Formal methods in flood disaster response: the case of Porto Alegre, Brazil

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Abstract. This paper provides an account of the formal methods used to inform and examine the performance of Porto Alegre's Metropolitan Region road-circulation network after the May 2024 floods. Comparisons between the pre-disaster configuration and three post-disaster scenarios are made, using configurational analysis, highlighting how the urban grid cohesiveness was affected by the inundations, both at a local and at a regional scale. Key findings showcase important overall system performance shifts in terms of relative accessibility and preferential routes' choice, especially concerning vehicular movement. Results also indicate that local movement patterns tended to be preserved, despite the floods dimension, which aided to maintain the internal cohesiveness of the network. Furthermore, the paper also demonstrates how those formal methods were incorporated into pilot decision-support actions, co-designed through the engagement with local authorities, to provide the early-responders and decision-makers on the field with information about the network viability changes, useful to identify priorities in de-obstruction and which road-elements were to be preserved to avoid a larger system collapse.

Keywords: Disaster-Risk, Floods, Formal Methods, Network Analysis, Configurational Analysis

1 Introduction

Increasing in severity and recurrence due to climate change, flooding events are the main cause of urban disasters in Brazil [1], being an extensive source of infrastructural, economic and life losses. From late April, 2024 and throughout the month of May, torrential rains have drenched the state in Rio Grande do Sul, southern Brazil, as a result of an atmospheric block, caused by a high-pressure system, leading to higher than average temperatures in the central part of the country, which prevented the displacement of typical meteorological systems. The abnormal rainfall has triggered the worst floodings in the last 80 years, affecting 91% of the Rio Grande do Sul state's municipalities [2,3], displacing over 580.000 people, submerging entire towns [4], and greatly disrupting the road-circulation network connections between Porto Alegre, the state capital, and its surrounding metropolitan area. As Brazil is heavily dependent on road-transport [5], these interruptions conveyed immense challenges for the authorities in organizing the emergency response to this disaster, as well as early recovery actions which, in turn, required prompt efforts regarding data production, communication and decision-support.

On that, formal methods derived from architecture, such as configurational analysis, played an important role in conjunction with other knowledge domains to provide meaningful information about the state of the road-circulation network after the disaster, guiding early-responders and stakeholders in assessing their priorities. Through these methods, it was possible to evaluate the overall performance of the road-circulation network under different scenarios, visualizing the variations in patterns of accessibility, identifying the road-elements to be protected as *preferential routes* and guiding actions to be taken to avoid the road-system collapse.

This paper provides an account of these formal methods and how they were used to examine the performance of the most flood-affected sections of Porto Alegre's Metropolitan Area road-circulation network.

The objective is to present the stable, pre-disaster road-network as of April 28th, 2024, along with three post-disaster scenarios, that illustrate possible outcomes of the flood disaster evolution and early-response actions taken by the local authorities between May 2nd and May 10th. 2024. Comparisons among these scenarios provide insights into how the urban grid was affected, revealing how changes in the viability of certain road-elements caused changes in the movement patterns, measured through configurational analysis. The diachronic analysis is based on the assessment of two measures: Normalized Angular Integration (NAIN) – for *relative accessibility*; and Normalized Angular Choice (NACH) – for *preferential routes choice*. For considering the effects at different spatial scales, NAIN and NACH are modelled both for local and global radii: 400, 800, 1,200 meters for local pedestrian movement; 2,000 and 5,000 meters, for local vehicular movement; and Rn, topologic, for vehicular movement within the whole system.

The conclusions discuss how these scenario simulations were implemented into a pilot decision-support strategy, through the engagement with local authorities to provide early-responders and stakeholders information about network changes useful to identify which road-elements should be preserved to avoid a larger system collapse. While highlighting the potential value of formal methods, particularly configurational analysis, in generating meaningful information for supporting emergency management operations, the paper presents an account of limitations that currently affect the swift adoption of the approach by local actors. Additionally, it outlines promising future research avenues to better integrate configurational analysis into outcome-driven Decision Support Systems.

1.1 The urban and the disaster context

A significant portion of the road-network in the state capital, Porto Alegre, and the Metropolitan Region is set at the Guaíba Basin outlet. This basin consists of four important rivers (*Caí, Sinos, Jacuí*, and *Gravataí*), and covers around 85000 km^2; with its drainage flowing into the Lake Guaíba through the Jacuí Delta, where Porto Alegre is set, making it highly susceptible to flooding (Fig. 1).

In normal conditions, Porto Alegre's Metropolitan Region (PAMR) road-circulation network relies on mobility axes comprised by the national highways: BR-116, BR-290, and BR-448. Those constitute the main connections between the state capital, Porto Alegre, its Greater Region (comprised by the municipalities of Alvorada, Cachoeirinha, Canoas, Gravataí and Viamão); the Vale dos Sinos, region (which has, as main municipalities, Novo Hamburgo and São Leopoldo); as well as towards the municipalities of Montenegro, Eldorado do Sul and Guaíba in the west bank of the Guaíba's basin. Moreover, those highways also connect Porto Alegre with Rio Grande do Sul's inner and coastal areas, respectively to the southwest and east, as well as the remainder of Brazil, in the north. Other axes, comprised by national and state highways are important as secondary connections for interurban mobility within the regions, also providing redundancies for the regional system, including the BR-386, RS-118, RS-240, and RS-020. Further regional axes such as RS-030, RS-040 state highways, connect Porto Alegre to the coast and provide redundancies for the BR-290 (Fig 1).

Heavy rains across the Guaíba Basin between April 29th and May 5th, 2024, caused historic flooding in the direct tributaries and an elevation of the Guaíba Lake level [6]. Several rain gauges in the region recorded 24-hour precipitation values well above 300 mm. The widespread precipitation across the basin and the prolonged rainfall period caused the water level to peak at 5.35 meters in Lake Guaíba on May 5th, resulting in major flooding in Porto Alegre's Metropolitan Region [7, 8]. The event was exacerbated by the failure of Porto Alegre's flood protection system, increasing the impact on urban areas.

Several sections of the road-system were interrupted by the flooding inundation, which remained relatively unchanged from May 6th to May 8th when images from the Sentinel-2 satellite (ESA) of the European Copernicus Earth Observation Program enabled the monitoring and validation of the flood extent. This validation process was conducted by a multidisciplinary team with collaborators from various sectors of the Federal University of Rio Grande do Sul (UFRGS) and external volunteer researchers [8] (Fig.2;Fig.3).

From May 10th, the Humanitarian Emergency Corridor (Fig.3b;Fig.4) – a relief access – was set in operation to reconnect Porto Alegre's city centre to the highway network. It established a linkage from the *Túnel da Conceição* to the *Av. Castello Branco* and the BR-290 (Fig.3b;Fig 4).

Reestablishing this connection allowed for improved accessibility conditions between *Canoas* and *Porto Alegre*, providing a shorter route to access *Canoas* airbase, where a logistical hub was established for receiving relief supplies coming through airlift from the rest of Brazil.

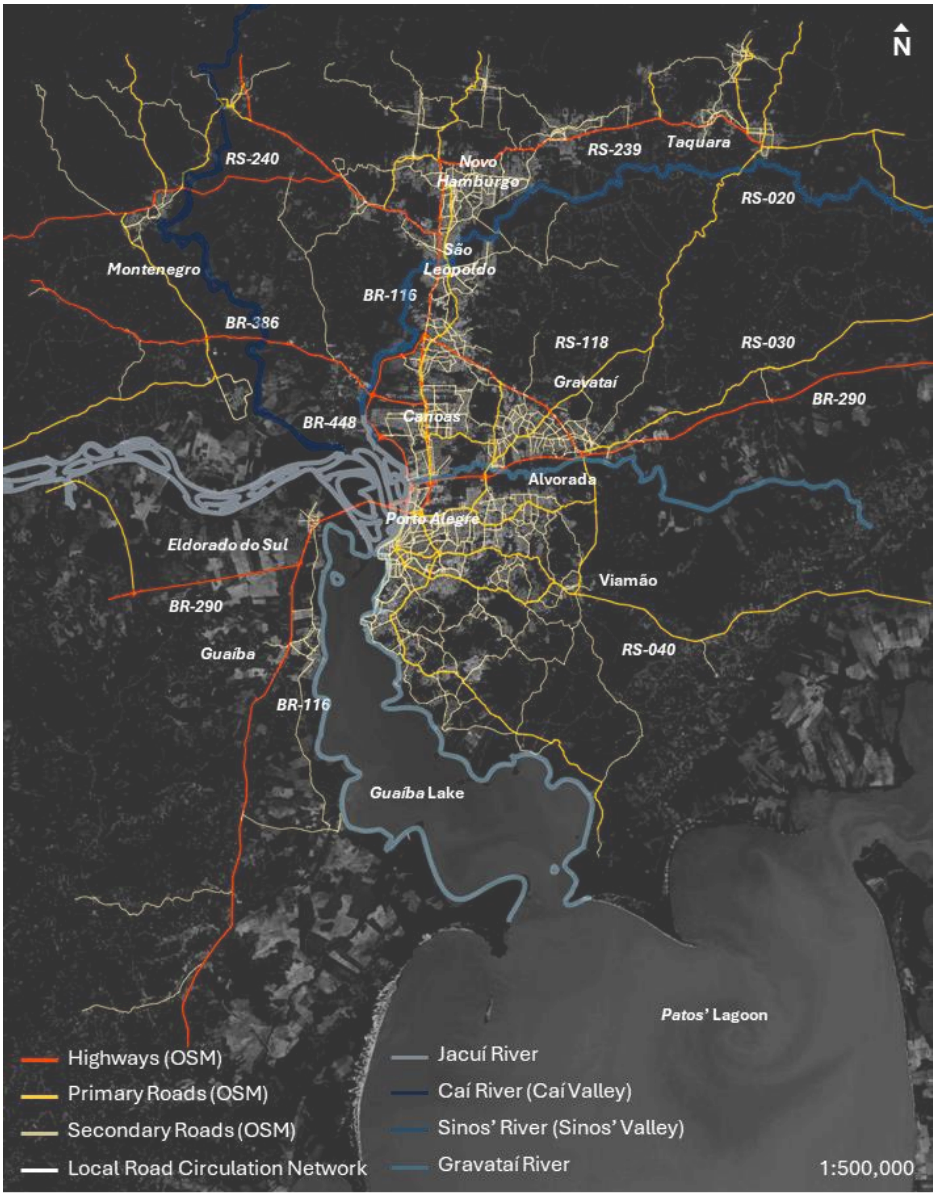

Fig. 1. PMAR road-structure and the rivers that comprise the Guaíba Basin.

However, the connection remained extremely fragile, with few redundancies, therefore being still at risk since sections of BR-116 and BR-290 were affected by floodings and blockages at some points. In that regard, the only stable connection continued to be through the RS-118.

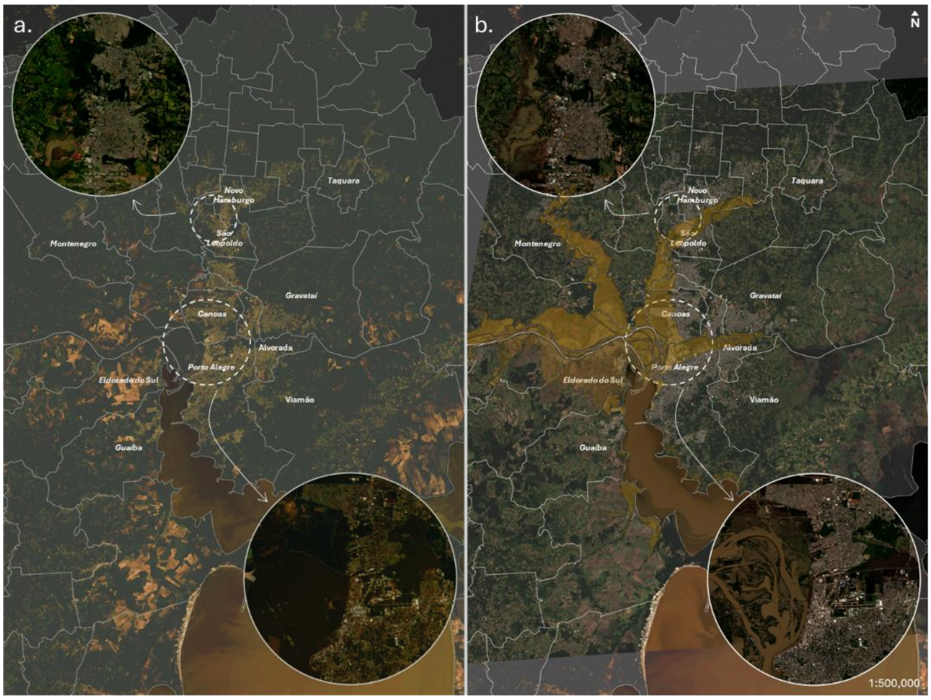

Fig. 2. PMAR urban area: a) 28th April, 2024; b) 6th May, 2024 – after floodings [9]

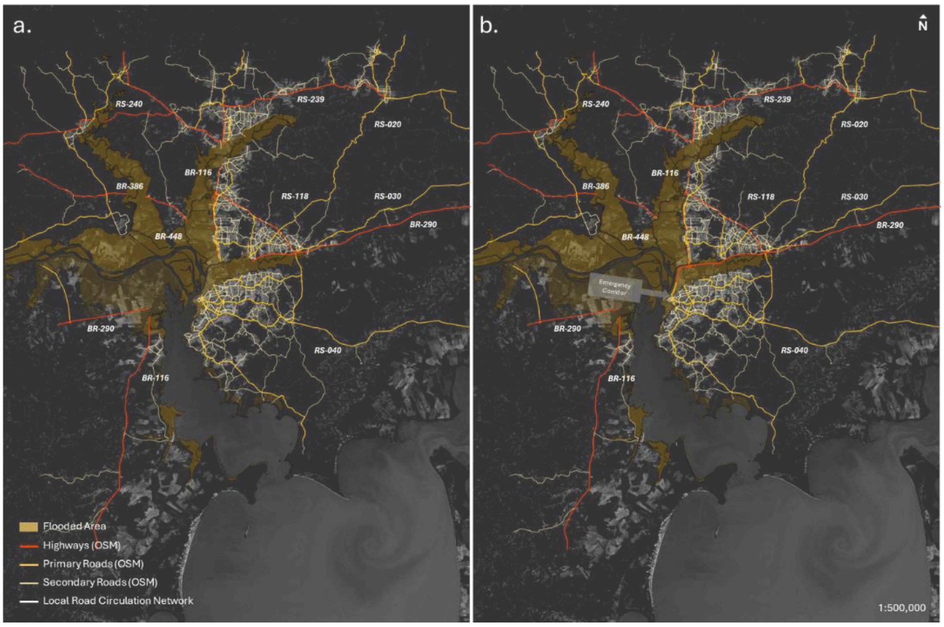

Fig. 3. PMAR road-structure after flooding: a) 6th-8th May, 2024; b) 10th May, 2024

Fig. 4. Emergency Corridor structure in August 2024 (source: authors' archive).

Road interruptions persisted for an extended period, with access from BR-116 to the city entrance being fully restored only on June 1, 2024.

2 The formal approach for flood disaster response

2.1 Previous experiences in merging formal methods and configurational analysis to disaster risk management

Materialized as outcomes of inadequate planning and risk governance, several urban areas are currently subjected to structural conditions of fragility. Due to that, natural disasters reflect enduring flaws in their development processes, as cities tend to present limited capacities in reducing, coping with and responding to hazards [10] which, because of climate change, are to increase in frequency and severity.

Integrating disaster risk management and multi-domain formal methods in urban analysis, within a decision-support framework, is then crucial for adequately overcoming such challenges.

A cohort of studies has established a substantial track record regarding those aspects, above all, with reference to urban disasters associated with flooding events. Approaches such as [11,12] aim to develop instruments to map and monitor rainfall hazards, with some [13,14] also observing their impact on urban network restrictions. Other studies [15,16], instead focus on the impact of urban layout and morphology on mobility under disaster conditions, also exploring nature-based solutions for mitigating risks.

Furthermore, a particular branch of formal methods, associated with configurational analysis [17] – a network-oriented approach –, is emerging as a promising way to assess urban areas' performance when subjected to disaster conditions, while also engaging with planning post-disaster scenarios [5,18,19]. Nevertheless, issues remain in their diffuse application, as accurate modelling often extensive and complex road-networks in short spans of time [20] tend to be both data and computationally intensive.

Moreover, there is the question of integrating these methods into decision-support frameworks, especially in terms of disaster early-response. One side involves their use in establishing post-disaster scenarios and the comparison of the system under different stresses, supporting post-disaster phases of recovery and preparation [5,18]. The other, encompasses rendering information accessible and understandable to the decision-makers, enabling them to consider possible outcomes for their actions [21].

The experience with the response actions to cope with the Porto Alegre floods is associated with the integration between different knowledge domains, as it involved not only the use of formal methods, but also, the creation of instruments to communicate with stakeholders and to raise awareness about the potential socio-spatial impacts of their decisions [22,23,24]

2.2 Datasets and Methods

The integration of different spatial datasets in a common GIS-based platform was crucial for associating different knowledge-domains, enabling scenario-based analysis to provide decision-support to stakeholders.

Given the strict time requirements of disaster early-response actions, an open-source database, OpenStreetMap (OSM), was used capitalizing on existing protocols for preparing road-graphs [25,26]. The whole Southern Brazil road-network was extracted and the PAMR was filtered out from it to cover only the affected area. A simplified road-graph was built without road-elements that corresponded to unpaved tracks and rural paths as these were deemed inaccessible to heavy rescue vehicles or unsuitable for vehicular traffic routing due to the heavy rainfall.

The road-network was then restricted considering the validated flooded area after the disaster. Elements that intersected the flooded area – or that its accesses intersected the flooded area, such as elevated highways – were considered inaccessible. The validation process was conducted by a multidisciplinary team from the 6th to 8th May, with collaborators from various sectors of the Federal University of Rio Grande do Sul (UFRGS), and external volunteering researchers [8]. It is important to precise that the validated flooded area – and the overall analysis – does not consider mapping sediments and alluvions, as those were not available during the disaster-response phase.

Based on these datasets, four post-disaster scenarios were considered for the configurational analysis (Table 1):

Table 1. Configurational analysis scenarios description

Road-Network	Description	Independent Road-Graph Networks
Stable Road Network (Scenario 0)	Pre-disaster road-network, without flooding and under normal conditions.	1
Scenario 1	Scenario post-disaster, considering the verified flooded area on 6th-8th May, 2024.	3
Scenario 2	Hypothetical scenario post-disaster, considering the RS-118 interruption, the single remaining point of connection of Porto Alegre's greater metropolitan area in Scenario 1.	4
Scenario 3	Scenario post-disaster 1, adding the emergency humanitarian corridor opened on 10th May, 2024. It reconnected Porto Alegre's city center flooded access to the elevated highway network.	3

Graph networks were modelled in DepthMapX 0.8, using Space Syntax's normalized Angular Segment Analysis (ASA) [17,27,28,29,30], a formal method developed by architects, social scientists and computer scientists that allows to estimate people and vehicular movement patterns, at different scales (building, neighborhood, urban-region). It enables comparisons between relative accessibility and preferential routes choice patterns in different scenarios. Models can comprise both the entire road-network – radius n – and local metric radii, which relate to different types of movement [17,31]. For this analysis, six radii were considered to compare the changes at different types and scales of movement (Table 2). The used Space Syntax configurational measures are formally defined and conceptualized in Table 3:

Table 2. Definition and significance of the configurational analysis metric radii.

Distance	Measure	Type	Significance
400m	R400	Metric	Local (Pedestrian)
800m	R800	Metric	Local (Pedestrian)
1200m	R1200	Metric	Local (Pedestrian)
2000m	R2000	Metric	Semi-Local (Pedestrian); Local (Vehicular)
5000m	R5000	Metric	Local (Vehicular)
n (system)	Rn	Topological	Global (Vehicular)

Table 3. Formal definition, concepts and references for the configurational analysis measures.

Formula	Concept
$AIn = 1/ 2((1/k-1)\sum_k d\theta_{Ck})/k-2)/D_k$	Measures *farness* between network elements, considering their count (k) and the system angular total depth sum ($\sum_k d\theta_{Ck}$), or topological distance between network elements. Denotes a road-element relative accessibility or movement potential (to-movement), informing how reachable, in comparison to all others in the system, it is thus its closeness centrality. The normalized formula relativizes angular total depth and allows comparisons between different systems [17,27].
$NAIN_{Rn} = k^{1.2/})\sum_k d\theta_{Ck}$	
$NAIN_{Rmetric} = \log(AIn) +2$	At metric radiuses, NAIN indicates the spatial hierarchies and distribution of local sub-centres of relative accessibility, as well as their density [17,28].
$ACh = \sum_j \sum_k g^{(i)lg\ (j<k)}$	Sums the number of times a road-element is traversed, through the shortest paths route, considering all origin-destination pairs. Denotes the hierarchies of preferential routes choice (flow probabilities, through-movement), thus its betweenness centrality. The normalized formula relativizes angular total depth and allows comparisons between different systems [17,27].
$NACH_{Rn} = \log(ACh+1)/ \log()\sum_k d\theta_{Ck})+3$	
$NACH_{Rmetric} = \log(ACh) +2$	At metric radiuses, NACH indicates the spatial hierarchies of the local sub-centres, informing their weight for the intermediate preferential routes structure [17,28].

Once completed, the configurational models were exported to a GIS-based environment [32], spatialized and statistically distributed using an equal count (quartile) range. Maximum and minimum values are associated to each individual system showcasing its internal patterns of relative accessibility or preferential routes in visualization. Scenarios that have more than one system are numerically aggregated for attaining their overall element count, average and maximum values for each configurational measure, providing means of comparison with the stable road-network.

3 Results and Discussion

Comparing the stable road-network conditions (Fig 5, Fig 6) with the different post-disaster scenarios demonstrates the flooding event impact in the overall road-network performance. For a cartographical overview of all described configurational analyses, refer to [33].

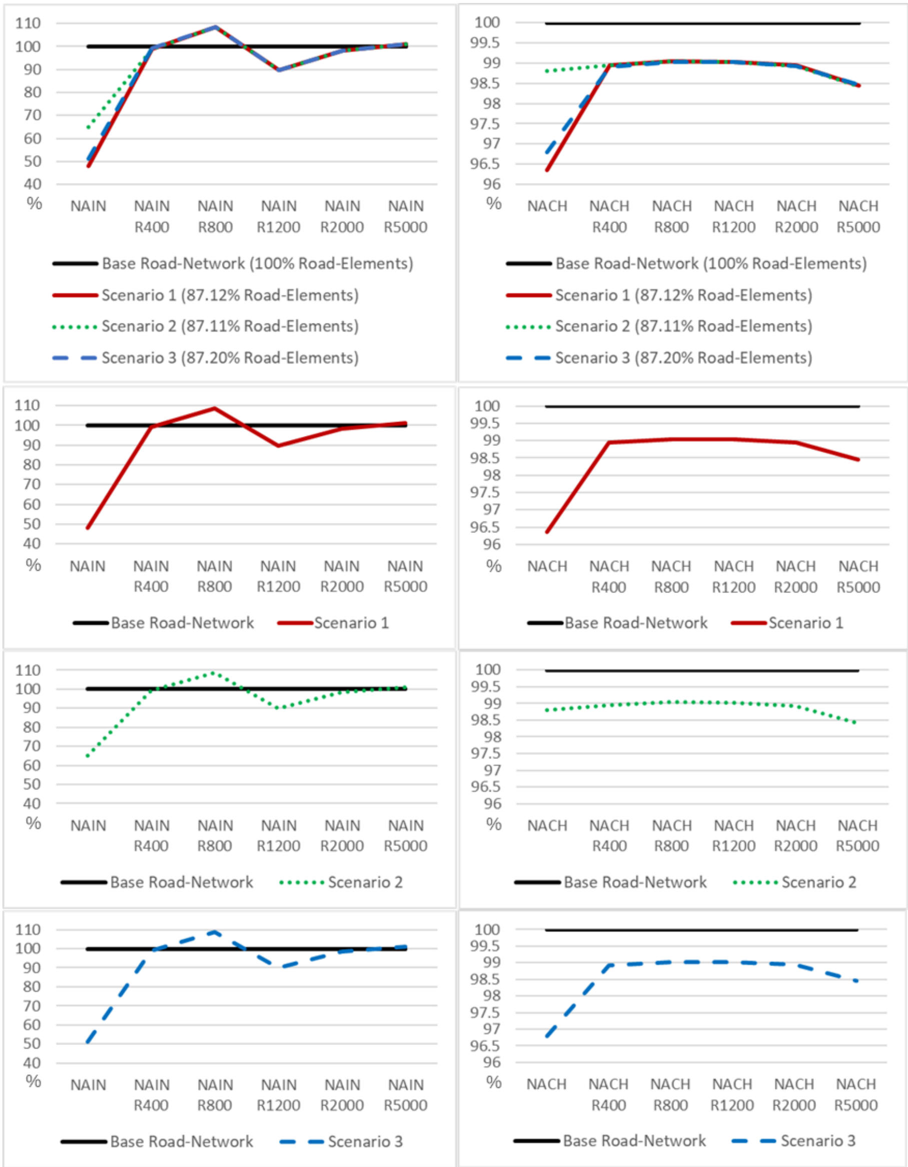

Fig. 5. Comparison of NAIN and NACH (Rn-Metric) for the different post-disaster Scenarios.

In Scenario 1, that corresponds to the road-network state on May 6, 2024, flooding rendered 12.8% of the total urban system inaccessible to both pedestrians and motorized vehicles (Fig.5,Fig.6). While this is a relatively small percentage, the road-elements affected, such as the BR-290, BR-116 and BR-448, as well as primary roads within Porto Alegre’s urban area, are part of key connectivity axes linking the metropolitan core to its larger metropolitan area. This disruption resulted into three isolated “independent systems,” as road-access from the metropolitan core to the northwest –

and especially to the southwest – was severed (Fig.6,Fig.7). Overall relative accessibility is then critically impacted in this scenario, with $NAIN_{Rn}$ showing a 47.9% reduction in its average values compared to the stable road-network. Core-centralities (highlighted as red-orange road-elements) shifted from Porto Alegre's urban area towards RS-118, the sole viable connection remaining after the flood (Fig.7,Fig.8).The effects on relative accessibility highlight the importance of BR-290 as a connective structure for Porto Alegre, towards its metropolitan area as, even if its infrastructure was mostly unaffected by the floods, due to its elevated position, the inundation of its accesses has led to a general collapse in terms of system integration. Furthermore, due to interruptions towards the north, affecting the BR-116 continuity, urban areas that corresponded to core-centralities in the stable road-network (Fig. 6) were relegated to a segregated status (highlighted as green-blue road-elements), reflecting the significative compromise in their accessibility due to the increment on distance. Access to this region from the metropolitan core, was guaranteed only through regional routes towards the northeast (RS-020, RS-239), located farther from the main urban settlements (Fig.7).

Despite the impact on general accessibility, the same behaviour is not verified at local scales, as the flooded road-network values for NAIN metric radii tend to remain close to the stable road-network (Fig.5). This denotes that the severity of the effects in relative accessibility is dependent on scale. A similar logic is verified for $NACH_{Rn}$, and its metric radii counterparts (Fig.8). The overall *preferential routes* structure (highlighted in red) is not subject to significative changes in position and value (Fig.9). These results attest that, although there is a collapse in terms of regional relative accessibility, a certain degree of cohesiveness was maintained at local scales and among *preferential routes*. These information on the general state of accessibility and route viability within the road-system was communicated to authorities and early-responders [22,23,24], serving as a guide to pinpoint which road-elements had to be preserved, both to ensure the system cohesiveness and to guarantee access to urban facilities (e.g. logistic hubs, material collection points, emergency shelters and hospitals).

Scenario 2 showcased the importance of preserving certain road-elements, providing a complete system collapse simulation, where the RS-118, the sole axis of connection within the larger system is severed (Fig.6;Fig.10). Although, this scenario tends to exhibit a better performance in terms of relative accessibility when $NAIN_{Rn}$ values are considered – 65.0% from the stable road-network, when confronted with the 47.9% from Scenario 1, this increment is mainly due to the formation of four isolated road-networks, with greater internal compactness (Fig.6;Fig.10). In essence, those "independent systems" become representatives of a local context, within a regional setting, as demonstrated in the similarities between Porto Alegre's core-centralities in Scenario 2's $NAIN_{Rn}$ and $NAIN_{R5000}$ (Fig.10; Fig.11).The overall shift in regional core-centralities is, however, noticeable. While Porto Alegre's relative accessibility tends to increase, and return towards its city centre, the centrality in the metropolitan area northern section shifts towards the municipalities linked by the RS-020 and RS-239, both unaffected in terms of river-bound flooding (Fig.9). While relative accessibility impacts seem limited, the severance of the RS-118 would have affected the *preferential routes*, since this road-element established the connection between the two systems.

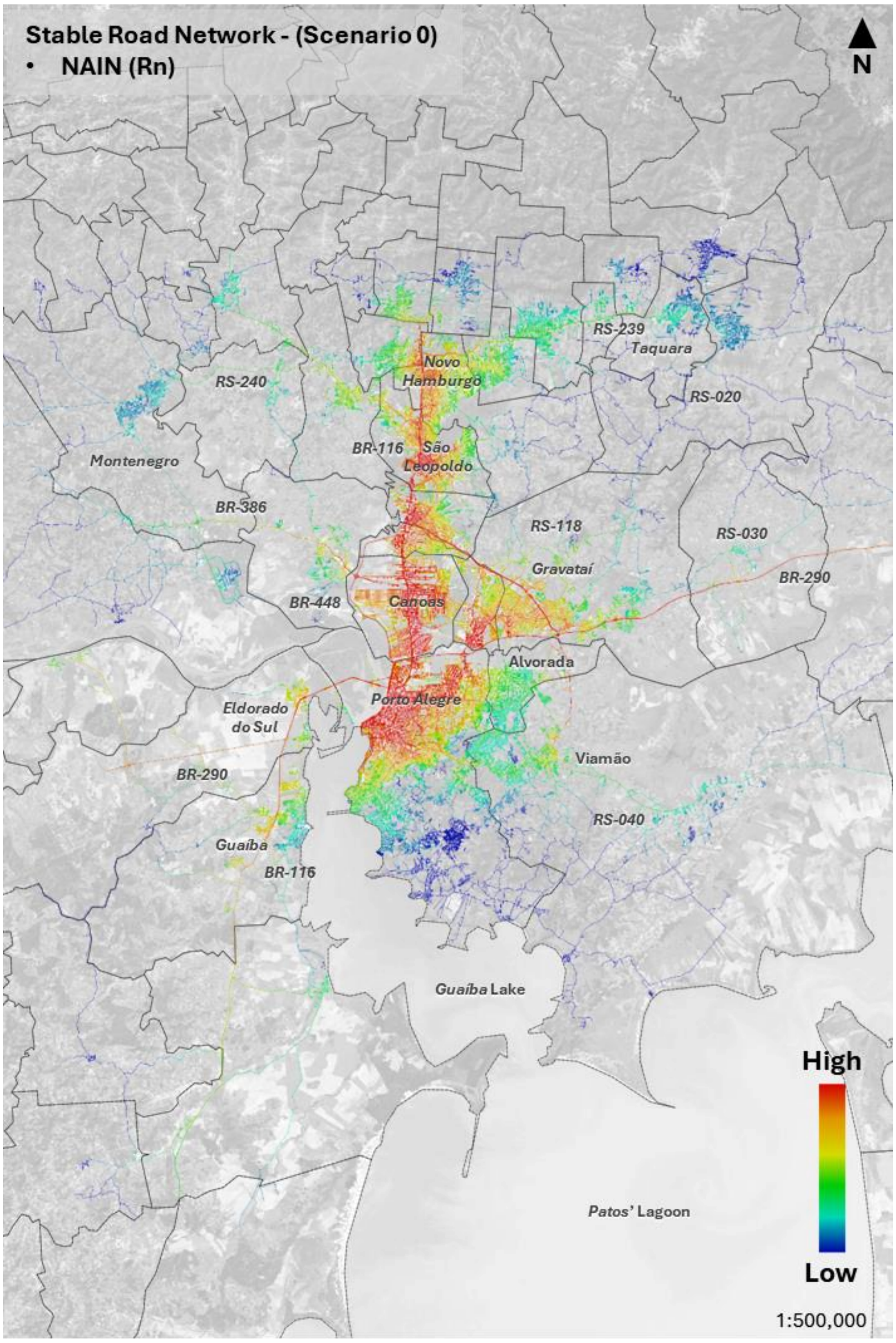

Fig. 6. NAIN RN – Scenario 0

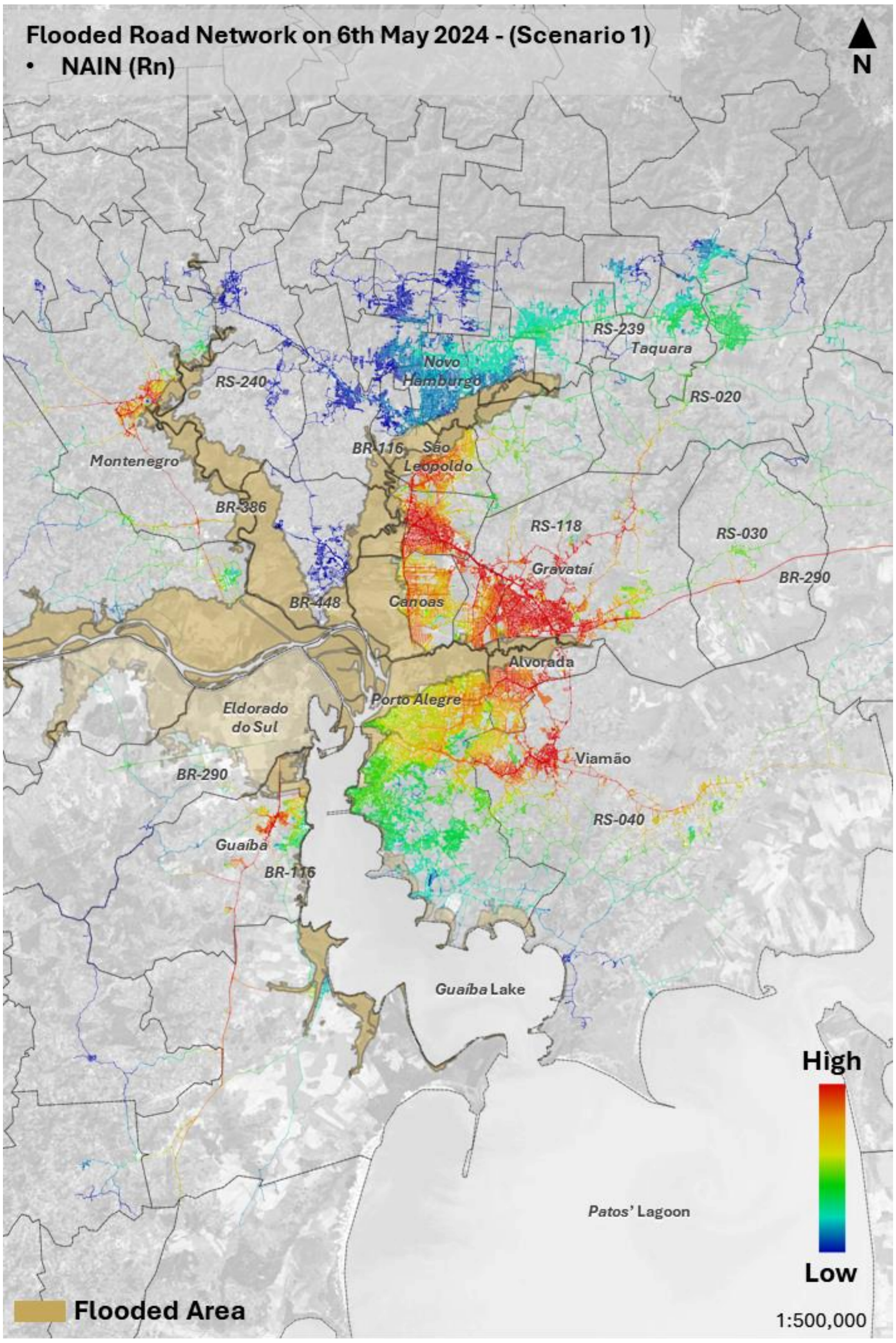

Fig. 7. NAIN RN – Scenario 1

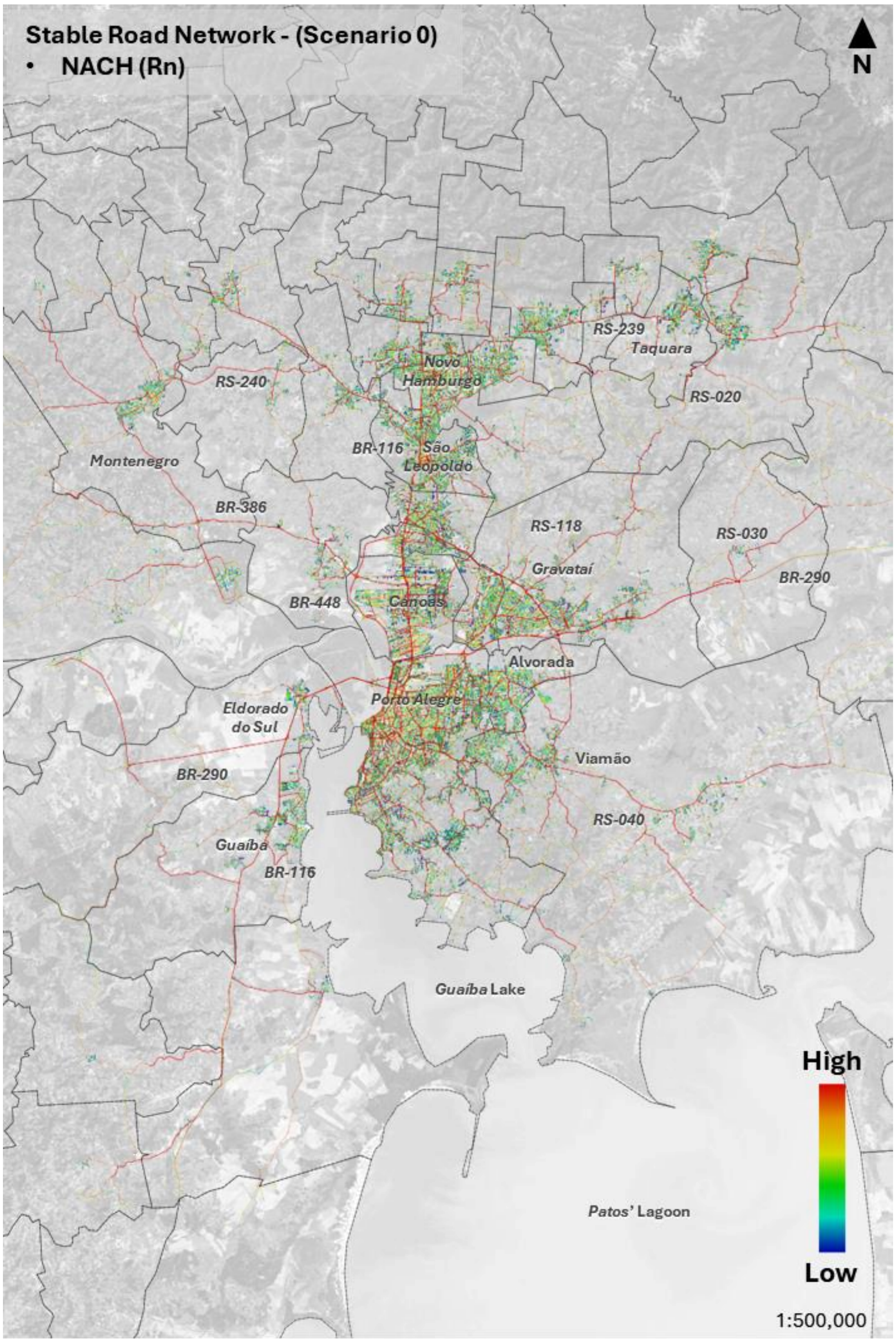

Fig. 8. NACH RN – Scenario 0

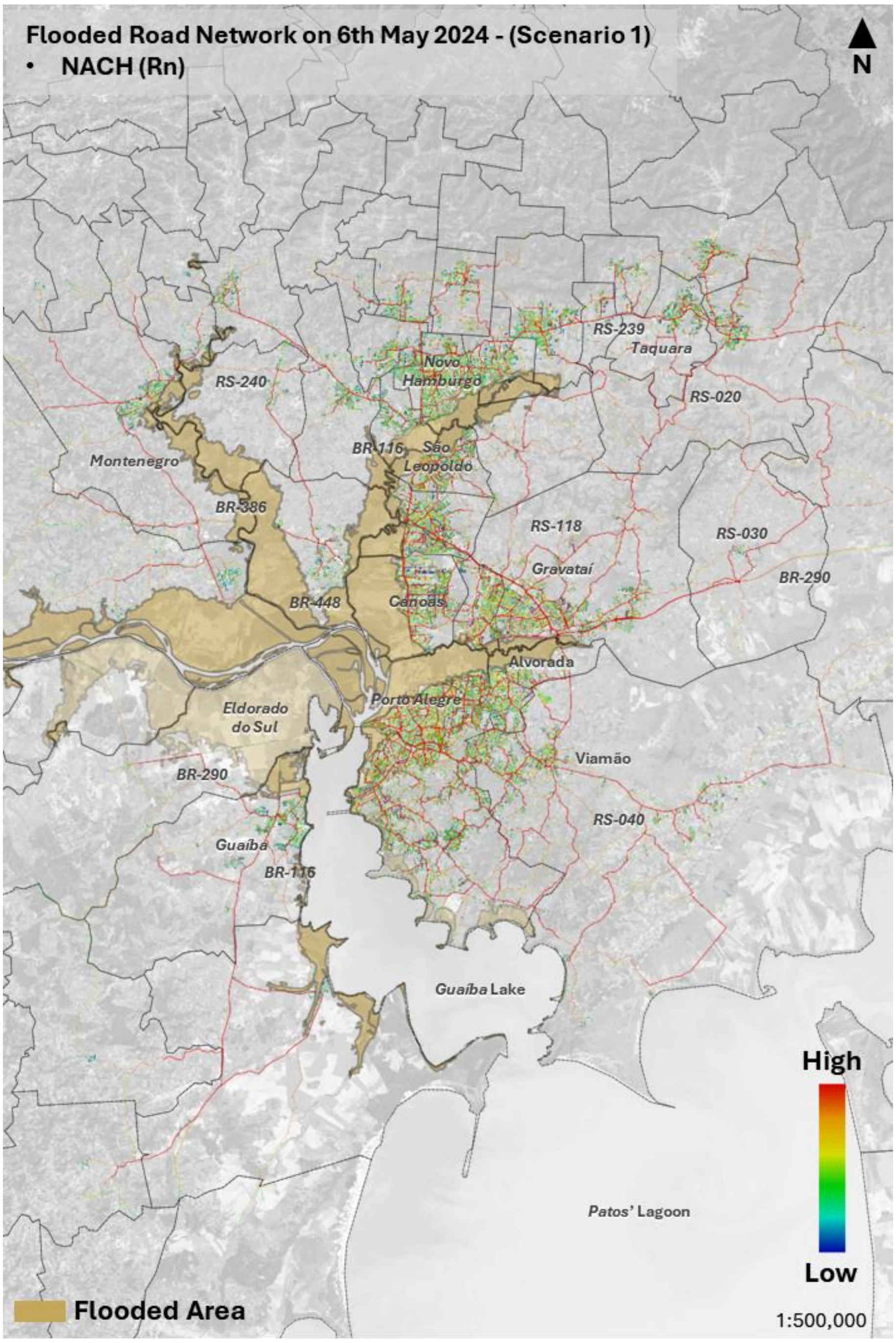

Fig. 9. NACH RN – Scenario 1

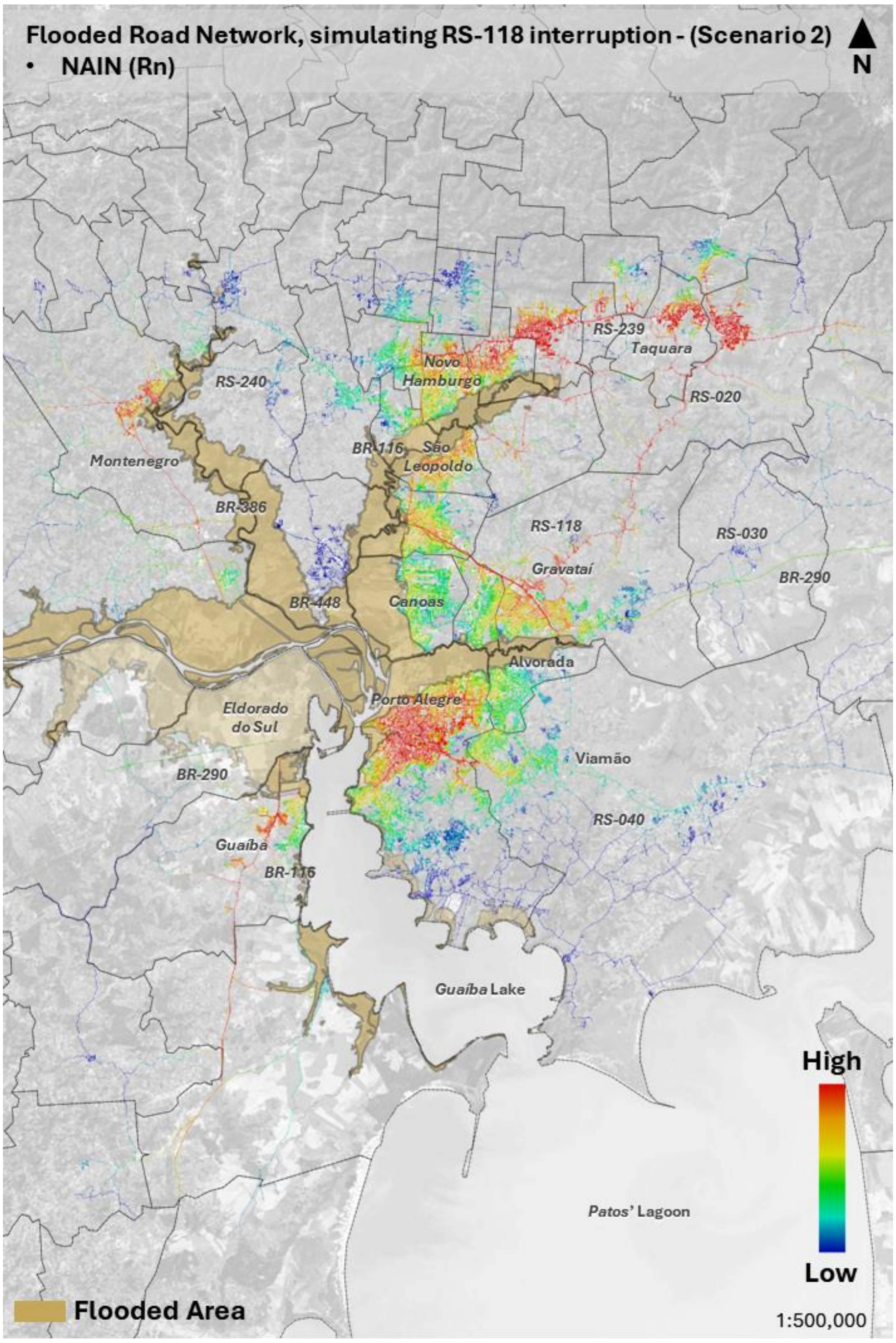

Fig. 10. NAIN RN – Scenario 2

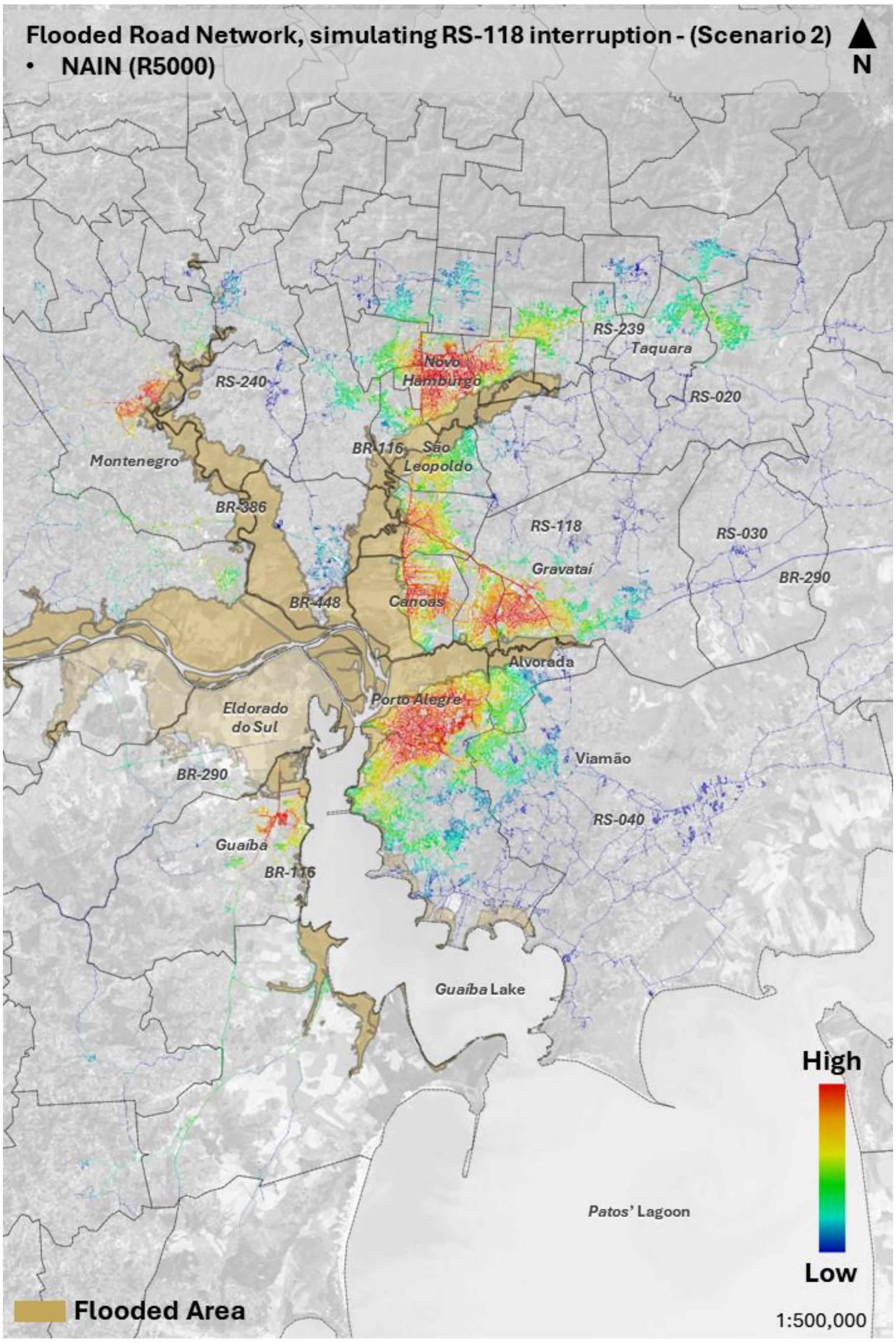

Fig. 11. NAIN R5000 – Scenario 2

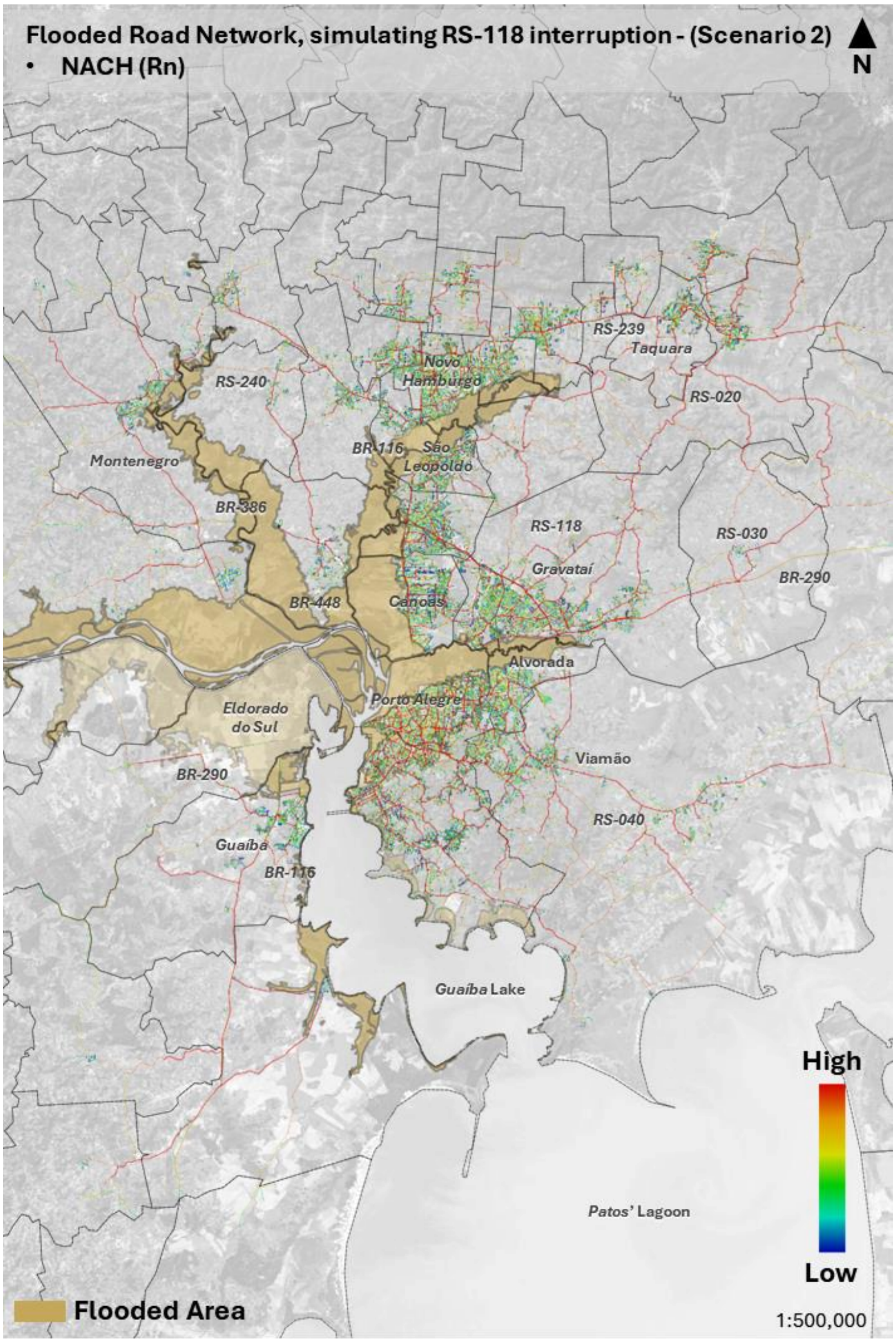

Fig. 12. NACH RN – Scenario 2

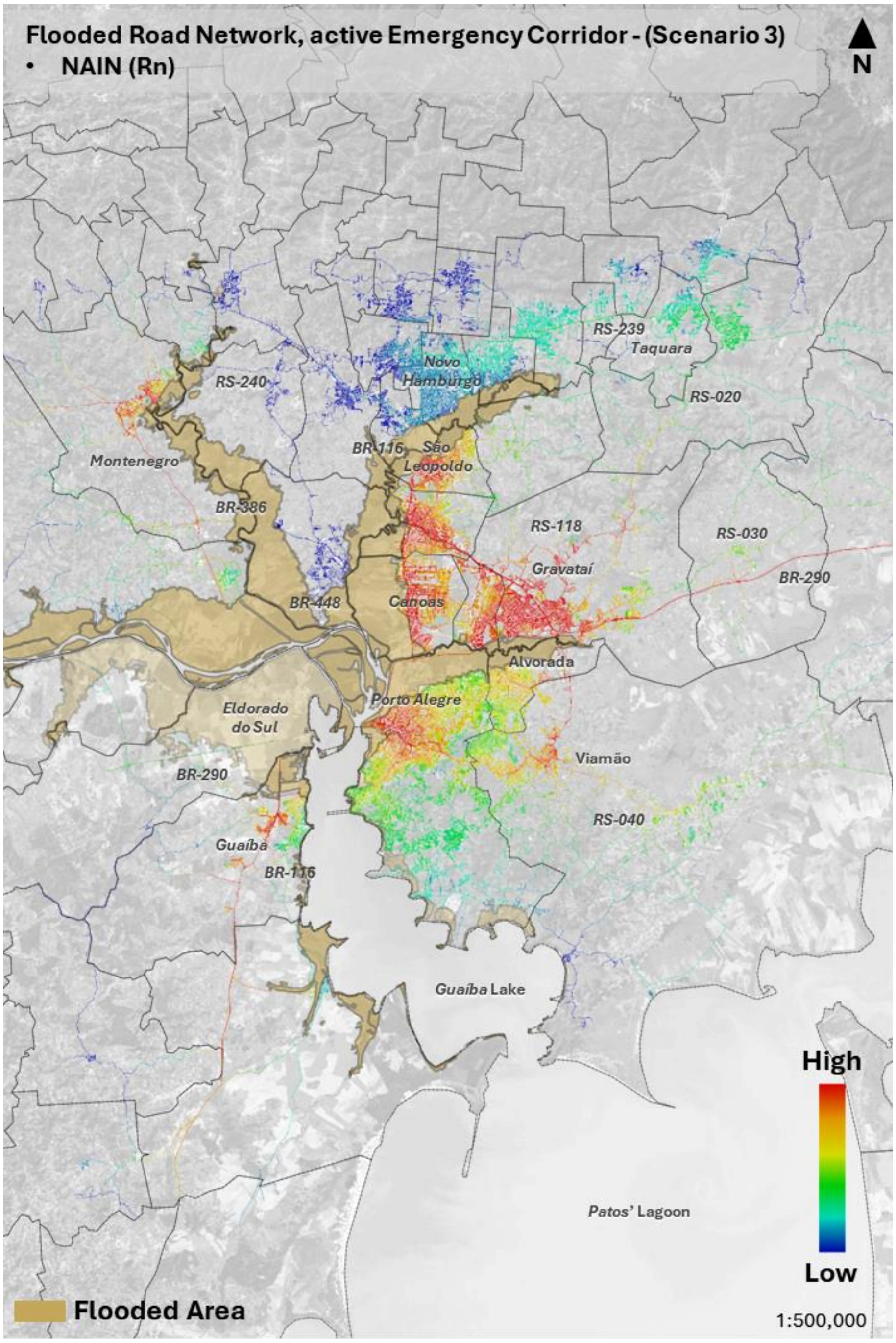

Fig. 13 NAIN RN – Scenario 3

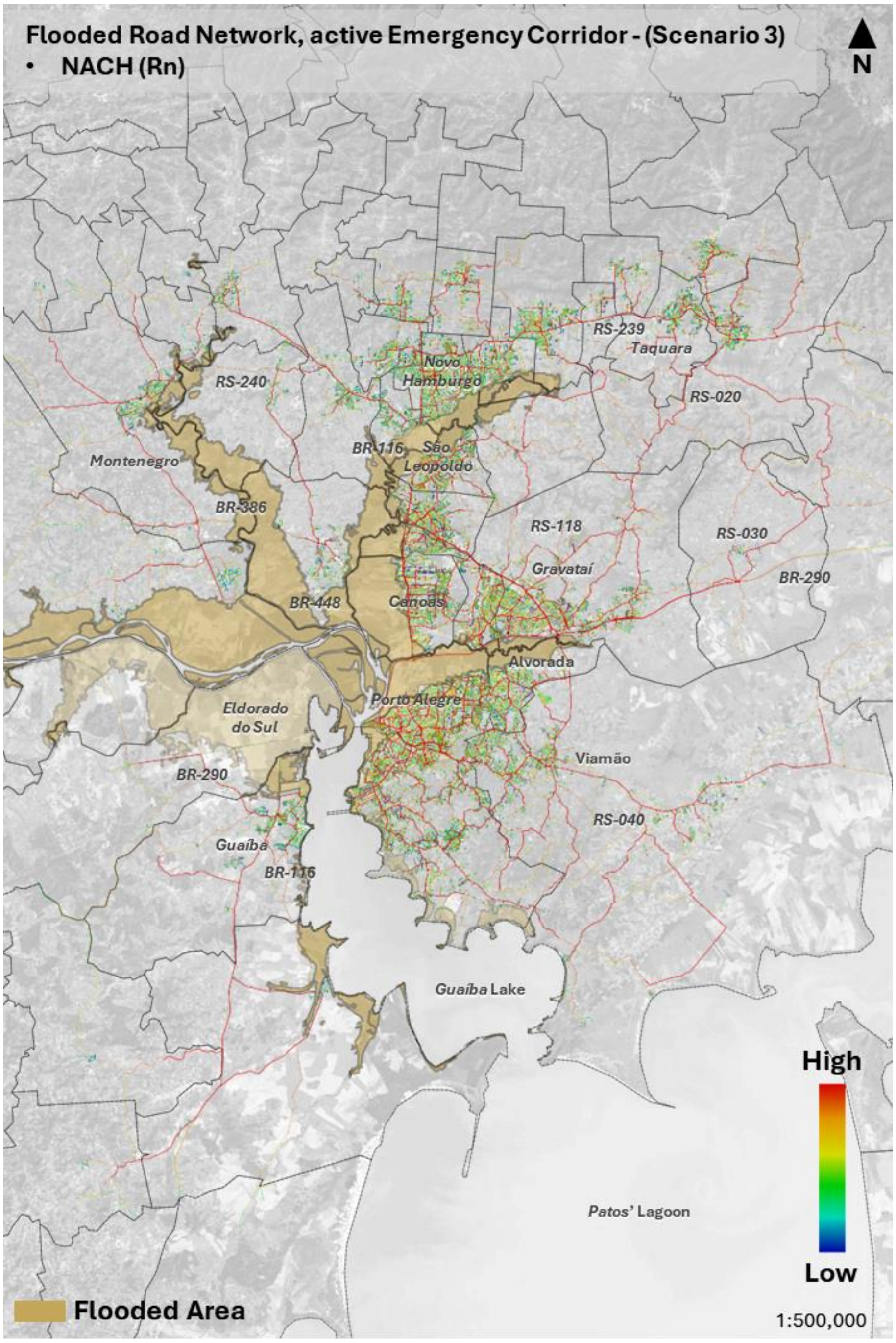

Fig. 14. NACH RN – Scenario 3

This would have an important impact on supplies within Porto Alegre, as it would have isolated the city from the only logistical hub in function, set at Canoas Military Base. Since Porto Alegre's International Airport was flooded, it would have rendered the city unable to receive emergency aid from the rest of Brazil. Moreover, all access would have to be shifted towards Viamão and the RS-040, linked to the coast, a highway with much less vehicle capacity when compared to the BR-290.

Scenario 3 explores the configurational effects of the BR-290 accesses reconnection at Porto Alegre's city centre, which were disrupted on May 6th, 2024 (Scenario 1) and led to the expressive shift of the core-centralities and relative accessibility patterns in the metropolitan area. This scenario reflects the emergency humanitarian corridor construction, finalised on May 10th, 2024, that increased the height of the flooded roads, allowing access between the elevated sections of the highway (Fig.6;Fig.13; Fig.14). In terms of relative accessibility, the corridor manages to slightly increase average $NAIN_{Rn}$ values to 51.0% of the stable road-network (Fig.5).

The core-centralities are, again, shifted towards Porto Alegre's city centre, and reflect a scenario closer to the stable road-network (Fig.6; Fig.13), improving the relative accessibility conditions towards Canoas and the rest of Porto Alegre's metropolitan area. Although, this scenario exacerbates the segregation of the Sino's Valley municipalities (São Leopoldo and Novo Hamburgo), caused by the BR-116 and BR-448 floodings (Fig.13), accessing the BR-290 and, through it, Canoas and Gravataí municipalities, recovered an important part of the *preferential routes*, within the metropolitan area – opening a crucial second redundancy path on the system (Fig.14).

Moreover, it provided a closer access point to the logistical hub, being important for response and relief actions delivered from outside the state. Overall, it can be said that Scenario 3 indicates the most critical point of intervention to render the system accessible in terms of vehicular movement, an information that was taken in account by stakeholders [22,23,24].

Together, these scenarios highlight the critical role of scenario-based planning in enhancing urban resilience, illustrating how targeted interventions can maintain network functionality and enable effective emergency response during severe flooding events.

4 Conclusions

This study of Porto Alegre's metropolitan area road-network response during the 2024 floods demonstrates the potential of configurational analysis as a formal method in disaster response. Scenario-based evaluations allowed stakeholders to readily understand the issues, and were instrumental in providing decision-support information, demonstrating how the flood events impacted and altered Porto Alegre's road-system and its metropolitan area performance, in terms of *relative accessibility* and *preferential routes choice*.

Scenario 1 showcased the extent of the flood-derived disruptions to key regional routes, particularly how it isolated the main road-network from certain parts of metropolitan areas towards the northwest and southwest. Moreover, it emphasized the vulnerabilities of critical infrastructure connections, such as the BR-116, the BR-290 and the RS-118. This information is useful, not only for early-response, but also for recovery and preparation phases.

Scenario 2, simulated a complete severance of the remaining access point set in the RS-118, demonstrating the potential for a total system collapse. It underscored for the stakeholders and early-responders the necessity of preserving key *preferential routes*, and the overall absence of road redundancies in those critical points of accessibility.

Lastly, Scenario 3 visualized how the emergency corridor managed to establish partial connectivity within the metropolitan area, enabling vital access for emergency logistics and supply distribution. In that aspect, the information provided by the configurational analyses, reinforced that the point of intervention was the one that could provide the best results in terms of re-integrating the road-circulation network, and re-distributing *relative accessibility* in a manner similar to that of the pre-disaster stable road-network.

Collectively, formal methods provide decision support to effectively cope with emergency responses during large-scale floodings. However, challenges remain, first in the realm of formal methods themselves, as despite the relatively quick construction of the model, computational demands still limit real-time applications of such analysis. Addressing these limitations will be essential to embedding these methods within comprehensive decision-support frameworks. Moreover, the communication of the results is also relevant, as information must be tailored to the decision-maker understanding [22, 23]. As discussed in [21], these models can be embedded in an outcome-driven decision-support framework for disaster management.

Ultimately, this research underscores formal methods, such as configurational analysis as a promising tool for enhancing urban resilience by providing actionable insights that bolster both pre-disaster planning and post-disaster recovery. Its ability to convey critical information in an accessible format supports the agility of emergency responses, which is increasingly vital in flood-prone urban areas facing frequent natural disasters. This approach offers a valuable model for strengthening urban infrastructure resilience, enabling cities to maintain critical connectivity and continuity during crises.

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