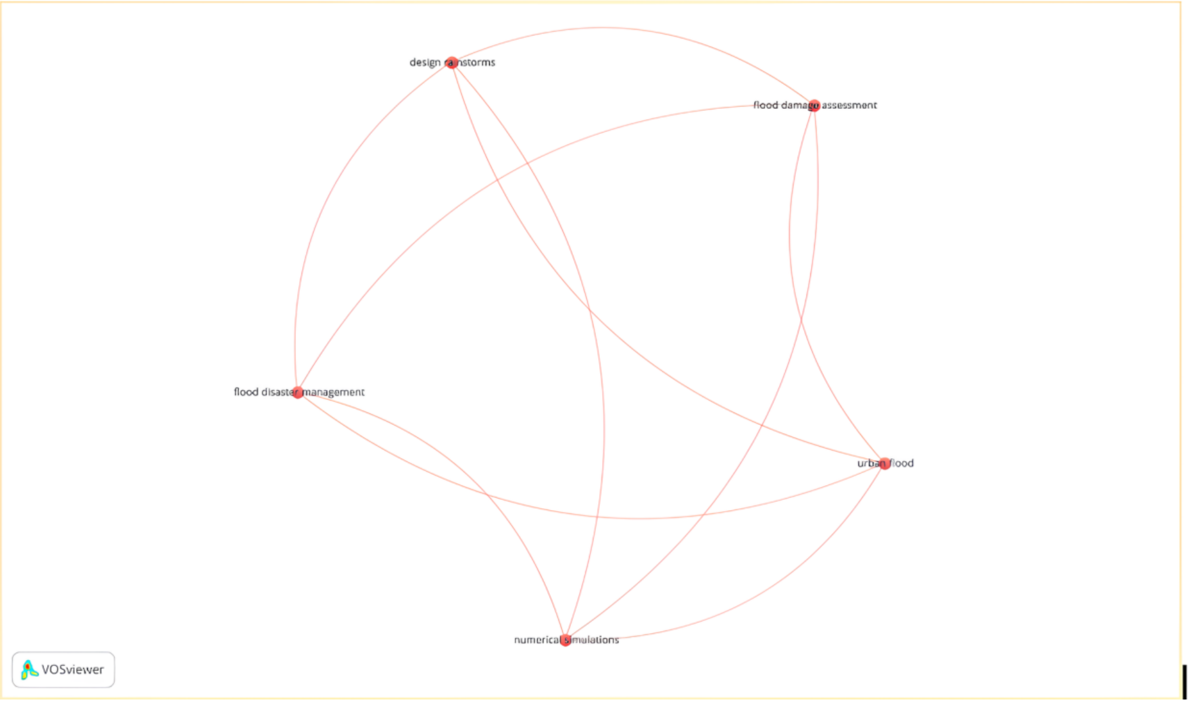
With the proposal to analyze the flood zone and after obtaining the ICR data, the overlay between the 2024 flood zone in Pelotas and the ICR values was carried out. The analysis considered the scenario in which the level of Lagoa dos Patos reached 3.13 meters, allowing for the correlation of the extent of the flooded area with the different levels of roughness.

RESULTS AND DISCUSSION

Co-occurrence Map

The keyword co-occurrence map helps visualize thematic connections in the scientific literature on urban flooding. The keywords analyzed are linked to the dynamics of floods in urbanized areas, being relevant for academic studies and disaster management. The most frequent terms are: "Urban flood", "flood damage assessment" and "flood disaster management", which stand out as core concepts in the literature review (Figure 1).

Figure 1 - Co-occurrence Map generated by VosViewer



Source: The authors (2024).

The temporal analysis of the bibliographic corpus covered a 33-year period (1991–2024), without chronological restrictions, in order to incorporate studies that are considered "classics." The average year of publication, 2020, highlights a recent intensification of scientific production, directly associated with the increase in extreme hydrometeorological events, attributed to climate change and unplanned urbanization. Keyword co-occurrence analysis, visualized with VOSviewer software, revealed a central cluster of interconnected terms, highlighting the main thematic areas of the scientific literature on urban flooding.

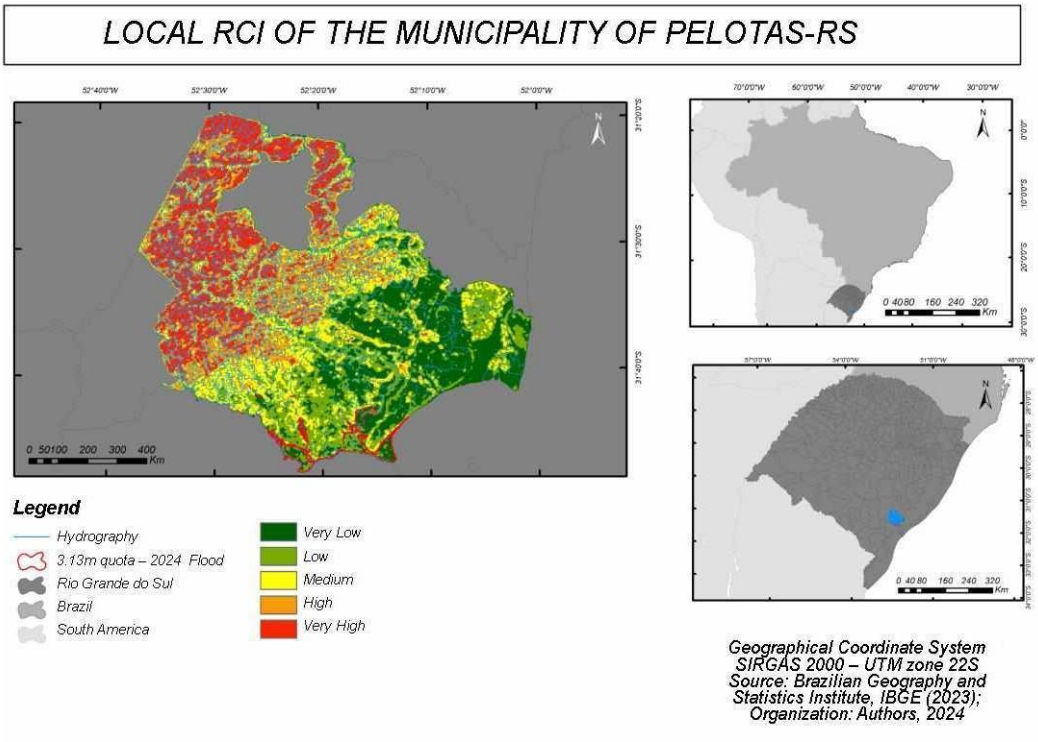
The clusters indicate the existence of strongly connected thematic cores, reflecting the focus on disaster management and mitigation policies, through the term “flood disaster management”, and on the assessment of impacts caused by extreme events, identified by “flood damage assessment”. The expression “urban flood” reflects the growing concern with urban environments, while “design rainstorms” and “numerical simulations” point to the use of predictive approaches and scenario planning, demonstrating the increasingly frequent use of simulation and numerical modeling tools in the study of floods. Additionally, terms such as “Roughness Concentration Index (RCI)” and “relief dissection”, though less frequent, highlight emerging approaches that integrate geomorphological analyses with flood forecasting and management practices. “RCI” allows for the identification of areas with greater topographic roughness – consequently, areas that are more susceptible to the concentration of surface runoff –, while “relief dissection” contributes to the understanding of the fragmentation of the terrain and its influence on drainage patterns.

The results of the bibliometric analysis not only reinforce the growing scientific relevance of the topic but also the urgency to deepen adaptation and mitigation strategies in light of the current scenario of intensifying extreme climate events in urban areas.

Local Roughness Concentration Index

The detailed analysis of the results found shows a direct correlation between the lower local roughness of the terrain and the extent of the 3.13m flood mark recorded in the city of Pelotas-RS in the year 2024 (Figure 2). This pattern reinforces the relevance of integrating geomorphological variables, their spatial interactions, and the underlying morphological patterns in studies aimed at risk analysis and territorial planning.

Figure 2 - Map of the Local Roughness Concentration Index (Local RCI) of the municipality of Pelotas, Rio Grande do Sul- Brazil



Source: The authors (2024).

According to the methodology of Sampaio and Augustin (2014) and the applicability of Paganotto (2022), the local RCI was divided into five classes based on quartiles (Table 1).

Table 1 - Analysis of the Local Roughness Concentration Index in the Flood Zone of the City of Pelotas in 2024

Local Roughness Concentration Index	Total Area of Pelotas- RS (km^2)	Total Area in the 2024 Flood Zone in Pelotas- RS (km^2)
Very Low	316.42	13.75
Low	329.75	15.45
Average	318.90	1.90
High	313.68	0.025
Very High	330.45	–

Source: The authors (2024).

The chart shows the relationship between the Roughness Concentration Index (RCI) and the spatial distribution of the total area of Pelotas-RS in comparison with the area affected by the 2024 flood zone. The results indicate that the areas classified with "Very Low" and "Low" roughness were the most impacted, totaling 13.75 km² and 15.45 km² of the flooded regions, respectively. These values correspond to the largest affected areas, which highlights the vulnerability of these surfaces to flooding. Low roughness surfaces, due to their lower resistance to surface runoff, facilitate the rapid propagation of the water sheet and hinder the attenuation of water flow. This hydrological behavior results in greater water accumulation and contributes to the intensification and expansion of the flood area.

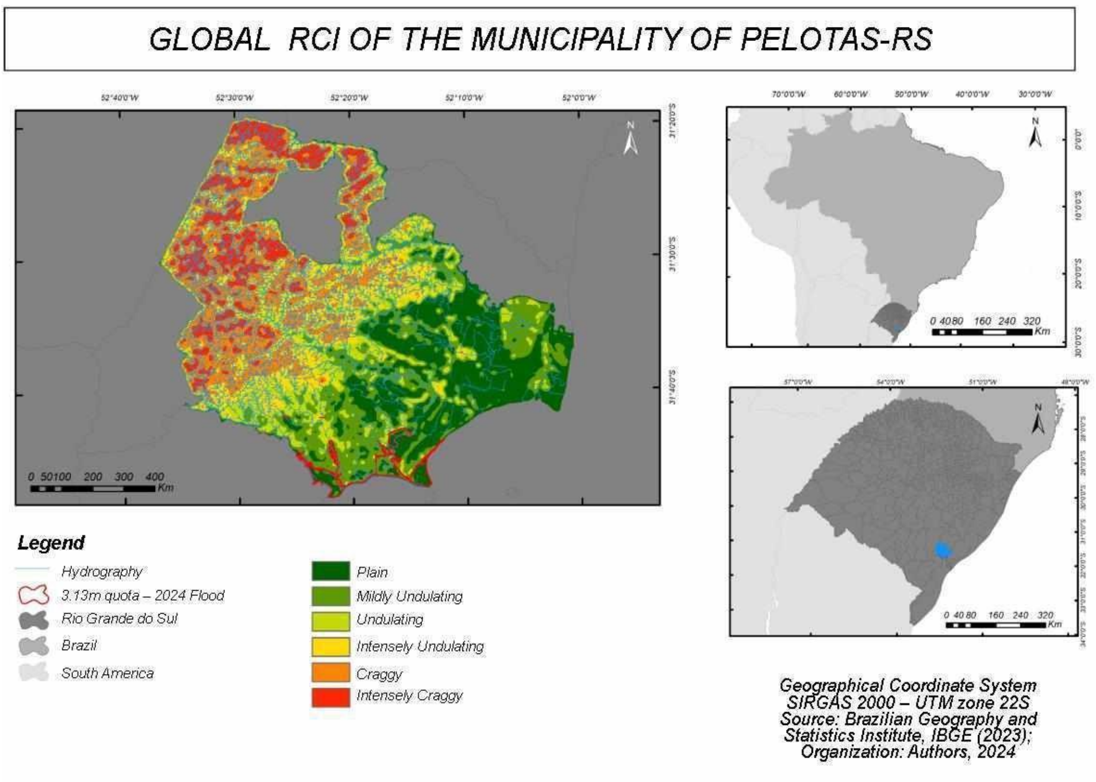
In contrast to the low roughness areas, the "Medium," "High," and "Very High" roughness classes showed a significantly lower interaction. The areas with "Medium" roughness recorded a flooded extension of only 1.90 km², while those with "High" roughness totaled only 0.025 km², a practically residual value. Notably, in the regions classified as "Very High," no overlap with the flood area was observed. This pattern highlights the role of elevated roughness as a natural barrier to the advancement of the water sheet, as more irregular and fragmented surfaces contribute to the dissipation of surface runoff energy, promoting infiltration and delaying the accumulation of water on the surface. Moreover, the greater topographical complexity of these areas tends to direct the flow to zones of lower elevation and lower roughness, functioning as natural protection areas against the spread of flooding.

One may notice that the absence of overlap between the "Very High" roughness class and the 2024 flood zone is due to the location of these areas, as identified in the spatial analysis. These zones, generally associated with steeper terrain and pronounced topography, facilitate the rapid runoff of rainwater and limit surface accumulation. As a result, they have low susceptibility to flooding, functioning as natural drainage areas that prevent the concentration of flow and the formation of floods.

Global Roughness Concentration Index

For the application of the Global RCI, the same methodology used in the calculation of the Local RCI was adopted, differing in the classification of the results into six classes, according to Sampaio and Augostin (2014). The classes were defined based on the RCI values: plain (RCI below 2.5), indicating surfaces with minimal altimetric variation; mildly undulating (RCI from 2.5 to 6), areas with slight irregularity; undulating (RCI from 6 to 14), terrains with moderate slope variation; strongly undulating (RCI from 14 to 30), more pronounced relief; craggy (RCI from 30 to 45), areas of high relief energy; and very craggy (RCI above 45), corresponding to the most rugged terrains (Figure 3).

Figure 3 - Map of the Local Roughness Concentration Index (global RCI) of the municipality of Pelotas, Rio Grande do Sul, Brazil



Source: The authors (2024).

One may notice that the classes of this index were not uniform throughout the study area. That being said, an analysis was conducted on how this classification was divided in the flood zone. The flood extent corresponds to the extreme hydrological event that occurred in May 2024 in the municipality of Pelotas (RS). This is characterized as the spatial representation of the flooded areas, mapped through the interpretation of remote sensing data and/or field validation, highlighting the extent and severity of the hydrometeorological impact in the region.

Table 2 - Analysis of the global roughness concentration index in the flood zone of the city of Pelotas in 2024

Global Roughness Concentration Index	Total Area of Pelotas-RS (km²)	Total Area in the 2024 Flood Zone in Pelotas-RS (km²)
Plan	305.05	18.11
Mildly undulating	309.33	11.63
Undulating	207.81	0.55
Intensely undulating	239.86	0.00272
Craggy	335.91	–
Very Craggy	166.28	–

Source: The authors (2024).

Table 2 presented relates the global roughness concentration index to the impact of the 2024 flood zone in the city of Pelotas-RS, presenting data that reveal a clear influence of the global relief pattern on flood susceptibility, highlighting flat areas as the most affected, with 18.11 km² flooded, followed by mildly undulating areas, which accounted for 11.63 km².

The morphology of terrain has a direct influence on the dynamics of rainwater. Plain and mildly undulating surfaces, due to the low slope, have a greater tendency to accumulate water, increasing susceptibility to flooding. On the other hand, in craggier areas, surface runoff is accelerated, reducing water retention but intensifying the erosive potential and the risk of concentrated flash floods.

In the categories with greater undulation and irregularity of the terrain, the impacts decrease substantially. Areas classified as "Undulating" showed only 0.55 km² of flooded area, while in the "Intensely Undulating" category, the extent was minimal, with 0.00272 km². Areas classified as "Craggy" and "Very Craggy" did not record significant flood values, which suggests that more rugged terrain plays a relevant role in the dispersion and infiltration of water, reducing vulnerability to extreme hydrological events.

These pieces of evidence underscore the importance of incorporating the analysis of local and global roughness index in territorial planning and risk management studies. Understanding hydrological behavior based on terrain morphology is essential for defining priority areas and mitigation strategies. For the most vulnerable regions, it would be a fruitful strategy to improve urban drainage, use green infrastructure to increase infiltration, and strengthen monitoring and zoning to control occupation in risk areas. On a broader territorial scale, although the application of this type of analysis is still more frequently directed towards studies of erosion dynamics, as shown in the investigations of Goulart *et al.* (2018), its contributions are equally relevant for the integrated understanding of the geomorphological processes that influence susceptibility to flooding and environmental degradation. The expansion of this approach beyond erosion studies represents a promising opportunity to advance in the identification of critical areas and in the formulation of more effective public policies for urban and regional resilience.

FINAL CONSIDERATIONS

The conducted research highlights the importance of integrating geomorphological variables in risk analysis and territorial planning. The Co- occurrence Map revealed five central keywords related to urban flooding, highlighting the growing relevance of the topic, especially in light of the adverse consequences of climate change and the intensification of extreme hydrometeorological events.

The application of the Local RCI demonstrated a direct correlation between the lower classes of terrain roughness and the extent of flooded areas. Areas classified as having "Very Low" and "Low" roughness proved to be more vulnerable, corresponding to the largest affected extents, which reinforces the need to consider terrain roughness in the formulation of mitigation and adaptation strategies for extreme events.

Additionally, Global RCI indicated that plain and mildly undulating areas are more susceptible to flooding, while regions with greater topographic accentuation have lower vulnerability. These results highlight the potential of roughness indices as tools to support risk management and land-use planning.

Targeted mitigation strategies should be adopted, such as the expansion of buffer areas through linear parks, the enhancement of urban drainage systems, and the definition of priority zones for water risk management, supported by a careful environmental zoning. The integration of roughness indices in territorial planning instruments, such as master plans and environmental impact studies, contributes to increasing urban resilience in the face of flood events.

Finally, there is great relevance in further research delving into the relationship between terrain roughness, the degree of soil impermeability, and the efficiency of urban drainage systems. Investigations in this regard could expand the applicability of the analyzed indices, promoting more integrated and effective solutions for urban flood management.

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