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Spatial reconfigurations within flood-prone areas:

the case of Porto Alegre Metropolitan Region – Brazil

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ABSTRACT

Porto Alegre's Metropolitan Region (PAMR), located in the state of *Rio Grande do Sul*, Brazil, lays within the *Caí, Jacuí, Gravataí* and *Sinos* river basin. Its lowlands, that comprise the capital city of *Porto Alegre* and the bordering municipalities of *Alvorada, Cachoeirinha, Gravataí* and *Canoas* are historically flood-prone areas. In the last decades, a considerable urban spawl followed the metropolitan regional mobility axes towards these lowlands, given the demand for low-cost land for housing development. This phenomenon characterizes Brazilian urbanization patterns, in that advances towards unsuitable areas result in pressing socioeconomic problems. Until recently, the Metropolitan Planning Agency (METROPLAN) had at disposition only dated information about the areas' hydrogeological risk, which hindered their envirionmental studies, hindering risk management strategies, and land parcelling policies. Considering that water-floods are a main urban disaster cause in Brazil, and the regional climate changes, the paper verifies, under the light of the most recent hydrogeological risk assessment, the potential spatial configuration changes that a flood-event can cause to the road-infrastructure at municipal and regional scales. Normalized Angular Integration (NAIN) and Choice (NACH) measures are used to compare the current spatial system to a simulation of the flood affected system, depicting a) the critical nodes and system collapse tendencies; b) the reconfiguration of the urban grid under flood-events; c) land-parcelling feasibility under risk areas. The results' discussion addresses the road-network transformations and the multiscale resilience tendencies, indicating parameters to analyse novel parcelling permissions requests based on flood-risk constrains and the maintenance of spatial system integrity.

KEYWORDS

Water-flood risk, disaster management, space syntax measures, network resilience, metropolitan areas

1 INTRODUCTION

In Brazil, the housing developments that drive the urban expansions and sprawl tend to follow a sparse, spatially-discontinuous, and fragmentary process, which is based on the use of peripheral low-cost, unoccupied land that borders the main regional centre and its road-circulation network mobility axes. This reiterates the notion of metropolisation (Elissalde, 2004), in a process in which land parcelling and housing developments characterized by sparse connectivity between spaces define morphological and functional qualitative transformations in the urban network. One of its results consist in the emergence of a discontinuous and heterogeneous spatial configuration, in which a polycentric rearrangement prevails; small functional centres are loosely connected to a large urban centre through single road-infrastructures that cross expanses of unoccupied land. The expansion of these small functional centres, however, is often not well-supported from a planning standpoint. Result of irregular occupations, unguided urban sprawl creates a plethora of socioeconomic problems and is susceptible to a series of unaddressed risks.

In Brazil there are 69 metropolitan regions, that differ in extension, population size and functional composition. As stated, historically, Brazilian metropolitan peripheries sprawl is related to informal urbanisation, following the accessibility at local scale and, more importantly, the mobility at regional scale – which characterizes new expansions with a linear morphology, that subsequently guides the sprawl tendencies. Due to their unregulated nature, newly urbanized areas are often set within territories that are quite susceptible to environmental risks. Among natural hazards, seasonal flooding is among the main urban disaster causes in the country, affecting almost 40% of Brazilian municipalities and 30% of its urban network (IBGE, 2013). Such disasters often implicate in recurrent road-circulation infrastructure collapses, homelessness, significative financial losses for public and private institutions, and more than often, a significative loss of life (Figure 1).

Figure 1. Porto Alegre 1941 flood-event (©PREFPOA); Porto Alegres' 2017 and 2021 flood-event (©g1.oglobo.com)

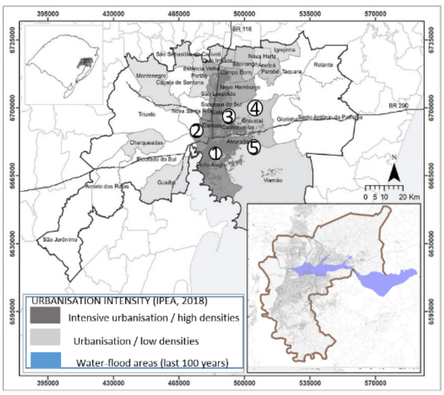
Vulnerability to environmental hazards (Huq et al., 2020) became one of the main concerns for municipal and metropolitan regions management administration, since their impacts on citizen´s lives, public infrastructure and economic development lay at the core of several long-term planning problems. From the 2000's onwards, the *Agenda 21's Sustainable Development Objectives (SDO) and Disasters Risk Management (DRM)* actions underline metropolitan planning goals in Brazil (IPEA, 2015). Therefore, addressing urban resilience and urban sprawl control and integrating them into water-basins management, became a priority when novel urban developments and land-parcelling policies were considered. In the same manner, studies that consider the configuration of the urban road-circulation network can contribute to guide such urban expansions, determining how the structure would react to interruptions, and identifying the possible risks to the network structure.

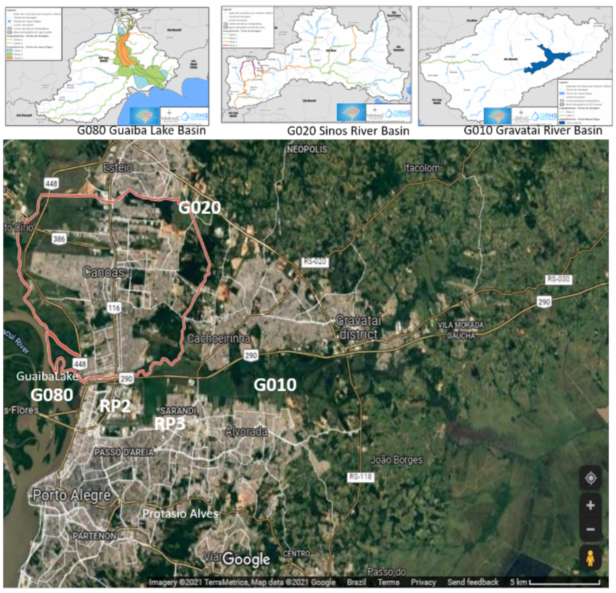
The relevance in addressing water-flood risks relays on the requirements for incorporating these actions into public polices, the absence of up-to-date studies about water-flood risk and impacts on Porto Alegre's Metropolitan Region territory (PAMR) (METROPLAN, 2018a and 2018b). The analysis considers spatial configuration changes imposed by water-flood related disasters on the metropolitan system and overall vulnerability on the circulation network. Depict spatial configuration radical changes is one of the most important datum enabling to address the vulnerability levels of urban agglomerates and communities under disaster risk. Therefore, apposing current and simulated situations provides tendencies for the possible outcomes of a disaster event. The focus is on how these changes can compromise accessibility and mobility patterns within metropolitan circulation networks, damaging the commuting and transport systems, as well as isolating the population from services and urban equipment.

The spatial modelling combines the configurational component, based on Space Syntax' Network Analysis (Angular Segment Analysis - ASA) with a risk assessment spatial analysis based on the hydrogeological risk area for the river basin. The water-flood patch perimeter informs the areas under flood risk that lie within the urbanization limits. Its superimposition to the current road-circulation network enables to verify: a) the current metropolitan road-circulation network configuration, addressing relative accessibility (through Normalized Angular Integration – NAIN) and preferential routes system (through Normalized Angular Choice – NACH); b) the network configuration after suppressing the urban grids' segments that could be affected by flooding events; c) to evaluate new land-parcelling proposals based on the two modelling results and on the overall risk presented. The objective is to outline water-flood impacts on relative accessibility at municipal scale, and changes to preferential routes systems at metropolitan scale, identifying potential choke points on the road-circulation systems´ under water-flood risk. Discussion and conclusions draw from an empirical case within the Porto Alegre Metropolitan Region, an area recurrently affected by water-floods which displays several new peripheral centralities, emerging due to population densification and functional restructuring; that is, undergoing intensive and fast metropolisation processes.

1.1 The Porto Alegre Metropolitan Region - PAMR: a disaster risk context

Porto Alegre's Metropolitan Region (PAMR) (08/06/1973; Martins, 2013) currently encompasses a territory of 10 346,00 km² (IBGE, 2002) divided across 34 municipalities. In terms of population, the PAMR possess more than 4,317.508 inhabitants, an average population density of 417 inhabitants per km² (IBGE, 2018). The metropolitan area extends from the cities that constituted the early colonizers' ports. In the 17th century the Portuguese docked on the site where today lies *Porto Alegre, Rio Grande do Sul's* state capital. In 1824, German colonizers reached the place where *São Leopoldo* municipality is set, on the *Sinos* riverbanks. Other ports were eventually set on the *Jacuí, Caí,* and *Gravataí* rivers towards the municipalities of *Alvorada, Cachoeirinha, Gravataí* and *Canoas*. *Porto Alegre* is set on the conjoined delta of these four rivers, and eventually has grown to occupy the whole western shore of the *Lago Guaiba* – an inland lake formed by these river basins – that has a connection to the *Lagoa dos Patos*, the largest inland lagoon in South America and, through it, to the Atlantic Sea. From 1874 onwards, a railroad heading north connected *Porto Alegre* to the rest of Brazilian territory, structuring the inland territory's occupation, which led to an incipient urbanization that spread from the cities and villages that grew around this railroad axis' railway stations. From 1967, highways assumed the main role in urbanization patterns, as the BR-116 construction connecting the Brazil-Uruguay border to the State of Ceará, in the northeast led to the growth of several municipalities in *Porto Alegre's* borders. From this period onwards, PAMR urban expansions were mainly guided by the range of influence of the new highways – both national and regional – as several roadways such the RS-030 (*Porto Alegre – Atlantic Coast*) and the BR-290 (*Brazil – Argentina*) became highly demanded axis both for intra and extra metropolitan circulation effectively structuring *Porto Alegre* and its neighbouring cities (Figure 2).





Municipality	Pop. (inhab)	Area (km²)	Density inhab/km²	River Basin x Munic. area	Urban landuse (%)
PORTO ALEGRE	1,409.351	495	2837,53	G010 Gravataí 19% G080 Guaíba 81%	100%
CANOAS	323.827	131	2472	G10 Gravataí 15% G20 Sinos 56% G80 Guaiba 29%	99%
CACHOEIRINHA	118.178	44	2688	G010 Gravatai 82% G020 Sinos 18%	100%
GRAVATAI	255.360	463	552	G010 Gravatai 85% G020 Sinos 15%	94%
ALVORADA	195.673	72	2743,94	G010 Gravataí 100%	100%

Figure 2. Porto Alegre Metropolitan Region – PAMR – urbanisation intensity; cut-out and river basins water-flood risk areas (IPEA, 2015; Melchior et al., 2018; IBGE, 2013; SEMARS, 2020).

The already complex metropolitan highway system was further extended in the late 1990's, when a regional ring-road (RS-118) was constructed to connect the north-south axis (BR-116) to the east-west axis (BR-290; RS-040) through the municipality of *Viamão*. In the late 2010's, another addition to the road-system was made when the BR-448 was finished, which connected *Porto Alegre* to *Canoas* and created an alternative to the saturated BR-116. Both highways cross the *Gravataí* river and are important contributors to the ring structure that formed across the region, which defines both the boundaries and the urban expansion axes of growth, densification, and conurbation within the PAMR. Still, an uneven population distribution and municipalities´ size, associated with a different share of urbanized land and economic diversity characterises the PAMR, as *Porto Alegre* holds a position of relative importance when compared to the other cities. This turns this metropolitan region into a prime example of the Brazilian metropolisation process. Its configuration draws from the concept of socioeconomic community, and more than often the problems of its urban agglomerates exceed the municipalities' territorial frames and executive sphere, which motivated the metropolitan area institution (Martins, 2013) in order to provide a sustainable regional development.

As stated, the PAMR area comprises the *Gravataí, Sinos, Caí* and *Jacuí* river basins, tributary to the delta and the *Lago Guaíba* (*Porto Alegre*), forming six different hydrographic basins. These different watersheds are inserted within the most dense and consolidated parts of the metropolitan area (Figure 2). *Porto Alegre*, the capital city, displays an urbanization index of over 90% and houses 35% of the metropolitan population; the bordering municipalities of *Canoas, Cahoeirinha, Gravataí and Alvorada* constitute together, another continuous urbanized and densely populated area, with 42.5% of the metropolitan population distributed across the four municipalities. In the latest Brazilian Institute of Statistics Census (IBGE, 2021), it was identified that there are more than 3,205 dwellings and 10,706 inhabitants under permanent flood risk in *Porto Alegre* alone, a city that has undergone several severe flood episodes during its history (Figure 1, p.2). Since the metropolitan core is set within a delta, it was object of several water management and risk mitigation studies and projects conducted between 1940 to 1990 by the Federal Government's Department for Sanitation Works (DNOS), then extinct due to political reasons. Between 1990 and 2015 there weren´t any studies on the basins, coinciding with the PAMR significant growth in built-area and densification as well as periphery municipalities sprawl, when some of the most severe flooding events occurred. In 2015, a contract to perform updated hydrogeological surveys finished in 2018, comprising several technical reports addressing these different river basins (MinC; METROPLAN, 2018a and MinC; METROPLAN, 2018b). These data allowed us to determine the conditions of the water-flood patches and their territorial extension. A cut-out was established depicting the most flood-prone area within the PAMR, encompassing the Northern Planning Regions of its core - *Porto Alegre* - and the entirety of *Canoas, Gravataí, Cachoeirinha* and *Alvorada* municipalities (Figure 2, p.2 Figure 3, p.9). This provided a comparative framework to analyse disaster risk effects on road network configuration and spatial system resilience, pinpointing potential road-circulation collapse links. Regarding planning policies at municipality and regional levels, this cut-out also has the potential to illustrate advisable parameters for analysing land parcelling permissions location, a pressing issue for planning authorities, since new housing development's function answer for more than 50% of urban expansion, driving sprawl patterns. Based on this delimitation, it was possible to discuss the impacts of future floods, including the ones regarding regional and local accessibility aided by Space Syntax theory and methodology, which is the main purpose of the present paper.

1.2 Disaster-risk management and Space Syntax Theory

Space Syntax intertwine to disaster risk management, since its theoretical fundamentals and modelling instruments were widely applied in pre and post disaster-risk analysis (Guiliani et al., 2019, Pezzica et. al 2021), aiding planners to outline the main problems related to road-circulation blockages and emergency infrastructure in urban environments. For the past 15 years, extensive research into variable subjects related to disaster risk management has been explored in-depth through Space Syntax methods by authors like Cutini & Di Pinto (2010) and Fakhrurrazi and Van Nes (2012). Within this field, recent research conducted in Italy (Cutini, 2013; Cutini, et al., 2019; Guiliani et al., 2019; Rusci et al. 2021; Pezzica et. al, 2021), spam across a diversity of hazard risk situations – flood risks, seismic risks –, while exploring Space Syntax methodological potentials to analyse and evaluate sudden road-network transformations, towards developing strategies for limiting their negative effects on urban life. More recent works (Pezzica et. et al, 2022) focus on addressing spatial system structure and, in particular, their resilience towards disaster effects and abrupt changes, and strive to identify the elements that are more "fragile" in the road-circulation network. Evaluating spatial system´s vulnerabilities facing high hazard risk probability is foremost to address preventive planning and cope with potential urban system´s permanent or periodic transformations (Cutini, et al., 2019).

Research problems related to disaster risk management combining multivariable modelling to spatial configuration analysis remains steady and prolific within space syntax community, acknowledging its importance in outlining disaster risk management long-term strategies (De Falco & Giuliani, 2019). The statement that "natural disasters" impacts relate to multivariable interactions within the built environment, therefore, are context dependent, underlines the relevance of space syntax methods in approaching a problem shared historically and periodically by most part of Brazilian urbanised areas: water-flood risk. It is so since most Brazilian city cores grew along riverbeds, therefore subject to potential – and frequent - losses and regional circulation disruptions (Caiado et al., 2012).
Space syntax methods and tools allow comparative analysis between the actual system and the disrupted circulation system, forecasting alternative scenarios to mitigate the negative effects of periodic or seasonal floods. According to Gil & Steinbach (2008) floods have a serious impact on the circulation and transport network stressing that other authors point out that the circulation system disruption on particular nodes of the network have different degrees and impacts on the disruption of the whole spatial system. That is, a water-flood patch can give emergency to a different spatial configuration in which patterns of accessibility and mobility are changed. Outcomes of that phenomena spam from insulating parts of the metropolitan whole to cutting main regional connections.

Esposito & Di Pinto (2014) research on flood-risk scenarios draws from "the concept of urban resilience taken as a net property in a continuous process", which contemplates its complexity and a set of structural and non-structural measures to increase recovery rates. They stress that flood-risk effects extrapolate the directly endangered areas, and therefore change patterns of accessibility and mobility at local and regional scales. This corroborates Gil & Steinberg (2008) findings: areas insulation is one of the main effects of river floods, when ephemeral spatial configurations emerge, altering the circulation network s nodes roles and producing changes along the connected or disconnected areas. They propose a typology according to an area degree of insulation to its surroundings: islands (without land access); peninsulas (single connection or critical route for emergency access); periphery (difficult to reach); bridges (more central role than before). Recommendations for performing risk analysis encompass the entire spatial system or a significant part of it, to depict water-flood indirect outcomes, stressing that space syntax methods are useful to identify disaster related effects on the urban network structure, supportive to natural risk disaster planning strategies (Esposito & Di Pinto, 2015). This converges to the objectives pursued here, since new land parcelling projects analysis should consider if their location contributes to weakening spatial system resilience and becoming a liability to dwellers. The authors evaluated if measures oriented to risk reduction can effectively improve the efficiency and disaster recovery of urban structures "according to their different specific influence on the global reaction of the city to risk event" (Esposito & Di Pinto, 2014). Abshirini & Koch (2017) findings on spatial system resilience weakening factors endorse the above: archipelago-style developments (sparsely connected to rest of the system) and weak integration patterns.

Cutini (2013) also indicates that Mean Connectivity (Cm) metric, which depicts the density of alternative paths within a given area in case of disaster, is a useful evaluation variable. Esposito & Di Pinto (2014) examined changes in angular analysis for indexes proposed in Cutini (2013) and demonstrated that variations where despicable, attesting to the circulation system´s resilience under flood-related disasters (Esposito & Di Pinto, 2014). Markov-based centrality models, such as the ones developed by Altafini et al (2022), are being incorporated into Space Syntax and can prove useful for future endeavours in disaster-risk and resilience analysis. Those models are tailored to depict the road-circulation network connections relative importance, highlighting which road-elements are crucial to maintaining system cohesion. Hence, these novel metrics can highlight which potential abrupt changes collapse in the urban-regional circulation structure. Its relevance for future analysis of the empirical case is noted, above all, in identifying if elements that are interrupted by the potential flood-patch are actually responsible for the overall global system structure.

In this paper, these directives area followed to analyse and discuss the results found for the Porto Alegre Metropolitan region proposed cut-out, Nevertheless, this approach resumes to the currently established Angular Segment Analysis (ASA) for a preliminary evaluation of the phenomena, to instruct new land parcelling proposals and risk-based analysis according to potential major changes in accessibility patterns. The literature review suffices to identify sensitive water-flooded paths as much as the probable insulation of streets or areas (Cutini et al, 2019).

2 DATASETS AND METHODS

2.1 Our approach for Space Syntax modelling

Recent methodological developments in Space Syntax Angular Segment Analyses (ASA) proved themselves efficient in analysing urban-regional spatial configuration regarding disaster risk management (Hillier and Iida 2005).

Current ASA methods are based on road-circulation network graphs in which the nodes are represented by Road-Centre Lines (RCL) (Turner, 2007), therefore models represent an accurate depiction of the urban structure. The application of different network centrality measures to a same network – or Multiple Centrality Assessment (MCA) – is a methodology of quantitative spatial analysis that highlight different network properties (i.e. *Integration and Choice*), allowing to understand the movement patterns of that urban structure – be using metric distance (a link attribute assumed as impedance) or topological distance (in which the hierarchical relations between elements are highlighted). In Space Syntax, normalising ASA metrics (*Angular Integration and Angular Choice*) is a crucial step for comparing urban systems with different depths (Hillier et. al, 2012). Normalized Angular Integration (NAIN) is a *closeness centrality* mathematical approximation and depicts the *relative accessibility* – or the topological proximity to other segments, therefore informing which spaces people tend to converge to under disaster events. Normalized Angular Choice (NACH), instead, is a mathematical approximation of the *betweenness centralities*, therefore indicates the most probable travelled shortest paths within the system, which consists in road-elements that are important for connections between urban areas, and, if interrupted, can collapse the system. Normalising these centrality measures incorporates this impedance and this topological hierarchy (depth), suppressing the necessity to perform metric pondered modelling to compare local and global changing effects on urban grids. Therefore, models enable to depict changes in road-network hierarchies within different territorial frames, forecasting potential impacts on metropolitan mobility and local accessibility, in a scenario of occupation removal or different degrees of areas insulation, due to river floods in watershed areas – at the same time, a topological approach can highlight the elements which are “more important” to the network given its overall hierarchy in the global structure.

In our approach, we have chosen to model NAIN and NACH for the case-study area in the PAMR, using a topological approach in DepthMapX 0.8 (2018) in order to identify the hierarchy of each element in the global structure. Resulting datamaps are then spatialized in a GIS-based environment (QGIS, 2020) and establishes a before-and-after scenario, in which the Road-Centre Line system is processed at its current state, and without the elements encompassed within the water-flood patch, providing the tools for a comparative analysis.

2.2 Methodological proceedings for modelling the PAMR flood-risk areas

The PAMR road network, extracted from an OSM base (OpenStreetMap, 2021), comprises the metropolitan region case study cut-out, that encompasses the totality of *Gravataí, Cachoeirinha, Alvorada* and *Canoas* municipalities´ continuous urban grids. *Porto Alegre,* however, has its total urban grid reduced to the North and Northwest planning regions (PR2 and PR3), as those areas are the most affected by flooding risks, and the large size of *Porto Alegre's* system could lead to a biasing of those areas *Angular Integration* measures. Therefore, the empirical study area limits have been set on two important urban avenues: the *Castello Branco* Avenue*,* whose extension directly links to the BR-290; and the *Protásio Alves* Avenue, which establishes a ring-road axis between the *Castello Branco* Avenue at *Porto Alegre's* centre, towards the *Alvorada municipality* and the RS-118 connection (Figure 3).

From this database two maps were produced to support the space syntax measures modelling of NAIN and NACH exclusively for radius *n*, as the main objective is to address the urban-regional road-circulation network effect in the flooding-events. The first map (Figure 3) comprises the current state of the road-circulation network, without flood-related interruptions. On a GIS platform (QGIS, 2020), we overlaid the flood-patch extracted from MinC and METROPLAN (2018a,b) reports comprised within road-circulation network cut-out; through symmetrical difference, areas susceptible to flood-risk were removed, considering terrain topography elevations: therefore, highways that are built above water-flooding levels, remained unaffected by the water-flood patch. Bridges, overpasses, and access roads built to keep the road-infrastructure above flood-prone waterlines were also maintained, whereas the bridges, overpasses, and access roads susceptible to interruption by flooding due to a lower placement were removed, producing the second map (Figure 4).

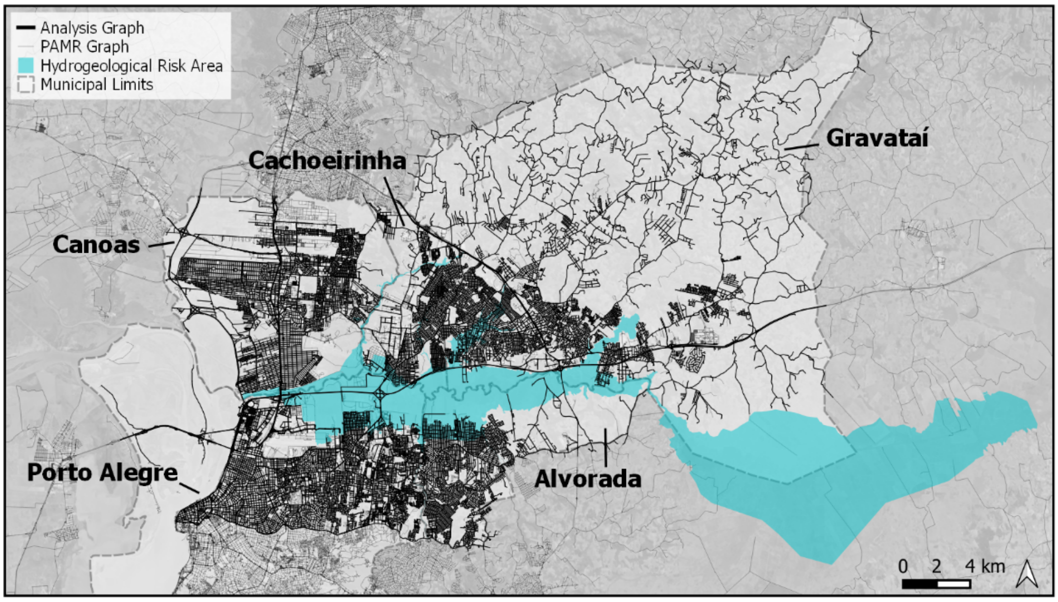


Figure 3. PAMR cut-out + water-flood risk area. Road-graph with flooded patch.

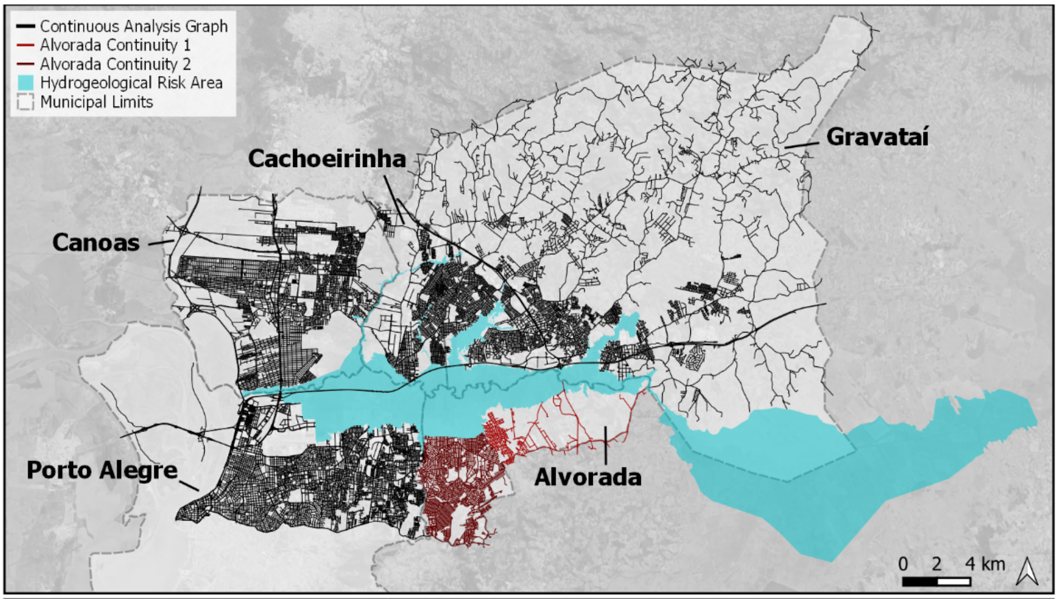


Figure 4. PAMR cut-out road-graph excluding flooded road-elements.

This second map represents the worst possible – yet quite recurrent – scenario regarding flood-risks. Its construction aims to identify the aftereffects in terms of urban system discontinuity within flood-risk patch boundaries. Through this map (Figure 4), it was possible to attest to the almost complete disconnection of *Alvorada* municipality from the rest of the urban agglomerate system and its partition into two distinct continuous spatial elements. This preliminary observation of the flood-prone patch effects on the empirical case circulation network induced the extraction of a partial cut-out focusing solely on the *Alvorada* municipality urban grid to further the analysis of the disconnection and road-system isolation effects on its circulation network performance at global scale. For this reason, this partial cut-out of *Alvorada* was modelled independently.

Maps were constructed in QGIS (2020) as shapefiles (.shp). The road-circulation networks were then exported as.dxf to DepthmapX 0.8 (2018) to estimate NAIN and NACH measures changes. All Depthmap analysis results were then exported as *Mapinfo* files, and then transferred back to the QGIS platform, where they were converted once again into shapefiles (.shp). On QGIS, a quartile selection for NAIN and NACH provided a better frame to analyse the system´s integration patterns and improve choice system visibility by highlighting only the two superior deciles for both models, hence highlighting the 20% of the total number of elements with highest NAIN and NACH measures – depicting both, the integration cores and *preferential routes* system.

Abshirini and Koch (2017) investigated resilience patterns drawing from road network integration and choice measures - consolidating their appliance in Space Syntax research (Hillier et al., 2012; Turner, 2007; Hillier and Iida, 2005). The latter concerns of comparing pre- and post-disturbance states (cf. Cutini, 2013). To do so, they suggest a double-check method based on Hillier (2009), and Cutini (2013) to simulate disturbances in the street network by cutting river-cross-connections and by removing segments with the highest choice value from the network. That is, to identify the network ´s portion binding the urban agglomerate together, since they depict positive correlations to pedestrian movement (NAIN) and attest to robust interactions between the street networks structure and local and regional scale flows (NACH). These findings substantiate the ongoing analyses since there is no need to impose a simulation since water-floods are effectively ongoing phenomena affecting the case study area.

The comparative approach goals are: a) to identify the ring-roads maintaining the spatial system integrity; b) the spatial system rupture point and the sensitive connections for metropolitan mobility; c) the areas where new developments should be avoided; d) tendencies to emerge an archipelago configuration and its local impacts on urban development; d) the spatial system s resilience and collapse tendencies.

3 RESULTS AND DISCUSSION

Water-floods impact differently urbanised areas within the PAMR proposed cut-out as demonstrated in the hydrogeological risk assessment. Results in terms of Integration (NAIN - Rn) and Choice (NACH - Rn) (Figures 5-10; Tables 1 and 2) reveal important dynamics regarding the relation between the current urban structure, the tendencies of urban sprawl, and the flooding risks. Comparing the results for the current and simulated systems for both models – NACH and NAIN (Figures 5-10) – we observe that the system tends to conserve a general structure. The most important road-circulation network elements – that compose the *Castello Branco Avenue* and the highways that connect *Porto Alegre* to *Canoas, Cachoeirinha* and *Gravataí* – are maintained, as those lay above the flood-prone waterline. This means that the man-made terrain elevations on where the highways are placed effectively protect the main core of the regional road-circulation network – a consequence of the considerations and risk assessments made during the 1970's, prior to the highway conclusion – and attribute a certain degree of resilience to PAMR's main road-infrastructures. Still, the results show that certain overpasses and access-roads can be interrupted by severe flooding-events, which may cause important punctual disconnections at the global scale, above all, between *Porto Alegre*, *Canoas, Cachoeirinha* and *Gravataí* municipalities (Figures 5 and 6, p.11; Table 1, p.12). In effect, while the overall patterns of integration are maintained between the municipalities, as the highway system is conserved, its only unaffected access roads towards the urban settlements are located at *Porto Alegre's* urban core and in the crossing between the BR-290 and the RS-118 at *Gravataí,* the endpoints of the metropolitan highway system (Figure 6, p.11).

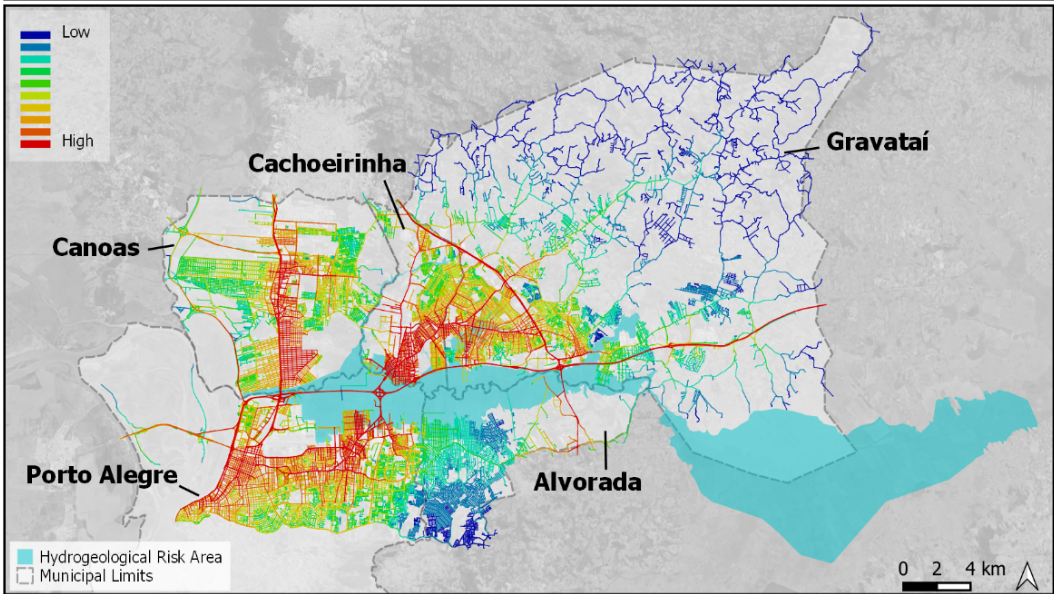


Figure 5. Results for NAIN (Normalized Angular Integration): road network unaffected by floods.

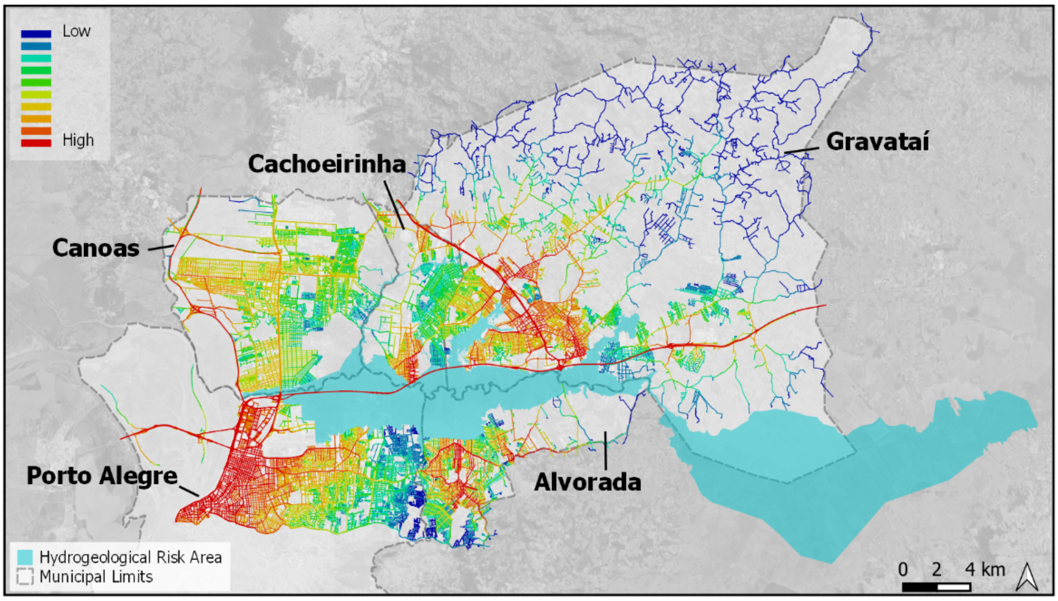


Figure 6. Results for NAIN (Normalized Angular Integration): road network affected by floods

Hence, despite a general maintenance of the system integrity in terms of general *relative accessibility*, congestion effects are certain due to the to-movement concentration in *Porto Alegre's* and *Gravataí's* urban cores, as indicated on the NAIN - Rn results for the simulation under a severe flooding event (Figure 6, p.11, Figures 7 and 8, p.13).

Table 1. NAIN Values (Normalized Angular Integration): PAMR road-network system and 10% restriction.

PAMR - Current	PAMR – Flood Area (Avg.)
0.14 - 0.44 (Low)	0.30 - 0.43 (Low)
0.44 - 0.53	0.43 - 0.48
0.53 - 0.59	0.48 - 0.52
0.59 - 0.63	0.52 - 0.55
0.63 - 0.66	0.55 - 0.58
0.66 - 0.68	0.58 - 0.6

0.68 - 0.71	0.6 - 0.62
0.71 - 0.74	0.62 - 0.66
0.74 - 0.79	0.66 - 0.70
0.79 - 0.97 (High) – 10%	0.70 - 0.78 (High) – 10%

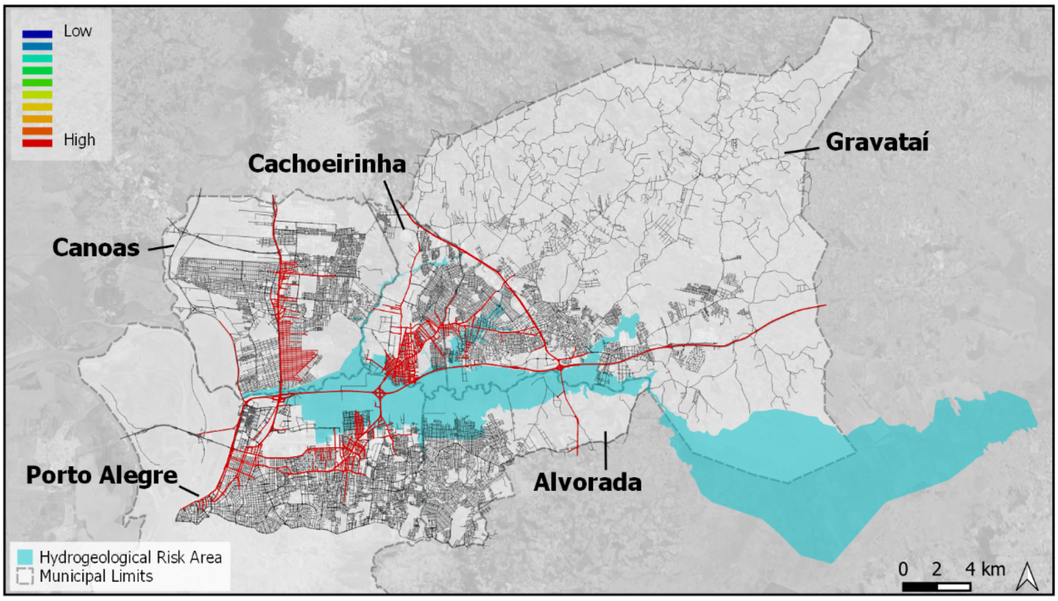


Figure 7. NAIN (Normalized Angular Integration) integration core (10%): road network unaffected by floods.

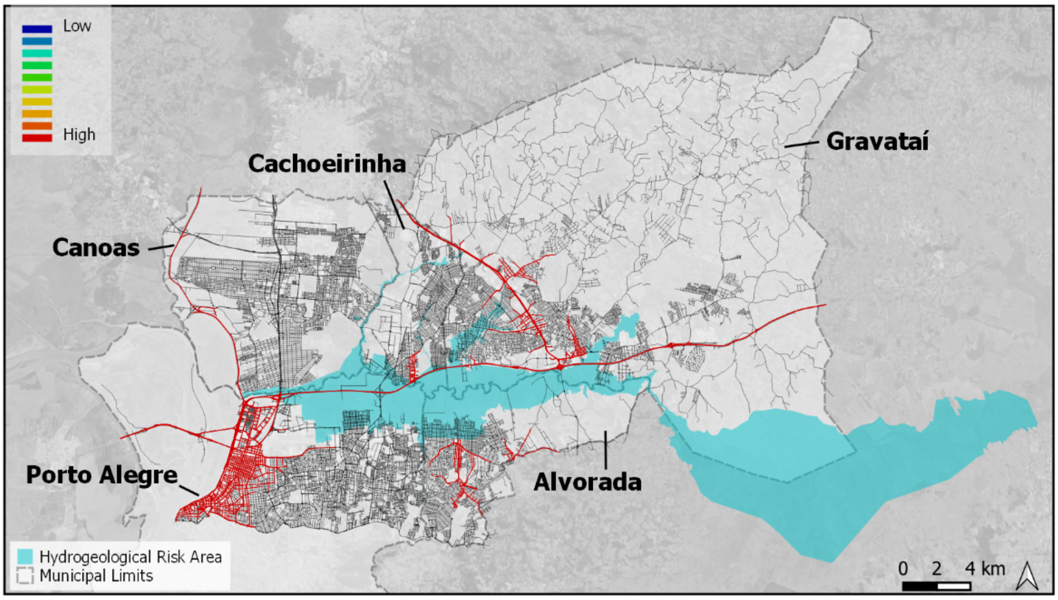


Figure 8. NAIN (Normalized Angular Integration) integration core (10%): road network affected by floods.

Contrary to Esposito and Cutini (2015) and Abissinian and Koch (2017) findings, in that the road-circulation network retained the same overall structure before and after the flood-events, therefore, systems that can be considered rather resilient, the same cannot be said for the PAMR, which, despite preserving its main road-infrastructure, observes a general collapse of the access that exist between the metropolitan municipalities. Drawing from NAIN, it is possible to identify that there are radical changes in the *relative accessibility* distributiveness and continuity to the integration core, that changes its direction and overall shape. This occurs due to a large portion of one of the main connections between *Porto Alegre* and *Canoas* (BR-116) to the North being suppressed from the original integration core given its disconnection by the water-flood patch. From that it is possible to identify certain road-intersections in the urban grid that seem to function as *bridges*, suppressed in flood events, which changes the overall integration system at local and especially at metropolitan scale. The new configurational pattern considering those interruptions changes the integration core logics, as observed in Figures 7 and 8 (p.12).

The NAIN – Rn analysis (Figure 5, p.11) reiterates the Brazilian urbanisation patterns and urban sprawl tendencies, as these follow along the highly integrated road-circulation network elements. However, the integration core that emerges in the metropolitan highway structure reveals a discontinuous urban structure in terms of *relative accessibility* (Figure 7, p.12), where there is an interruption on urbanisation in-between the municipalities due to the river lowlands, where borders are defined by the highway structures. City expansion then, tends to shift inland through what is mainly a patchwork of deformed grids, towards those river floodplains. Effectively, these floodplains are the areas where, due to low-cost land demand, densification has become rather intensive in the past two decades, with new land-parcelling on the area being presently evaluated.

Two areas exemplify divergences on the metropolisation process: *Canoas* municipality, which is structured around the BR-116, that collects integration and guide urban expansion towards the north, while also becoming a barrier between the two halves of its urban core (Figure 5, p.11) On the other hand, the portions of *Porto Alegre* Northern Region encompassed in-between BR-116 and the BR-290 tend to improve accessibility measures towards *Cachoeirinha*'s urban core. This indicates a robustness of the metropolitan connections, as *Cachoeirinha* itself is also connected to *Canoas* through its inner urban areas.

Nevertheless, the simulated flood-event (Figure 6, p.11) demonstrates that, despite its robustness, the system between these municipalities collapses, as the disruption of the highway overpasses and underpasses that connect *Porto Alegre* to *Cachoeirinha* cut-outs the access between both cities; as well, the flooded tributaries of the *Gravataí* river interrupt the roads between *Cachoeirinha* and *Canoas*, weakening the *Canoas* integration core and conditioning *Cachoeirinha* access from *Porto Alegre* to be dependent on *Gravataí* municipality access through the RS-118 – effectively reversing the current system logic. From the analysis (Figure 6, p.11), it also becomes clear that *Alvorada*, although possessing a continuity of its urban grid associated to *Porto Alegre's* Northern Region, remains a periphery, an aspect that is coherent with its role as satellite city for *Porto Alegre* (Melchior et al. 2018). Moreover, its overreliance on urban access to connect itself to the metropolitan system fragilizes its urban system condition as the interruptions caused by the flooded tributaries of the *Gravataí* river completely severs the connection with *Porto Alegre*. A feature of the simulation under a severe flood-event is the emergence of a strong integration core at *Alvorada* municipality, which is due to the collapse and its severance from the metropolitan system. This phenomenon results in two definite urban patches within *Alvorada* territory also disconnected a *Gravataí* river tributary: its central area becomes an island despite the urban grid continuity to *Porto Alegre*; and its industrial district remains disconnected from *Alvorada's* centre and also deprived of its connection with *Cachoeirinha,* through the RS-118, functioning like an isolated peninsula (Gil and Sonderberg, 2008) From the NAIN measure, we can conclude that water-flood greatly modifies movement patterns at the metropolitan scale. The road-circulation system, in terms of integration, tends to collapse since vital connections within the metropolitan conurbation are suppressed at a local scale. From results, it is possible to infer that these changes, unevenly distributed across the road-network, suggest the fragility and low resilience of the PAMR metropolitan system, in terms of maintaining the connection between its urban settlement The scarcity of connections in-between the municipalities – which are mainly reliant on the BR-290 highway – participate in forming a fragmented foreground network, that is, it attests the fact that Brazilian cities are incredibly deep spatial systems, connected by few privileged segments of the national and state road system, intertwined to the urban network, evident in this metropolitan context. Moreover, the NAIN analysis results evidence that the planned land-parcelling expansions towards the riverbank lowlands and the areas in their immediate vicinities should be avoided or undertake serious planning and mitigation works. This ought to be made, not only due to the innate flooding risks, but also, because of the consequential disruptions on the metropolitan spatial configuration and *relative accessibility* in the event of a flood disaster, which may render those areas isolated from the metropolitan system.

Evaluating the metropolitan system's structure through Normalized Angular Choice (NACH) measure (Figures 9 and 10, p.15; Table 2, p.16), informs that, from a general standpoint, flooding effects tend to be reduced regarding the flows' patterns at metropolitan scales. The *preferential route* system at this scale is largely preserved as a function of the ring-roads supplementary connections outside and inside the metropolitan core, that maintain the integrity of the metropolitan system at a larger scale. The role of the three main axes in the *preferential routes'* system resilience (in red - centre) is important, as those metropolitan highways, associated to the urban avenues that are higher in hierarchy (in red and orange), establish the regional connections that provide a great degree of redundancy to metropolitan system at larger scales, one of the factors that is associated with system resilience.

Nevertheless, while system integrity regarding flows is mostly preserved at metropolitan scale, at local scale several internal road-elements that have high values of NACH are interrupted by the flooding areas that cause localised sections in the system (Figures 9 and 10, p.15) – and are responsible for collapsing of NAIN at metropolitan scale, despite their limited impact on flows. This result demonstrates that, while general hierarchies are preserved at metropolitan scale, where the main axes of connection between the municipalities of the PAMR were planned to be resilient against interruptions caused by floods, at the municipal scale there is a relative neglect in the role that urban bridges between the municipalities play into connecting the urban areas. This is especially important considering the economic development and urban activity within the PAMR.

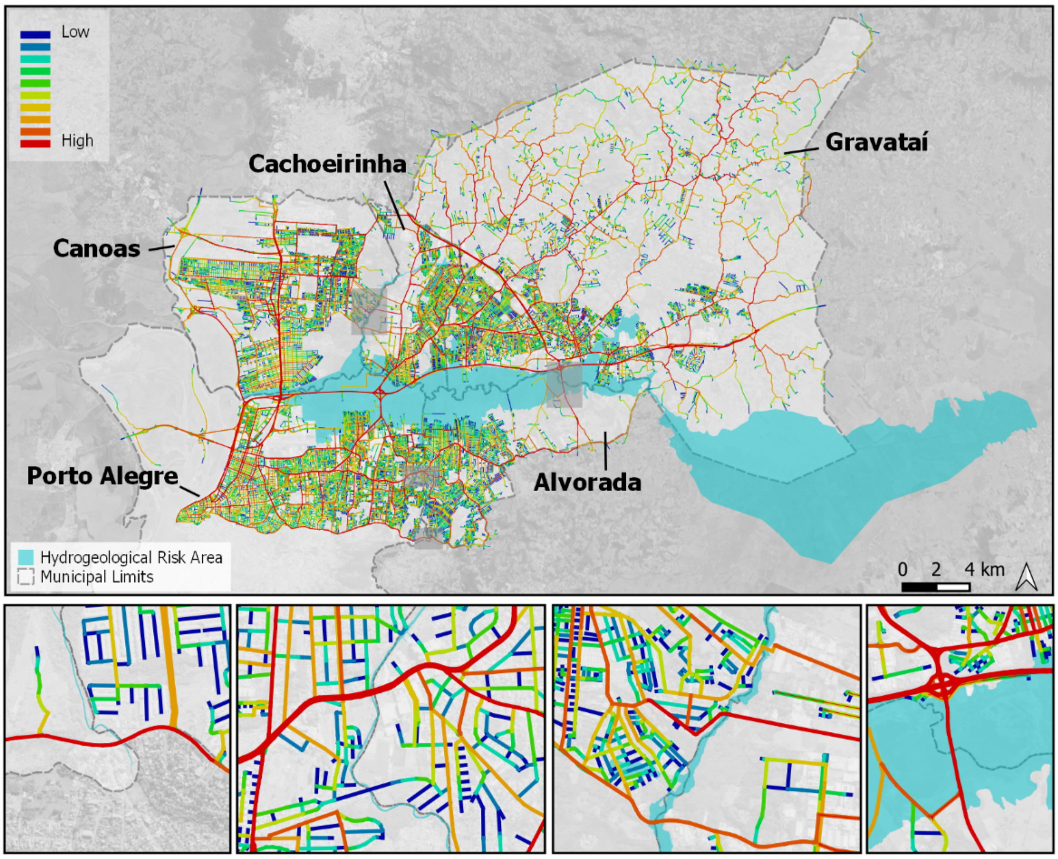


Figure 9. Results for NACH Normalized Angular Choice: road-circulation network unaffected by floods

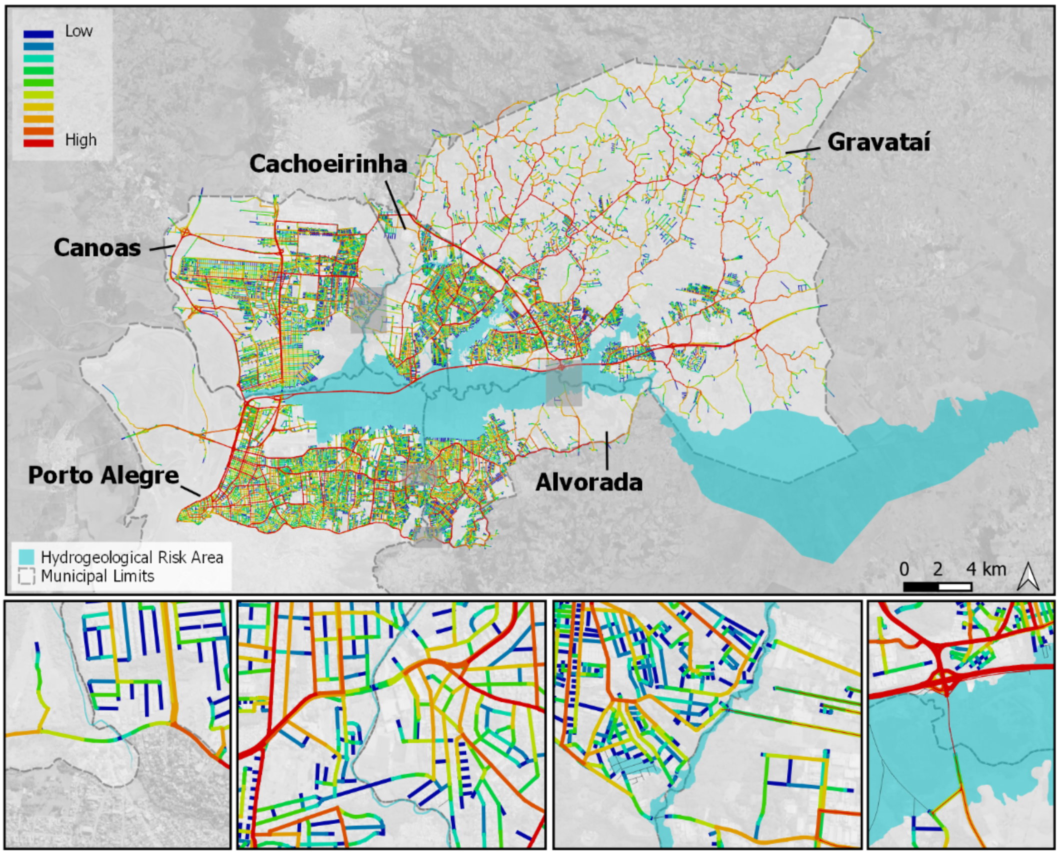


Figure 10. Results for NACH Normalized Angular Choice: road-circulation network affected by floods

Table 2. NACH Values (Normalized Angular Integration): PAMR road-network system.

PAMR - Current	PAMR – Flood Area (Avg.)
0.00 - 0.70 (Low)	0.00 - 0.66 (Low)
0.70 - 0.84	0.66 - 0.82
0.84 - 0.89	0.82 - 0.87
0.89 - 0.93	0.87 - 0.92
0.93 - 0.97	0.92 - 0.95
0.97 - 1.01	0.95 - 0.99
1.01 - 1.06	0.99 - 1.04
1.06 - 1.12	1.04 - 1.11
1.12 - 1.22	1.11 - 1.20
1.22 - 1.52 (High) – 10%	1.20 - 1.51 (High) – 10%

Nowadays, there is an intensive pendular movement due to the presence of job posts – mainly on industrial production and logistics – in the industrial districts located in the cities that are around the capital: *Porto Alegre*; which in turn, concentrates the services and retail activities (Altafini et al, 2021). Even though historic centre is losing visibly its role in fomenting economic development, it still plays an important part as a movement attractor and structuration point for the urban-regional road-circulation system – as proved by the fact that it helps to preserve the metropolitan connections disrupted by floods. Nevertheless, it can be attested that measures to improve metropolitan circulation system resilience disregard the recent metropolisation dynamics going on outside the once-metropolitan core. The BR-290, another important axis in the national road network, crossing the Brazilian territory up to its Northeast and along the coast, connects to RS-030, crossing *Cachoeirinha*, and defines the northern border of the NACH core preservation intact, as well as the urban extensions to *Porto Alegre* city core, and its connection to BR-448. This preserves freight circulation consistent. The highlight of NACH is also *Alvorada* municipality, which in NAIN becomes an isolated system. Albeit the robust interpenetration between the Porto Alegre urban grid and that of its central area, under flood risk, this municipality becomes isolated to the point of becoming an actual island. This is dramatic in the sense that Alvorada is a dormitory-city and commuting with Porto Alegre is intensive (Melchiors et al., 2017). Before the publication of the results of the METROPLAN hydrogeological studies, in 2018, a considerable number of developers applied for projects in areas affected by the flood impacts and metropolitan and municipal authorities happened to approve them, for not having updated data about the real extension of the overflow of those rivers.

This happened, especially, the municipalities of *Alvorada* and *Canoas* suffered the consequences of those decisions in its northern part of the territory. From the accessibility point-of view, the land sub-division projects approved in Alvorada represented the possibility of creating alternative routes to Getúlio Vargas Avenue, the only West/East-road in the northern part of the city. This opportunity will be highly affected from now on. In *Gravataí*, the overflow happened not only along the main river but also along *Barnabé Stream* a tributary of the *Gravataí* river along the core parts of the city, which are more densely occupied. There, land-parcelling projects were generally smaller, without the production of new parks or main streets, just popular housing, but represented the possibility of improving grid permeability. The northern part of *Porto Alegre* is subjected to a major the focus in real-estate development, especially on the lowland areas closer to BR-290. In that region, entrepreneurs insist on building large condominiums, taking advantage of the central positions in the metropolitan region, despite the existence of historical studies that indicate a high hydrogeological risk for the area. Those novel developments simply ignore the associated flooding-risks, while also not undertaking needed mitigation works. Their construction will affect not only the neighbouring areas in *Porto Alegre*, but also closer municipalities.

4 CONCLUSIONS

In Brazil, housing developments drive urban expansions that tend to follow a sparse, spatially discontinuous, and fragmentary process, thriving on cheaper peripheral unoccupied land bordering the main regional circulation mobility axes. This tendency reiterates the notion of metropolisation process and its characteristics (Elissalde, 2004) in which land parcelling and land developments constituted of morphological and functional qualitative transformations structure the urban network through connectivity. One of its results is the emergence of a discontinuous and heterogeneous spatial configuration that indicates tendencies of functional rearrangements related to polycentrality. Such changes tend to occur outside metropoles´ cores, driven by low land costs and regional mobility patterns. This is the case for PAMR: currently, its most robust functional centrality lies in its Northern Region, causing the decay of Porto Alegre's historical core.

Drawing from Abshirini, and Koch, (2017) findings on resilience as the degree to which a city retains the same segments forming the foreground network before and after a disturbance, we can conclude that PAMR is not a resilient system at municipality scale, meaning changes in NAIN are noticeable and affect directly the patterns of accessibility within the proposed cut-out. At the regional scale, we can conclude that the PAMR system is resilient if only regional flows are considered. A duality and a very interesting one, that demands further analyses. This both confirms and challenges Cutini's (2013) work. Studying effects on centrality patterns before and after change is informative, but the particular use of bridges as key actors in the system is refined when it comes to understanding the global properties of the network. That is why modelling NAIN-*n* solely was enough to evaluate the proposed study case.

The analysis also tests statistically some of Cuomo's, Koch's, and Miranda's ideas on a large sample. The regularity found in this study, however, does not signify by itself a higher generic resilience in river cities, since a generic measurement of resilience would be needed to take into account additional properties. It is noticeable that the findings displayed here on the syntactic structure of public spaces systems should be more resilient in river cities; this preliminary research did not supply enough evidence to confirm these findings. Also, it must be considered the differences in urban expansion patterns between Brazilian and European cities: in the first case, the urban expansion boom is effective after the diffusion of road transportation. Therefore, highways and main roads play an important role in informing patterns of suburbanisation and the emergence of new kinds of functional centralities associated with private vehicle mobility.

The article brings back to discussion multi-scale mobility issues related to the intensification of land subdivision and changes from rural to urban land use, which disregard environmental risks. It is urgent an effective action from the State Government on managing urban expansion, urban structuring, and territorial planning coordination, against real estate sector intensive pressure for housing developments approval within flood risk areas, and against municipal government resistance on accepting inter-federative approaches on managing water resources and river basins, once this is, not a local, but essentially a regional problem.

Further studies plan to integrate novel instruments and configurational measures, such as the *Markov-based* measures developed by Altafini et al. (2022), that can address the urban road-circulation network resilience and identify which road-elements are crucial to the system structure; then, we can propose guided policies for risk mitigation.

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