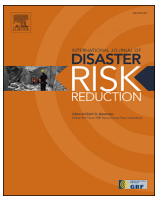
International Journal of Disaster Risk Reduction 110 (2024) 104645



Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr



Analysis of the hydrological disaster occurred in the state of Rio Grande do Sul, Brazil in September 2023: Vulnerabilities and risk management capabilities

Regina Célia dos Santos Alvalá [a, b], Daniela Ferreira Ribeiro [a, *], Jose Antonio Marengo [a, b, c], Marcelo Enrique Seluchi [a], Demerval Aparecido Gonçalves [a], Larissa Antunes da Silva [a], Luz Adriana Cuartas Pineda [a, b], Silvia Midori Saito [a, b]

[a] National Center for Monitoring and Early Warning of Natural Disasters/CEMADEN, São José dos Campos, Brazil
[b] Graduate Program in Natural Disasters, UNESP/CEMADEN, São José dos Campos, Brazil
[c] Graduate School of International Studies. Korea University, Seoul, South Korea

ARTICLE INFO

Keywords:
Extreme weather events
Hydrometeorological risks
Vulnerability assessment
Disaster risk management

ABSTRACT

Understanding disaster risk in all its dimensions is a priority on global agendas. This study developed an integrated analysis of flood risk drivers using a methodology based on meteorological and hydrological analyses, population vulnerability assessment, and municipal risk management capabilities from public data sources. Rio Grande do Sul, Brazil, was selected due to extreme rainfall that affected more than 400,000 people in September 2023. The results showed that a stationary frontal system caused unprecedented rain and floods between September 1 and 4, 2023. A quasi-stationary cold front from Argentina intensified precipitation, exacerbated by an upper-level low-pressure area. Attributed to the 2023 El Niño, these events resulted in heavy rainfall exceeding normal levels by 200–300 mm, leading to floods that affected 107 municipalities, resulting in 54 deaths and extensive property damage. The Caí and Taquari-Antas river basins were particularly affected, with river levels exceeding critical limits, causing severe floods and most deaths. Vulnerability was higher among populations of low socioeconomic status living in housing with precarious infrastructure, especially in small municipalities dependent on agriculture. The high vulnerability is due to the lack of public policies that improve socioeconomic conditions, such as social action policies for agricultural workers, combating educational delays, and improvements in household infrastructure. Furthermore, municipal administrations must invest in strengthening tools, actions, and policies focused on risk response and management, and promoting educational activities in civil protection and defense, with special attention to the elderly population.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) AR6 report [1] highlights that human-caused climate change is already affecting meteorological and climate extremes worldwide. Notwithstanding, between 2010 and 2020, human mortality due to floods,

* Corresponding author.
E-mail address: daniela.ribeiro@cemaden.gov.br (D.F. Ribeiro).

https://doi.org/10.1016/j.ijdrr.2024.104645
Received 18 March 2024; Received in revised form 16 May 2024; Accepted 25 June 2024
Available online 26 June 2024
2212-4209/© 2024 Elsevier Ltd. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

droughts, and storms was 15 times higher in highly vulnerable regions compared to those with very low vulnerability. Globally, in 2022, the Emergency Events Database [2] recorded 387 disaster events, resulting in the loss of more than 30 thousand lives, impacts on 185 million people, and losses of around 223 billion dollars.

Particularly in South America, Brazil has been impacted by extreme weather and climate events in various regions, such as in the Amazon [3,4] and in the Northeast region [5,6], which suffered from prolonged droughts, while severe floods caused major losses in the Southeast and South regions, culminating in several deaths and a significant number of dislodged and homeless people [7–9]. Specifically, regarding floods Brazil ranked second in the total studies developed on the topic from 2000 to 2020 compared to other countries in Latin America and the Caribbean [10]. The analysis provided in 2023 by the National Confederation of Municipalities (CNM, in Portuguese) [11] showed that 93 % of Brazilian cities (more than 5000 municipalities) were hit by some hydrometeorological disaster that culminated in the registration of an emergency or state of public calamity, because of storms, floods, flash floods or urban floods in the last 10 years. Still, according to the CNM, from 2013 to 2022, more than 2.2 million homes were damaged across the country due to these events, directly affecting more than 4.2 million people, who had to leave their homes in 2640 municipalities across the country.

Between October 2021 to February 2023, heavy rainfall associated with floods and landslides impacted several cities in different regions of Brazil, such as Petrópolis, located in the mountainous region of the state of Rio de Janeiro [12] in February and March 2022; in the city of Recife, Northeast region [13] in May–June 2022; and in São Sebastião, north coast of the State of São Paulo [14] in February 2023, among others. Such events culminated in more than 500 deaths in the period. Considering the period from 1991 to 2022, 57,581 disaster events were documented, with over 47 % attributed to hydro-geo-meteorological phenomena.

From September 1st to 7th, 2023, the state of Rio Grande do Sul (RS) experienced an unprecedented episode of extreme rainfall, resulting in disasters primarily associated with floods. These events marked the most significant disasters to affect the state in the past four decades, impacting 107 municipalities, resulting in 54 fatalities, and affecting over 400,000 individuals.

Additionally, the latest report on the consequences of these disasters indicates that five individuals remain missing, 943 were injured, more than 5000 people were left homeless, and over 22,000 were forced to relocate [15]. Considering the recurrence of disasters and the number of affected individuals in the state of RS, in-depth investigations focusing on the vulnerability and disaster risk management capacities of the municipalities directly affected by such events are imperative.

Effective disaster risk management demands a thorough comprehension of disaster risk across its entirety, encompassing vulnerability, capacity, and exposure of individuals and assets, as well as the attributes of hazards and the environment [16]. Vulnerability is characterized as a dynamic and multifaceted process intricately tied to a system's predisposition, conditions, and characteristics predisposing it to damage from hazards. This perspective encompasses exposure to the hazard, susceptibility to its impacts, and the capacity for recovery [17,18].

Vulnerability extends across diverse dimensions, including social, economic, and institutional aspects, exhibiting temporal and spatial variability [19]. Capacities are conceptualized as a combination of resources, attributes, and strengths within a society or community that contribute to the management and mitigation of disaster risks. These include elements such as infrastructure, institutional frameworks, knowledge, expertise, and collective attributes like social networks, leadership, and governance [20].

The social dimension is linked to demographic characteristics associated with physical and mental well-being, contributing to populations' preparedness, response, and recovery in the face of the adverse impacts of disasters [21,22]. This dimension may encompass factors related to socioeconomic status, gender, age, homeownership, and access to financial resources in post-disaster periods, which directly influence susceptibility and exposure to risks [19,23]. The economic dimension is associated with livelihoods and economic assets, about a system's susceptibility to absorb and cope with the impacts of disasters and economic losses [19]. This dimension involves aspects that represent economic characteristics or conditions resulting from economic situations [24].

The environmental dimension is linked to the degradation of environmental services and functions that can lead to damage [19,25]. Lastly, the institutional dimension is concerned with existing institutions and their ability to shield communities from the negative impacts of hazards [24]. The institutional dimension typically pertains to the modes and constraints in governance, underlying rules, and normative systems that govern society, as well as the capacity or incapacity of formal organizations to deal with risks and adaptation challenges [19].

The capability to assess vulnerability to disasters is a fundamental necessity for aiding in the formulation of risk reduction strategies, providing decision-makers with pertinent information concerning the locations of more susceptible infrastructures. This, in turn, enhances planning and management processes [19]. Consequently, analyzing the diverse dimensions of vulnerability to disasters through indicators and indices becomes imperative for evaluating the impact of disasters associated with social, economic, and environmental conditions [26]. The dimensions of vulnerability can encompass characteristics related to social, economic, environmental, and institutional aspects [19].

Studies addressing frameworks for measuring vulnerability across different dimensions are found in the scientific literature [27,28]. For Brazil, Ribeiro, Saito, and Alvalá [29] conducted a pioneering study through an analysis of vulnerability and disaster risk reduction capacities in small municipalities affected by floods and landslides. The study employed a set of quantitative and qualitative indicators related to social, economic, occupational, infrastructural, institutional, and community dimensions. The results indicated that vulnerabilities and risk reduction capacities were primarily associated with specific aspects related to the size of the municipalities, socio-economic development levels, and the implementation of public policies.

Specifically related to disaster risk management, Brazil has adopted some public policies. In 2011, beneath Presidential Decree No. 7513, the country established the National Center for Monitoring and Early Warning of Natural Disasters - CEMADEN [30]. Currently, the Center monitors 1.133 municipalities and issues warnings related to geodynamic and hydrological events. The monitoring process and decision-making for issuing disaster risk warnings are carried out in a control room, where specialized teams analyze en-

vironmental variables, identify potential hazards and vulnerabilities, and communicate alerts to an emergency response team [31]. Concerning the mentioned event that affected RS, it is noteworthy that CEMADEN identified and alerted about the situation that led to the disaster in the state five days in advance.

Therefore, Brazil has been affected by extreme climatic events responsible for triggering natural hazards, which, when combined with characteristics of vulnerability, exposure, and response capacity, resulted in disasters with several impacts. It is imperative to conduct studies aiming on multidimensional analyses of disaster risk, especially focusing on cities recently impacted by disasters triggered by hydrometeorological extremes. To achieve resilience, cities around the planet need to be prepared for the increasing extremes of both present as the future. Additionally, understanding disaster risk drivers in countries with scarce data is crucial, as the low capacity to collect data periodically can limit the use of established methods, such as modeling [32]. Studies on this topic have already been developed for various countries, such as Portugal [33,34], Costa Rica [35,36] and Bangladesh [37].

Thus, the present study aimed to analyze the drivers that led to the floods affecting 107 municipalities in the state of Rio Grande do Sul, Brazil, in the period from September 1st to 7th 2023. The hypothesis was that the vulnerability characteristics of populations and municipal disaster risk management capabilities influence the impacts of floods in affected municipalities. For this purpose, the specific objectives are as follows: 1) develop a comprehensive analysis of the meteorological and hydrological events that affected the municipalities, with a detailed focus on the Taquari-Antas River, since this region concentrated the municipalities that presented the most deaths from the floods; 2) evaluate population vulnerability, as well as the municipal disaster risk management capabilities.

The state of RS presents a higher record of disaster events in the period of 1991–2022, ranked as the second-most affected state in Brazil [38]. Specifically, concerning hydro-geo-meteorological disasters, RS endured 3913 events within the same timeframe, leading to 100 fatalities, displacing over 700,000 individuals, and incurring economic losses estimated to exceed 6 billion Brazilian reais (approximately 1,2 billion dollars) [38]. Moreover, although the understanding of risk in all its dimensions, which include vulnerability, capacity, exposure and hazard characteristics corresponds to a priority for action in the Sendai Framework [16], studies that focus on this multidimensional comprehension in the Brazilian context are still limited.

2. Study area

Rio Grande do Sul (RS) is one of the 27 states of Brazil, situated in the mid-latitude region at the southern extremity of the country. It encompasses a total land area of 281,707 km^2 [39]. The state is subdivided into 497 municipalities, and as of the 2022 Census, it boasts a population exceeding 10 million residents, constituting approximately 5.4 % of the total Brazilian population. This demographic ranking positions RS as the sixth most populous state in Brazil. Concerning population density, the state registers at 38.62 inhabitants per square kilometer, ranking thirteenth among the Brazilian states [39].

In terms of its environment, RS features diverse vegetation, including remnants of the Atlantic Forest and grassland vegetation. The topography encompasses elevations ranging up to 1398 m, characterized by four geomorphological units: I) Southern Plateau, located in the northern part of the state, harboring the highest elevations; II) Central Depression, situated in the state's center and marked by low-altitude terrains; III) Crystalline Shield, in the southern region of the state, with elevations not exceeding 600 m; and IV) Coastal Plain, corresponding to a sandy strip of 622 km, extending in a general north-south direction, predominantly featuring strings of lagoons and lakes [39].

In the context of climatology, according to Köppen [40] RS is characterized by a Cfa climate, without dry season and hot summer. Concerning precipitation patterns, a discernible regional heterogeneity prevails, with the southern sector averaging between 1299 and 1,500 mm, and the northern counterpart registering an average between 1500 and 1,800 mm, with heightened intensity documented in the northeast quadrant [39].

The occupation of RS is intricately interwoven with agriculture, specifically centered on the production of "charque", a distinctive form of jerky indigenous to Latin America. Since 1752, the influx of Azorean populations has been a pivotal force in territorial occupation, engrossed in agricultural activities that facilitated the establishment of diverse urban centers [39]. Throughout the 19th century, migratory flows from European populations played a seminal role in propelling heightened regional development, initially concentrating on agrarian pursuits and subsequently expanding to encompass commercial and industrial dimensions. Demographically, the state manifests a spatial heterogeneity, with a concentration of population in medium-sized municipalities in the southern periphery, while the northern precincts exhibit a more pronounced urban density [39].

The 107 municipalities located in RS state impacted by pronounced rainfall during the period spanning September 1st to 7th, 2023, are geographically scattered across the northern and central regions of the state (Fig. 1). Those reporting fatalities (Fig. 2), are primarily situated in the northern sector of the state, with a notable concentration in the Taquari-Antas River basin.

Most of the affected municipalities corresponded to small municipalities with populations ranging up to 5 thousand inhabitants, according to the 2022 Census [41], characterized by an economy strongly linked to the agricultural sector. Following data sourced from the Digital Atlas of Disasters in Brazil [38], the 107 impacted municipalities registered a total of 1672 disasters linked to natural hazards during the period spanning from 1991 to 2022, and approximately 69 % were attributed to hydrometeorological disasters.

3. Material and methods

3.1. Meteorological and hydrological analysis

In the present study, for the analysis of the meteorological information responsible for the causes associated with the rain events that triggered the floods that occurred in September 2023 in the state of Rio Grande do Sul, accumulated rainfall from September 1st to 7th, 2023 recorded by instruments from the CEMADEN environmental observational network was used. Additionally, gridded data

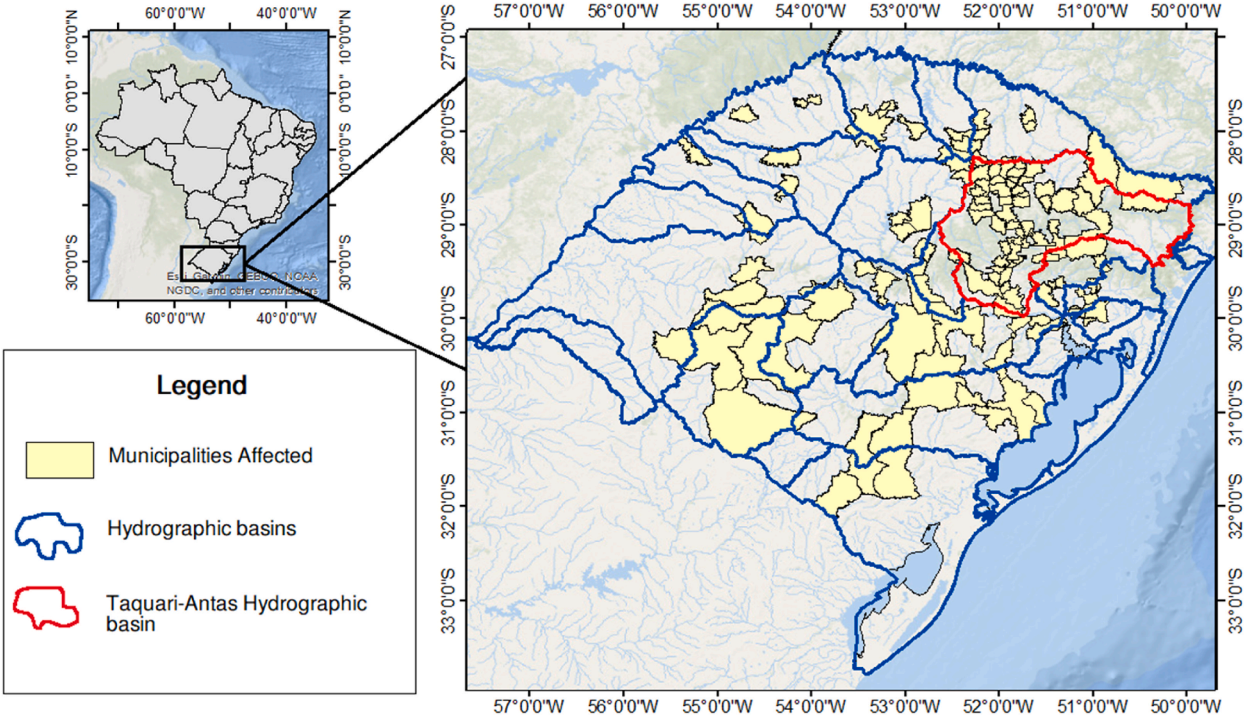


Fig. 1. Location of the municipalities affected by the hydrological disaster from September 1st to 7th, 2023 in RS state.

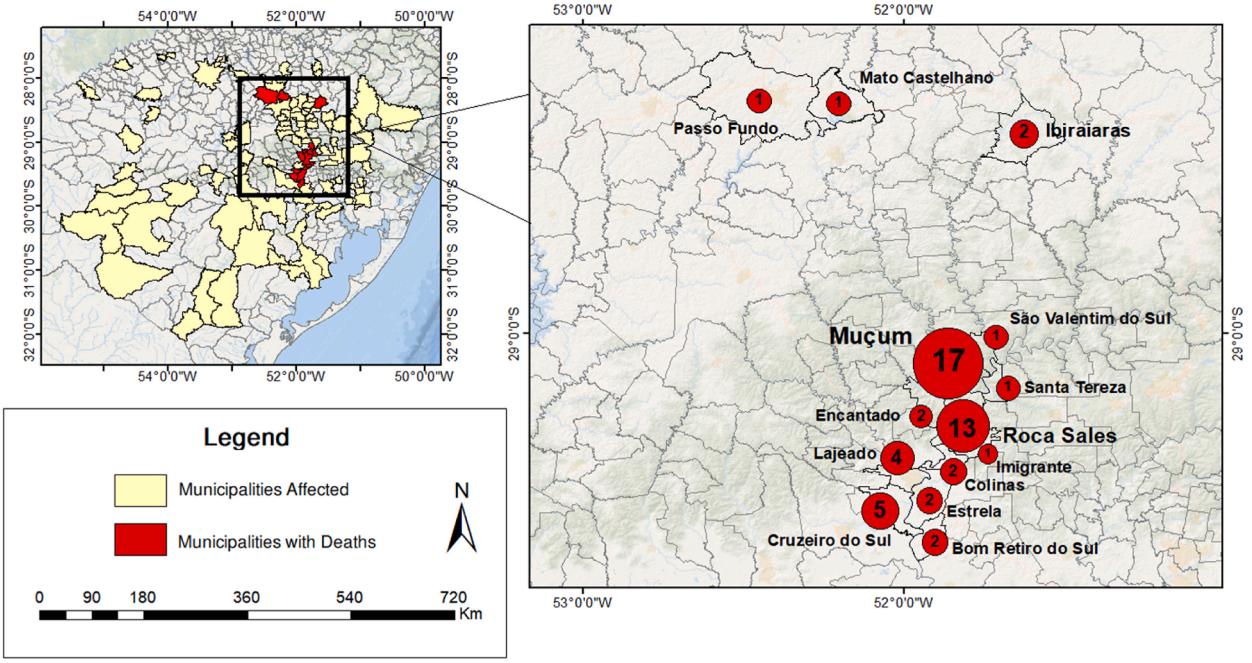


Fig. 2. Municipalities with recorded fatalities affected by the hydrological disaster from September 1st to 7th, 2023 in RS state. The numbers represent the total deaths registered in the municipalities.

for regional domains (Satellite-based Global Precipitation Measurement - GPM) – Integrated Multi-satellite Retrievals for GPM (IMERG) combined with data from surface observations – MERGE, from the Center for Weather Forecasts and Climate Studies – CPTEC [42] were evaluated.

The hydrological data, obtained from the National Water and Sanitation Agency (ANA) and Brazilian Geological Survey (SGB), were used to estimate the return period of the peak flood according to Gumbel distribution. To evaluate the severity of the flood event, the HEC-RAS software version 5.0.7 was used, and the input data were the digital terrain model of Copernicus (30 m horizontal

resolution) and the peak flood level at Muçum, estimated through High-water marks, to simulate the flood extent in the municipality. Due to the gauge station in Muçum being covered by water during the peak flood, the HEC-RAS software, developed by the US Army Corps of Engineers [43,44], version 6.1.0 for two-dimensional (2D) unsteady flood [45] was used to estimate the peak flood in Muçum. The hydrodynamic modeling is based on a Digital Elevation Model (DEM) to represent the topography of the floodplain to simulate the water flow end water stage. The input data were the digital terrain model of Copernicus (30 m horizontal resolution) and the peak flood level estimated through High-water marks.

3.2. Vulnerability and management disaster risk analysis

Data were obtained from the Brazilian Institute of Geography and Statistics (IBGE in Portuguese) to characterize the vulnerability of the region studied. An extensive literature review based on studies which examined population vulnerability and capacities using indicators were performed to support data selection [46–49]. Indicators correspond to variables representing aspects and characteristics of an object, providing information about susceptibility factors and the capabilities of a system to adapt, cope with, and resist the impacts of a disaster [27]. Indicators must correspond to the inherent conditions of a population, encompassing response characteristics, as well as aspects that contribute to recovery and adaptation, thus providing both short-term and long-term assessments, based on post-event scenarios [48,50]. Vulnerability indicators and capacities represent several dimensions, such as social, economic, infrastructure, community and institutional development.

Therefore, an evaluation was conducted using data from the 2010 census, encompassing 35 quantitative indicators related to population characteristics associated with social, economic, occupational, and infrastructural dimensions (Table 1). For the evaluation of risk management capacities 36 qualitative indicators associated with the infrastructure and institutional dimensions were selected, derived from the Profile of Brazilian Municipalities 2021 (Table 2). These indicators represent aspects that increase or decrease the population's vulnerability and the municipal disaster risk management capacities.

The social dimension comprised indicators representing social equity and educational inequality among populations. These variables aim to comprehend the level of social development, contributing to determining the ability to access information related to warnings and recovery. For the economic dimension, indicators related to population income, types of occupation, and the number of employers were chosen. Lower economic diversity can lead to a limited job supply, causing the population to migrate to other urban

Table 1
Quantitative variables utilized for vulnerability analysis (Source: 2010 Census IBGE).

Dimension	Indicators	Codification
Social	1 – Illiteracy rate	S1
	2 – % of the population with complete elementary education	S2
	3 – % of the population with complete secondary education	S3
	4 - % of the population with complete higher education	S4
	5 – % of people in households where no one has completed elementary school	S5
	6 – % of people in households where no one has completed elementary school	S6
	7 - % of female-headed primary households without complete elementary school and with children under the age of 15	S7
	8 – Aging rate	S8
	9 - % of children aged 6 to 14 not attending school	S9
	10 – % of the population aged 65 or older.	S10
	11 – Urban Population	S11
Economic	12 - % of people in households vulnerable to poverty and dependent on the elderly	E1
	13 - Gini Index	E2
	14 - % of the poverty population	E3
	15 - % of the population vulnerable to poverty	E4
	16 - Average income per capita	E5
Occupation	17 - % of employed individuals aged 18 and over who are self-employed	O1
	18 - % of employed individuals aged 18 and over who are employers	O2
	19 - % of the employed population with complete elementary education	O3
	20 - % of the employed population with complete secondary education	O4
	21 - % of the employed population with higher education	O5
	22 - % employed population in the agricultural sector	O6
	23 - % employed population in the commerce sector	O7
	24 - % employed population in the civil construction sector	O8
	25 - % employed population in the mineral extraction	O9
	26 - % employed population in the services sector	O10
	27 - % employed population in the public industrial sector	O11
	28 - % employed population in the transformation industry sector	O12
	29 - % employed population in the public sector	O13
	30 - % of non-formally employed population	O14
	31 - % of the formally employed population	O15
Infrastructure	32 - % of the population in households with water supply	I1
	33 - % of the population in households with garbage collection	I2
	34 - % of people in households with an inadequate water supply and sanitation	I3
	35 - % of people in households with inadequate walls	I4
	36 - % of people in households without electricity	I5

Table 2
Qualitative variables representative of risk management capacities. (Source: IBGE, 2021).

Dimension	Indicators
Infrastructure	Availability of a Fire Brigade Unit
	Availability of Municipal Guard performing Civil Defense activities
	Availability of a Civil Defense Nucleus (NUDEC)
	Availability of a Municipal Coordination of Civil Defense (COMPDEC)
	Concerning the COMPDEC, the person in charge of coordination acts exclusively in this role
	The COMPDEC carries out articulated and coordinated actions of the Municipal System of Protection and Civil Defense
	The COMPDEC knows the Integrated Disaster Information System - S2ID
	The COMPDEC uses its own system in the area of Civil Protection and Defense
	There is a provision for resources for civil protection and defense actions in the Annual Budget Law
	There are other sources of resources for civil protection and defense actions
	The COMPDEC has exclusive physical space
	The COMPDEC has a vehicle
	The COMPDEC has computers
	The COMPDEC has GPS
	The COMPDEC has vests available
	The COMPDEC has employees with an employment contract
Institutional	Master Plan Incorporating Prevention of Floods, Flash Floods, Urban Floods, or Landslides
	Land Use and Occupancy Law Incorporating Prevention of Floods, Flash Floods, Urban Floods or Landslides
	Specific Law Incorporating Prevention of Floods, Flash Floods, Urban Floods or Landslides
	Municipal Disaster Risk Reduction Plan
	Geotechnical Suitability Map for Urbanization
	Implementation Plan for Disaster Risk Reduction Infrastructure and Services
	Mapping of flood and landslide risk areas
	Housing program for relocating low-income population in high-risk areas of floods and landslides
	Control and inspection mechanisms to prevent occupation in areas susceptible to floods and landslides
	Contingency Plans
	Engineering Projects related to floods and landslides
	Early warning system for disasters
	The municipality carries out periodic cleaning of the city's storm drains, especially before the rainy season
	The municipality conducts educational practices aimed at raising awareness and perception of risk situations in schools
	The municipality conducts educational practices aimed at raising awareness and perception of risk situations in communities
	Environmental education in schools
	Environmental education in communities
	Campaigns to raise public awareness about disaster risks
	Training of civil protection and defense professionals
	Training of NUDECs

centers in search of better opportunities [51]. Additionally, greater economic diversification helps disperse occupation across various sectors, creating stability, as the economy does not rely solely on a specific sector [21,52,53].

The infrastructure dimension included indicators related to household infrastructure and the municipality's capacities for disaster risk management and planning. The data correspond to variables related to the presence of response infrastructure, represented by the existence of a fire department in the municipalities, and infrastructures focused on management and planning, such as the existence of the Municipal Civil Defense Coordination - COMDEC and the Community Center for Protection and Civil Defense - NUPDEC. COMDEC aims to execute, coordinate, and mobilize all civil defense actions in the municipality, while NUPDEC aims to promote interaction between municipal civil defense and communities [54]. Finally, the institutional dimension was linked to indicators reflecting the existence of legislation and actions contributing to the resilience of populations.

The quantitative indicators were scaled to the range (0, 1) using the data range normalization method (Eq. (1)):

$$Xn = \frac{X - Xmín}{Xmáx - Xmín} \tag{1}$$

where X is the data from the dataset of the indicator; Xmín is the minimum value for the dataset of the indicator; Xmáx is the maximum value in the dataset of the indicator; and Xn is the normalized data from the dataset of the indicator.

For the vulnerability evaluation, a factorial analysis (Principal Component Analysis – PCA) using Varimax rotation, were performed. The Principal Component Analysis (PCA) as a statistical method for assessing vulnerability is widely employed in studies [29,55–58]. Its objective is to extract information from numerous variables and express it in sets of variables known as principal components (PC). PCA reduces the dimensionality of multivariate data into two or three PCs, which can be graphically visualized with minimal loss of information. In a dataset, PCA identifies the main direction of variables, assuming that the primary linear directions in the data exhibit the greatest variance [21,48,59].

Testing of multicollinearity between variables were develop by the Bartlett's test of sphericity and Kaiser-Mayer-Olkin (KMO) measure. Bartlett's test of sphericity was used to check whether there was a significant correlation between the variables, presenting a value < 0.001, considered significant. The KMO test was used to evaluate the suitability of the data for the PCA analysis, with an

overall value of 0.870. The results of these tests indicated that the variables were appropriate for PCA analysis, ensuring that the results were not affected by multicollinearity.

PCAs were conducted for the group of 107 municipalities using Jamovi software, version 1.6.23, aimed to reduce input indicators and identify the principal components - PCs. The PCs with Eigenvalues >1 and with variables grouped around the same PC loading $>|0.5|$ were selected. A positive or negative sign was assigned to each component according to the cardinalities of the variables to the PCs. The vulnerability level for each component is determined considering that positive values represent higher vulnerability, while negative values indicate lower levels of vulnerability. The PC's scores were summed in order to obtain the final score of vulnerability. The final scores were normalized on a scale ranging from 0.00 to 1.00, where values close to zero represent lower vulnerability, and those near 1.00 are associated with higher vulnerability. To mapping the vulnerability indices the scores were classified using standard deviations from the mean, ranging from < -1.5 (low vulnerability) to $> +1.5$ (high vulnerability).

4. Results

4.1. Extreme rainfall and floods in September 2023 in the state of Rio Grande do Sul, Brazil

Between September 1st and 4th, 2023, a frontal system with quasi-stationary characteristics remained over the state of RS, causing historic rainfall and floods. Initially, this system moved on September 1 as a cold front coming from southern latitudes causing the first precipitation event over the west of the state of RS (see areas in red in Fig. 3, left, which indicate clouds of great vertical development). Between September 2nd and 3rd, this front became stationary, causing continuous heavy precipitation. On Monday 4, an area of low pressure in the upper levels of the atmosphere (which has the role of absorbing moist air from the surface to great heights) contributed to the strong increase in precipitation (See Fig. 3, right) and, subsequently, for the formation of an extratropical cyclone that quickly moved away from the continent. This extratropical cyclone, as informed by local media [60] was not the main reason for the extraordinary precipitation, since the determining factor was the presence of the semi-stationary frontal system and the area of low atmospheric pressure.

These intense rains due to stationary cold fronts in southern Brazil are one of the impacts of El Niño 2023-24 and started to manifest in September 2023, after almost 3 years of La Niña event and drought in the region [61,62]. The El Nino in 2023 (year 0) and its evolution are shown in NOAA reports, and according to the location of the warmest region could be characterized as the Eastern El Nino type. This type of El Niño is characterized by heavy rainfall in southern Brazil during the austral spring of year 0 [5,63].

Fig. 4 shows accumulated rainfall for September 2023 (right) and for the period September 1–7 (left) which was the period with heavy precipitation. Two data sets were used for confirmation: MERGE-GPM [64] represented in a raster image and from the CEMADEN environmental network [14] shown in points. The rainfall climatology for September for the state of Rio Grande do Sul is about 150 mm, and in September 2023 rainfall was about 200–300 mm above normal [65]. In the northern part near the municipality of Passo Fundo it rained above 300 mm, while at the Taquari and Cai River basins, it rained between 100 and 250 mm.

Heavy rain fell in the state from September 2nd until September 5th. The State Civil Defense informed that floods and storms have impacted communities in 79 municipalities. A total of 56,787 people has been affected, with 5894 people displaced. These heavy rains and flooding caused multiple fatalities and widespread material damage in the state of Rio Grande do Sul, and heavy rainfall and flooding affected the state throughout September and early October.

It is noteworthy that forecasts of geo-hydrological risks provided by CEMADEN/MCTI indicated the possibility of risks of hydrological events in the impacted region since September 3rd.

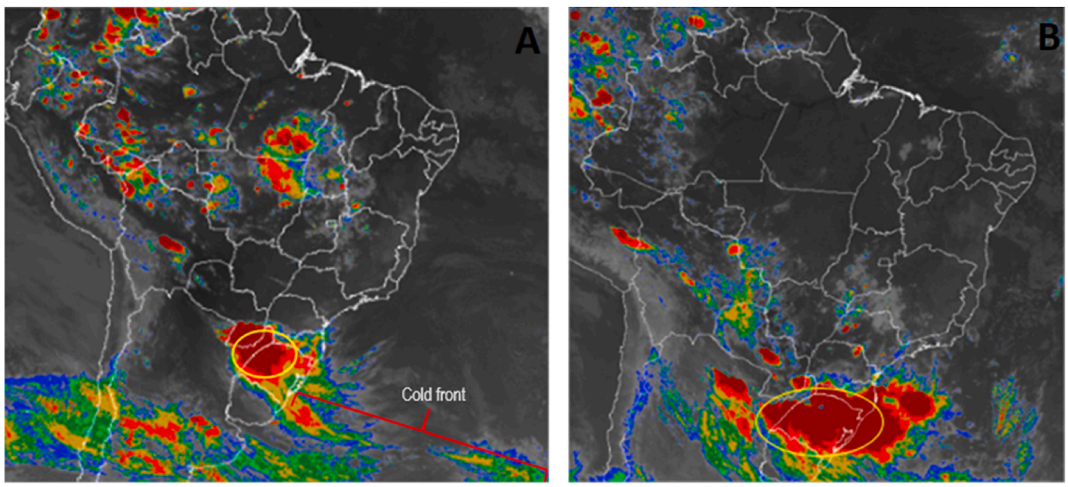


Fig. 3. a) Satellite images for September 1 at 18:40 h local time, b) For September 4 at 08:00 h local time. The red areas in the images show intense convection, indicators of heavy rainfall over the State of Rio Grande do Sul (Source: INMET). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

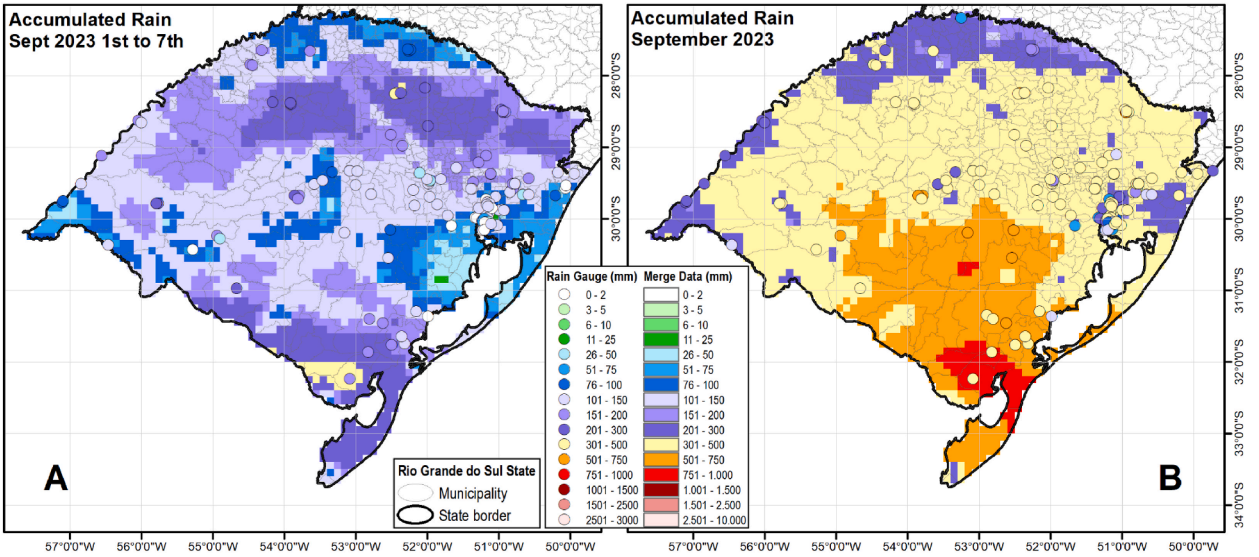


Fig. 4. Accumulated rain for September 1–7 and for September month in Rio Grande do Sul state registered by MERGE-GPM and CEMADEN environmental network.

Regarding specific alerts for the monitored municipalities (which indicate the type of disaster, the river, and the risk areas involved, as well as the potential for victims), on September 4th, approximately 48 h before the peak of the flood, they were issued 40 alerts, 22 for hydrological risk and 18 for geological risk. Of these 40 alerts, 11 were updated to a "high" level and 2 were updated to a "very high" level between September 4th and 5th, 2023.

As of April 17, 2024, 54 people have been reported to have died and 4 are still missing [66]. As a result of the September 2023 disaster, state authorities reported multiple locations recorded more than 300 mm of rain in 72 h to 04 September.

According to the site flood. list [67], rising rivers, swollen by further heavy rain, resulted in severe flooding in multiple parts of the state, in particular in the Caí and Taquari-Antas River basins. State Civil Defense released flood warnings for communities living close to the Antas, Taquari, and Caí rivers. Information from the Brazilian Geological Survey [60] shows that the Caí River has exceeded the highest warning level at São Sebastião do Caí, which reached 3.11 m above the flood level (10.5 m), and Montenegro, which reached 2.19 m above the flood level (6 m).

Meanwhile, the Taquari River reached dangerous levels, much higher than the flood level, in all gauge stations. The Taquari River levels rose by 22.6 m in 24 h at the José Júlio Line station, in the municipality of Santa Tereza, while the gauge stations at the municipalities of Muçum, Encantado, and Estrela did not record the peak of the flood because they were submerged in the water. The Taquari River level at Muçum reached 21.79 m at 7:30 p.m. on September 4th, almost 4 m above the flood-critical level. The peak of flood estimated by the hydrodynamic simulation was 26 m, equivalent to a 125-year return period, and by September 8th the levels dropped to about 7 m, 2 m below the alert level. In Encantado, the gauge station stopped transmitting data when the river reached the level of 20.73 m (37-year RP) at 10:15 p.m. on September 4th, while the gauge station in Estrela stopped transmitting data when the river reached the level of 27.20 m (8 m above the flood critical level) at 10:15 p.m. on September 4th. In the municipality of Bom Retiro do Sul, the level increased by more than 18 m between September 3rd and 5th.

Severe flooding has also impacted communities in the municipalities of Santo Expedito do Sul, Lajeado do Bugre, Nova Bassano, São Jorge, Bento Gonçalves, Caxias do Sul, and Ibiraiaras, among others [68]. Fig. 5 shows the HEC-RAS simulated flood extent in the municipality of Muçum. It is possible to see that more than 60 % of the municipality was underwater.

Most of the 54 deaths occurred in small towns in the Taquari and Cai River basins. Of the 54 deaths, 48 occurred in the two 2 river basins even though it rained less than over Passo Fundo. These regions are identified in Fig. 6, which shows the map of municipalities in which deaths occurred, overlaying the interpolated accumulated rainfall data recorded from the CEMADEN environmental network [13]. The daily rainfall amounts are in the bar chart. The wettest days were from September 2nd and 4th. In the Passo Fundo daily rain surpassed 160 mmm from September 2nd and 4th, but it concentrated 4 people's deaths, while in Taquari and Cai River basins lasted from September 3rd and 4th, with less than 90 mm per day but concentrated most of the deaths. This suggests that the highest vulnerability of the municipalities in the Taquari and Cai River basins, where it rained less and for fewer days as compared to Passo Fundo, although more than 80 % of the deaths occurred in those basins.

4.2. Vulnerability evaluation

The PCA analysis for the 107 affected municipalities in the state of RS, using data from the 2010 Census revealed that three components explained 70.4 % of the data variance (Table 3).

PC1 explained 32.5 % of the data variance, which was represented by indicators related to the education and occupation (Table 3). Indicators such as the percentage of the population with higher education loading positively, along with indicators of the employed with higher education. Indicators related to employment in economic sectors such as commerce, construction, and public in-

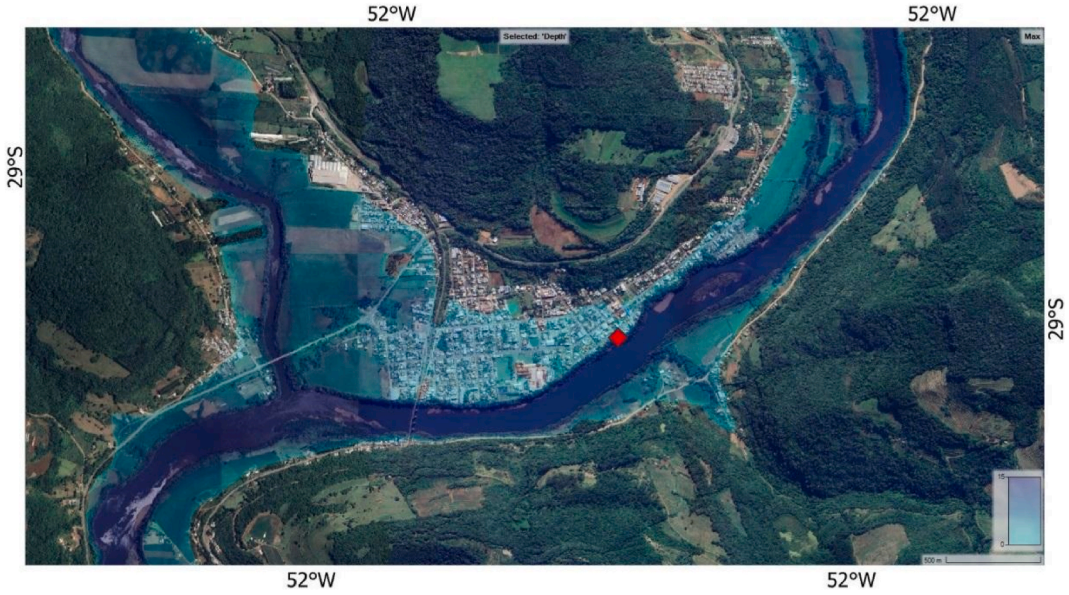


Fig. 5. Flood extent simulated with the 2D HEC-RAS model for a river stage of 26 m at the stream gauge ID:86510000 (red diamond) estimated by high-water marks in the urban area of the municipality of Muçum. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

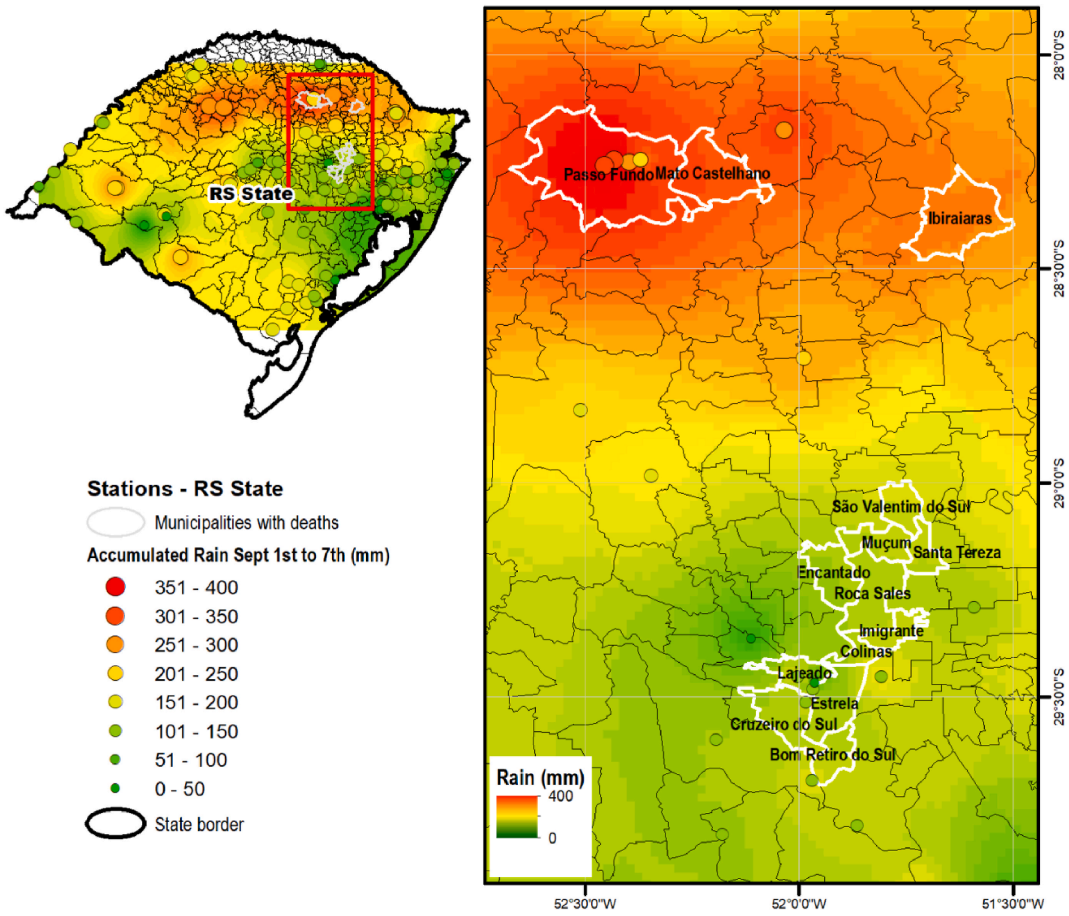


Fig. 6. Accumulated rain shown on a graph and map in the region of the state of Rio Grande do Sul where there were deaths resulting from disasters.

Table 3
Components, explained variance percentages, major drivers, and direction of influence of vulnerability (±) for the 2010 Census.

Component Name	Percentage of variation explained	Drivers (factor correlation)	Cardinality
PC1 - Education and Occupation	32.5	O5 (0.927) S4 (0.914) O3 (0.908) O10 (0.899) S3 (0.893) O3 (0.864) S2 (0.862) O6 (−0.740) O7 (0.719) S5 (−0.694) O8 (0.672) O1 (−0.659) O10 (0.517)	(−)
PC2 - Socioeconomic development	25.2	E4 (0.951) S6 (0.938) E3 (0.923) E1 (0.764) E5 (−0.751) S1 (0.727) S9 (0.631) I5 (0.622) I2 (−0.576) I4 (0.539)	(+)
PC3 - Industry Sector	12.7	O11 (0.758) O15 (0.696)	(−)
The formula for the calculation of the general score for each basin	PC2 + (1 - PC1) + (1 - PC3)		

dustrial services (related to activities such as electricity and gas transmission and distribution; water collection, treatment, and distribution; sewage and related activities; waste collection, treatment, and disposal; and recovery of materials; decontamination and other waste management services) also loading positively.

On the other hand, the indicator representing the percentage of employment in the agricultural sector loading negatively, along with the percentage of people aged 18 or older without completed elementary education, as well as the indicator representing self-employed individuals. Thus, the results indicate that higher percentage of agricultural workers, lower educational levels and populations engaged in informal employment indicated higher levels of vulnerability. PC1 has a negative cardinality, meaning that the higher the value for this component, the lower the vulnerability. The municipalities of Itapuca, São José das Missões and Lajeado do Bugre presented higher vulnerability to this component.

PC2 explained 25.2 % of the data variance and comprised indicators related to lower income and precarious household infrastructures (Table 3). Indicators such as the proportion of those vulnerable to poverty, the proportion of poor individuals, the percentage of people in households vulnerable to poverty and with no completed elementary education, and the percentage of people in households vulnerable to poverty and dependent on the elderly loading positively. Also, the indicator representing the percentage of children aged 4–5 years out of school and the illiteracy rate of the population aged 15 or older loading positively. However, the average per capita income loading negatively. Households with proper garbage collection also loading negatively. Conversely, households without electricity and with inadequate walls loading positively. PC2 has a positive cardinality, meaning that the higher the value, the higher the vulnerability. Therefore, lower socioeconomic and inadequate households indicated higher vulnerability in PC2. The municipalities of Lajeado do Bugre, Cacique Doble and Jacuizinho presented higher vulnerability in PC2.

Finally, PC3 explained 12.7 % of the data variance and was represented by populations employed in the industry sector, specifically in the manufacturing industry, and those employed with formal employment contracts, both indicators loading positively (Table 3). Thus, individuals employed with formal contracts, which guarantee labor rights and those employed in the manufacturing industry indicated lower vulnerability, since this component has negatively cardinality. Jacuizinho, Lagoão and São José das Missões were the municipalities with the higher vulnerability in PC3.

4.3. Municipal disaster risk management capacities

Concerning risk management capabilities, 96 % of municipalities had Municipal Coordination of Protection and Civil Defense - COMPDECs or similar entities.

COMPDECs are responsible for planning, articulating, coordinating, mobilizing, and managing Civil Defense actions at municipal levels. From COMPDEC, Civil Defense actions related to disaster prevention, emergency preparedness, response, and reconstruction are prioritized [69]. The high percentage of COMPDECS in Brazil can be attributed to Federal Decree 912 of May 2008, which determines that municipalities establish COMPDEC structures, which are qualified for the transfer of federal resources destined for protection and civil defense actions [29,53].

However, only 39 % of the affected municipalities had Fire Units, while 16 % had a Municipal Guard that received training in civil defense. These characteristics may indicate lower disaster response capabilities, as the military fire department, linked to state gov-

ernments, is responsible for rescuing the population in disaster situations [70]. The percentages of Community Nuclei for Protection and Civil Defense - NUPDEC were even lower, with only 7 % of the municipalities analyzed having this infrastructure.

Furthermore, although many municipalities have COMPDECs, they are precarious in terms of providing adequate physical spaces, their vehicles, and tools such as GPS, items that are essential to guarantee more effective disaster response actions (Fig. 7).

Regarding human resources, only 27 % of the analyzed municipalities had employees with employment contracts. The absence of employment contracts can compromise the efficiency of risk management activities, related to the lack of trained professionals, financial stability of employees, as well as continuity in project execution.

Concerning financial resources, only 36 % of the analyzed municipalities reported having budgeted resources for protection and civil defense actions in the Annual Budget Law. The result was even lower (15 %) for municipalities that had other sources of funding for protection and civil defense actions. The lack of financial resources can compromise response actions due to a lack of funding in this area.

These results are supported by the research titled "Diagnosis of Municipal Capacities and Needs in Protection and Civil Defense" [71] which included the development of questionnaires applied in 1055 COMPDECs in Brazil. Specifically, in the South Region, the results showed that the main challenges related to COMPEDCs corresponded to the lack of financial resources, as well as the scarcity of human resources and equipment.

For the institutional dimension, the results showed that 44 % of municipalities did not have any planning tools, mainly those related to landslides (Fig. 8).

Furthermore, only 34 % of the analyzed municipalities had a Municipal Master Plan - MMP including floods and landslides prevention actions. It is noteworthy that, of the total municipalities analyzed, 36 % did not have a Municipal Master Plan. The MMP is a

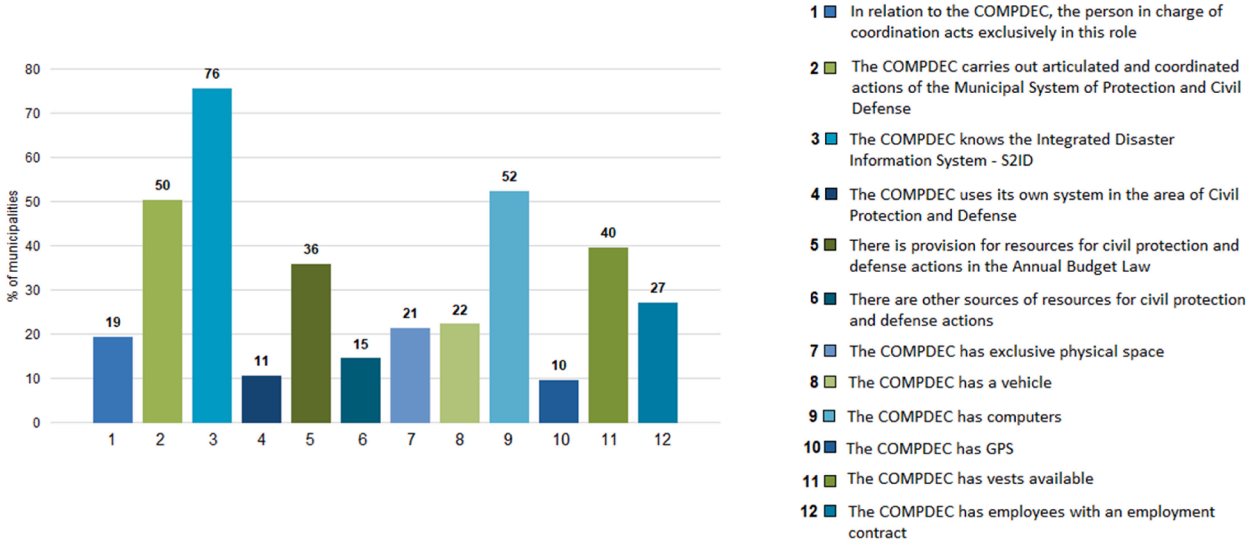


Fig. 7. Percentage of municipalities according to the characteristics and resources available in COMPDECs. (Source: IBGE, 2021).

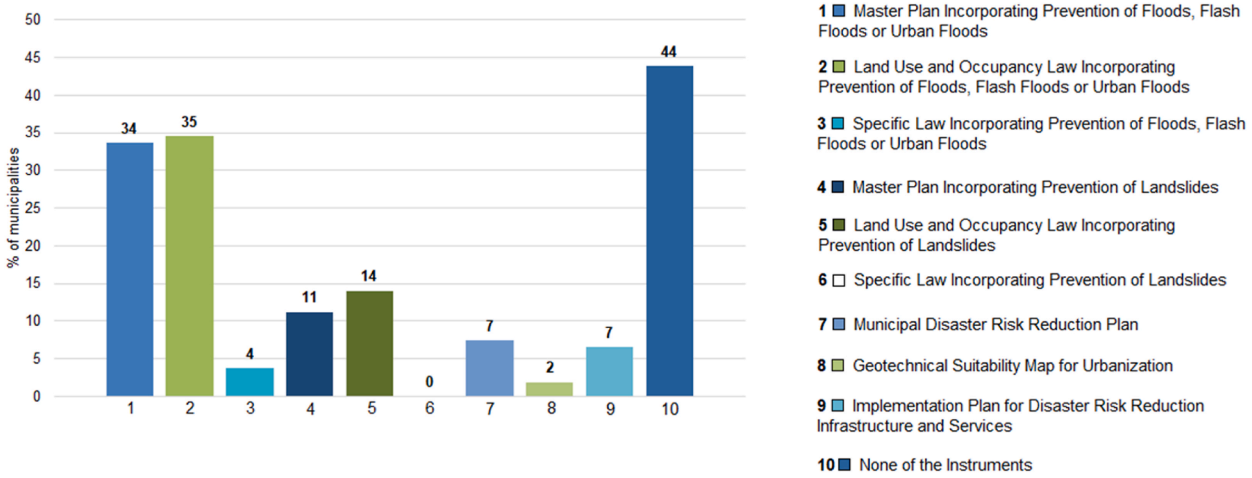


Fig. 8. Percentage of municipalities according to the availability of Institutional tools related to disaster risk. (Source: IBGE, 2021).

municipal law that guides urban development in terms of land use and must be mandatory for municipalities that meet at least one of the following criteria: cities with more than 20 thousand inhabitants; municipalities that are part of metropolitan regions; or municipalities in regions of special tourist interest; or municipalities in areas influenced by commercial activities with regional or national environmental impacts [29]. These criteria may explain the absence of MMP in the analyzed municipalities, as most of the cities had a population under 5000 inhabitants.

The PMRR is a document that outlines strategies, guidelines, and actions aimed at reducing disaster risks. It identifies risk-prone areas within municipalities and facilitates the formal request for federal resources dedicated to risk reduction and mitigation [54]. The PMRR suggests intervention alternatives and establishes a priority action order based on parameters such as risk level, the number of houses requiring relocation, the number of houses/families benefiting from interventions, and others [72].

The lower percentage of public policies and actions implemented by municipalities, focusing on landslides, may maybe because, of the total number of disasters associated with hydrometeorological risks recorded in the period from 1991 to 2022, only 1 % corresponded to landslides. On the other hand, disasters associated with floods, flash floods, and urban flooding represented more than 50 % of total records in the period, indicating the recurrence of these typologies in the municipalities analyzed.

Thus, specifically regarding disaster risk management related to floods, it was observed a higher percentage of analyzed municipalities with risk area mapped and contingency plans (Fig. 9).

The presented results may be related to the development of the Continuing Education Program in Protection and Civil Defense, established by the National Secretariat of Defense and Civil Protection (SEDEC), which emphasized the importance of contingency plan development and provided technical publications to support the elaboration of these plans [69]. Furthermore, the sectorization of geological and hydrological risks carried out by the Geological Survey of Brazil - CPRM, to support decision-making related to territorial planning and disaster prevention policies, may have contributed to the observed results. However, despite the recurrence of disasters associated with floods, the results showed that 27 % of the municipalities analyzed did not have disaster risk management tools associated with floods, flash floods, and urban floods, although these events are recurrent in the municipalities analyzed.

5. Discussion

The evaluation of vulnerability revealed that municipalities with higher vulnerability levels to rainfall extremes and related disasters in RS were characterized by populations with low socioeconomic status, marked by a higher number of individuals in poverty, vulnerability to poverty, lower education levels, and residents in households with precarious infrastructure. Additionally, higher vulnerability was observed concerning the disparity between populations employed with formal contracts and those self-employed and associated with higher percentages of employment in the agricultural sector. In general, these characteristics can be associated with lower socioeconomic levels (Fig. 10).

Specifically on the levels of human development index (HDI) for the state of RS, data from the Brazilian Human Development Atlas (2013), shows an evolution over the years, transitioning from a low index in 1991 (0,542 HDI) to a high index in 2010 (0,746 HDI), ranking this state as the 6th one with the highest HDI in the country [73]. Regarding the economy, according to 2017 data, ranked as the fourth-largest economy in the country according to the Gross Domestic Product - GDP, which constitutes the sum of all goods and services produced by the state's economy, driven by agriculture and manufacturing industries [63].

However, data related to the Socioeconomic Development Index - IDESE, exclusively performed for RS state since 2013, shows results of medium development for municipalities. IDESE is a synthetic index aimed at measuring the degree of development of municipalities in RS. The index considers a set of 12 indicators, divided into three blocks: i) education, relating to five indicators that are divided into four subblocks, according to age groups and level of education; ii) income, associated with two subblocks that include appropriation and income generation; and iii) health, characterized by five indicators, divided into three subblocks that include child health, general health conditions and longevity [39].

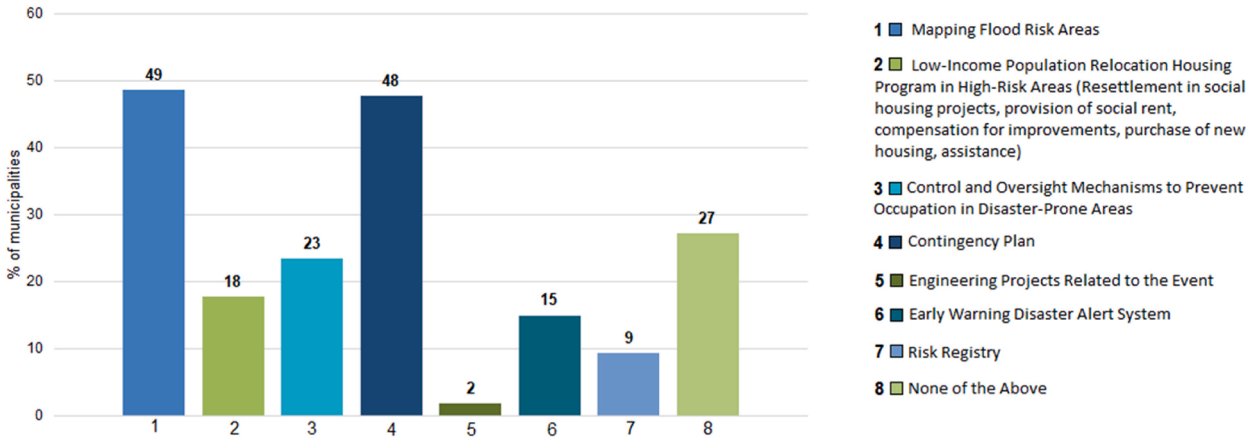


Fig. 9. Percentage of municipalities with specific projects, plans, and actions for flood risks. (Source: IBGE, 2021).

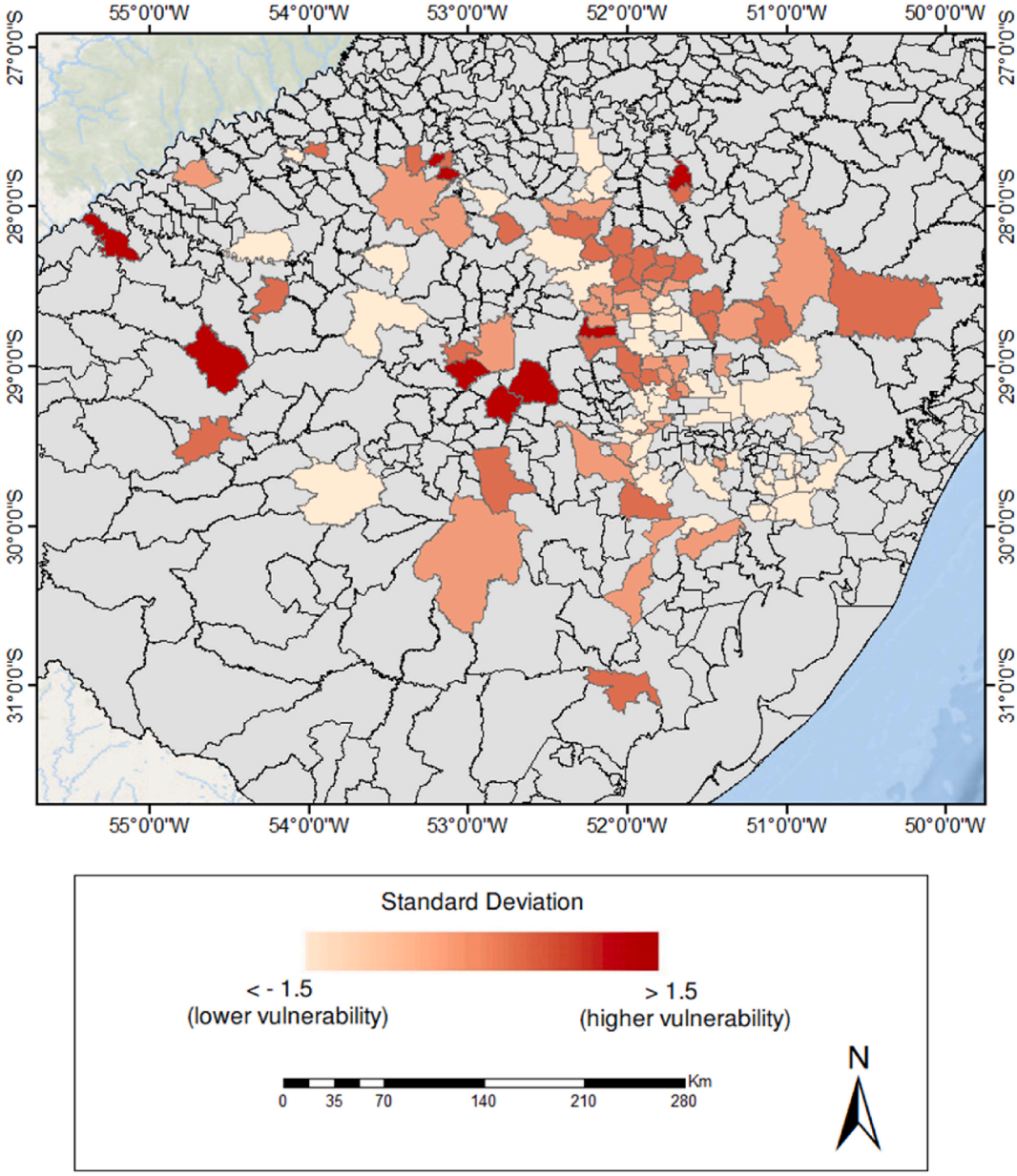


Fig. 10. Vulnerability index for the analyzed municipalities.

The IDESE level exhibited an upward trajectory from approximately 0.74 in 2013 to 0.78 in 2019, followed by a subsequent decline from 0.78 to 0.77 in 2020. Analysis of the three constituent parameters of IDESE reveals that education presented an increase from 0.68 in 2013 to 0.75 in 2020. On the other hand, the parameter associated with income showed decreases in the intervals from 2014 to 2016 (0.74–0.73) and from 2019 to 2020 (0.75–0.72). Regarding health, the results indicate high levels, demonstrating a progressive increase from 0.81 in 2013 to 0.84 in 2020.

Assessment of both HDI and IDESE for the year 2013, as well as the IDESE of 2020, for the 107 impacted municipalities, reveals medium and high values of social and economic development. Consequently, it becomes evident that such synthetic indices lack representativeness regarding their uses in addressing vulnerabilities and risk management capabilities. This finding is corroborated by other studies, which highlight that the size of municipalities and the dimensions of urban and institutional infrastructure must be considered in disaster risk analyses in small municipalities in Brazil. Therefore, these characteristics are not included in the indices [29,53].

The results highlighted that municipalities that presented higher vulnerability, are predominantly associated with specific dimensions, such as the size of the municipalities and the socioeconomic profiles of their populations, together with institutional factors associated with low urban development. The municipalities that presented low levels of vulnerability were characterized by popula-

tions greater than 100 thousand inhabitants, diverse economies, and greater urban development. On the other hand, municipalities that present high levels of vulnerability were identified as having populations of less than 10 thousand inhabitants, showing economic dependence on the agricultural sector and reduced levels of urban development. It is worth highlighting that a substantial portion – 44 % – of the total municipalities analyzed are characterized by agricultural activities and populations of less than 5 thousand inhabitants.

The high levels of vulnerability in the municipalities analyzed may be related to the specific characteristics of the locations, that is, small Brazilian urban areas. Such urban areas in Brazil present significant diversity and individuality in multiple aspects, which are associated with spatial growth; participation of social and governmental actors; cultural peculiarities, geographic locations; accessibility characteristics; and levels of integration in the globalized economy. Therefore, small cities in Brazil present a wide spectrum, ranging from places with approximately 5000 residents involved in rudimentary urban functions to cities with populations greater than 50,000, characterized by a high degree of urban complexity [29].

Previous studies indicate that small Brazilian urban areas with economies predominantly concentrated in primary sectors, such as agriculture and mineral extraction, may have lower socioeconomic levels. This phenomenon is attributed to the absence of a dynamic economic sector capable of generating new employment opportunities, combined with a deficiency in educational services that provide specialized technical training and higher education [29,51,70].

In a broader context, populations associated with rural sectors may demonstrate greater vulnerability, due to lower wages, indicative of a lower socioeconomic status [29,74]. The results of the present study corroborate these statements, as evidenced in the analyses carried out, that is, the population involved in the agricultural sector had lower levels of education, income, and households with more precarious infrastructure. These factors contribute to diminishing disaster recovery and response capabilities.

Similar findings were reported in the study conducted by Hummell, Cutter, and Emrich [57], who formulated a social vulnerability index for all Brazilian municipalities. The results revealed that regions characterized by a greater concentration of agricultural workers had attributes indicative of lower socioeconomic development, such as deficiencies in garbage collection services and sewage infrastructure. Ribeiro, Saito, and Alvalá [29], when analyzing vulnerability and disaster risk reduction capabilities in small Brazilian urban centers, also identified high vulnerability associated with agricultural workers, a demographic group associated with the lowest socioeconomic strata. These authors emphasized the importance of implementing social programs or initiatives in small Brazilian urban centers that are characterized by an economy centered on the agricultural sector, to improve the quality of life of these populations.

Therefore, based on data from the Profile of Brazilian Municipalities 2020 [75], in the present study it was found that 30 % of the municipalities analyzed, do not prioritize specific social programs or initiatives in support of agricultural producers. The implementation of such policies could significantly contribute to reducing the vulnerability of these populations. This is particularly crucial for RS, as 45 % of the state's gross domestic product comes from municipalities with a population of less than 10 thousand inhabitants [39].

Municipalities predominantly dependent on the agricultural sector may be economically dependent on local resources, making them particularly susceptible to the adverse impacts of disasters [29]. This vulnerability was evident in the municipalities analyzed, that is, based on S2iD data, losses of more than 1 billion reais (approximately 200 million dollars currently) for farmers were recorded. Furthermore, extensive economic losses in the agricultural and livestock sectors associated with disasters have been consistently observed over the years, totaling more than 19 billion reais (approximately 3.8 billion dollars currently) between 1991 and 2022 [38].

From the results obtained, it is also highlighted that municipalities with higher levels of vulnerability are characterized by low economic diversity, combined with a greater disparity between salaried workers and self-employed workers. Greater economic diversification contributes to the dispersion of employment across several sectors, thus promoting stability, as the economy does not depend on a single specific sector [21,51,52].

Concerning educational levels, the municipalities had a higher school dropout rate associated with secondary education, with an average rate of 9 % in 2010. For elementary schools, the average dropout rate decreased to 1 % in 2010. These results may be associated with the educational policies implemented in the municipalities since they all had a Municipal Education Council and Municipal Education Plan.

However, for the municipalities that presented high vulnerability the results indicated higher high school dropout rates among the municipalities examined, with emphasis on Lajeado do Bugre and Sagrada Família, which presented dropout rates above 20 %. In terms of educational projects, actions, or measures implemented by municipal education management institutions in 2021, the results revealed that only 8 % were related to aligning the ages of students with the years of schooling they attended, and only 18 % were associated with a reduction in dropout and absenteeism.

Academic delay is characterized by the rate of students with two or more years of age difference about the recommended age for the grade in which they are studying, which can compromise the quality of learning and accentuate social inequalities [72]. Thus, educational delay becomes a concern in the municipalities analyzed, considering that the factors of greatest vulnerability in the populations were associated with lower educational levels. Furthermore, 38 % of the municipalities analyzed did not have schools that offered the Youth and Adult Education (EJA) modality, indicating a greater challenge for the population to complete their studies in these cities.

Municipalities with high levels of vulnerability were also characterized by the absence of legislation, or environmental management instruments, related to selective waste collection and basic sanitation, according to data from 2020. The absence of such policies can contribute to the increase of vulnerability in municipalities, as evidenced by its association with households without adequate garbage collection and sanitary sewage.

These results may be associated with the lack of implementation of public policies and actions that contribute to the improvement of socioeconomic conditions, such as social action policies aimed at agricultural workers, policies to combat school delays, and initiatives that improve housing infrastructures. According to Akaishi [76], several small cities in Brazil face a lack of technical and legal apparatus, along with a shortage of essential financial resources to support the development of specific instruments, laws, and legislation intended to assist public administration in urban planning, which guarantees the well-being and quality of life of the population.

Additionally, the results concerning risk management capabilities revealed that, even though over 90 % of 107 municipalities had COMPDECs, they lacked improvements in their structure and instruments, as well as demand greater financial investments. When analyzing the 14 municipalities that reported fatalities (Fig. 2), the results regarding risk management capacities shows that these municipalities stood out with lower values, with a total of 9 lacking fire departments, including Muçum and Roca Sales, which recorded the highest number of fatalities. Additionally, none of the 14 municipalities had a municipal guard with civil defense trained. Regarding COMPDECS, only 5 out of the 14 municipalities had allocated resources for civil protection and defense actions in the Annual Budget Law, while only 2 had other sources of funding for civil protection and defense actions. It is noteworthy that the municipalities of Muçum and Roca Sales lacked both types of funding sources and did not have a dedicated space for COMPDECS, vehicles, or employees with formal employment contracts. Thus, although these municipalities do not present high levels of vulnerability, the results showed that the absence of disaster risk management capabilities may have contributed to the occurrence of fatalities.

Therefore, municipal administrations must invest in strengthening and allocating resources, especially for proposing and implementing actions and policies, as well as acquiring tools, relevant to support management and responses to disasters. Furthermore, it is crucial to promote civil protection and defense activities directly with communities, mainly through NUPDECs. The results revealed that only 7 % of the total municipalities analyzed had such structures, while none of the 14 municipalities with records of deaths have NUPDECs. It is noteworthy that the total number of fatal victims, 29 were male, 22 were female and 7 were not identified. Furthermore, of the total of 58 victims, 48 % (24) were aged between 62 and 99 years old, which is associated with the highest rate of aging in the state of Rio Grande do Sul reported in the 2022 Sociodemographic Census [41], which was recorded 115 elderly people for every 100 children.

Due to the specificities of the impacted municipalities, it is crucial to invest in actions aimed at raising awareness and perception of risk in communities, since many of the deaths recorded occurred due to a lack of knowledge about the damages in situations of flash floods and floods. Additionally, the fact that most of the affected population is over 50 years of age increased the impacts, especially in the three municipalities with high vulnerability and the highest number of recorded deaths.

The analysis conducted in this study has proven to be relevant in facilitating the identification of factors influencing the impacts of floods in RS. The proposed methodology, which relies on multidimensional analysis focusing on hydrological and meteorological characteristics, as well as the identification and assessment of population vulnerabilities and municipal risk management capabilities, has demonstrated its suitability for analyzing flood drivers in municipalities. These findings align with other studies that have employed similar methodologies to examine disaster risk drivers in Latin America, such as the study by Quesada-Román [36], which concentrated on developing a flood risk index for municipalities in Costa Rica. This index was formulated based on analyses pertaining to hazards, exposure and vulnerability. In another study also focused on Costa Rica, a risk index for informal settlements was developed, considering levels of hazard, exposure and vulnerability [36]. Therefore, studies that seek to understand risk drivers through methodologies that encompass both hazards, exposure and vulnerability to Latin America and the Caribbean are important in the current context, since it is expected flood consequences more intense due to the aspects related to the unregulated urbanization in inappropriate areas, environmental degradation, persistence of poverty, inefficient public policies, and inadequate infrastructures [10,77].

6. Conclusion

In the present study, the hydrometeorological situation that led to historic floods in more than a hundred municipalities in the state of Rio Grande do Sul in September 2023 was evaluated, as well as the population's vulnerability characteristics and risk management capabilities. The flooding events resulted in 54 deaths and dozens of displacements, as well as significant economic and environmental impacts.

The findings reveal that while risk predictions and early warnings were provided, they were insufficient to support life-saving actions and minimize the impacts of the extreme rains on cities and affected communities. This inadequacy may have been exacerbated by the exceptional nature of the rainfall and river levels recorded in the region, which lacked historical precedent for disasters of this magnitude.

The higher levels of vulnerability were associated with populations of low socioeconomic status residing in dwellings with precarious infrastructure, particularly in small municipalities heavily dependent on agriculture. The high vulnerability in these municipalities may be attributed to the absence of public policies and initiatives that could enhance socioeconomic conditions. This includes social action policies targeting agricultural workers, efforts to combat educational lag, and initiatives to improve household infrastructure. Many small Brazilian municipalities face a lack of technical and legal apparatus, coupled with a shortage of essential financial resources to support the development of specific instruments, laws, and projects intended to assist public administration in urban planning, thereby ensuring the well-being and quality of life of the population. This reality is observable in municipalities with high vulnerability, where there is a greater inadequacy in implementing targeted public policies.

Municipal governments must invest in strengthening tools, actions, and policies focused on response and risk management. Additionally, fostering educational activities in civil protection and defense is crucial, particularly focused on the elderly population. Such

policies could be done through the implementation of Community Nuclei for Protection and Civil Defense directly engaging with the communities.

In the face of climate change, with consequent extreme rainfall, very short, short, and medium-term investments are needed to minimize socioeconomic and environmental impacts and reduce the fragility of impacted cities. Immediate relief must include, in addition to the availability of shelter, medicine, food, and water, psychological support for all those impacted. In addition, identifying safe areas, establishing well-marked escape routes and building temporary shelters; prioritizing re-urbanization, afforestation, reforestation and drainage works, and recovery of vegetation on riverbanks and mountain tops are also imperative. The list of investments must also include carrying out simulations with the population, considering different disaster scenarios; improving communication, so that the population understands the risks, alerts, and alarms; developing risk perception through scientific dissemination in schools, civil defenses, and society in general, considering the use of contemporary educational strategies, for the development of a sustainable and resilient society.

It is crucial to invest in tools and policies for reducing vulnerabilities and disaster risks. The results of this study have shown that such actions are imperative, especially for municipalities that do not have a significant time history of disasters but may be impacted in the future. In this sense, considering the recent disaster that is impacting the entire state of Rio Grande do Sul in May 2024, the results presented corroborate the need for investments in broad management and reduction of disaster risks, due to the challenges imposed by climate change, responsible for more frequent and intense events in the region.

CRediT authorship contribution statement

Regina Célia dos Santos Alvalá: Writing – review & editing, Conceptualization. **Daniela Ferreira Ribeiro:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Jose Antonio Marengo:** Writing – review & editing, Methodology, Data curation. **Marcelo Enrique Seluchi:** Writing – review & editing. **Demerval Aparecido Gonçalves:** Data curation. **Larissa Antunes da Silva:** Methodology, Data curation. **Luz Adriana Cuartas Pineda:** Writing – review & editing. **Silvia Midori Saito:** Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

We thank National Council for Scientific and Technological Development (CNPq, Brazil) for financial support for the second, and sixth authors. This work was supported by Brazil's National Institute of Science and Technology for Climate Change Phase 2 under CNPq Grant 465501/2014-1; FAPESP Grants 2014/50848-9, and the National Coordination for Higher Education and Training (CAPES) Grant 88887.136402/2017-00. This paper is a contribution of the Brazilian Research Network on Global Climate Change FINEP/Rede CLIMA Grant 01.13.0353-00.

References

[1] K. Calvin, D. Dasgupta, G. Krinner, A. Mukherji, P.W. Thorne, C. Trisos, J. Romero, P. Aldunce, K. Barrett, G. Blanco, W.W.L. Cheung, S. Connors, F. Denton, A. Diongue-Niang, D. Dodman, M. Garschagen, O. Geden, B. Hayward, C. Jones, F. Jotzo, T. Krug, R. Lasco, Y.-Y. Lee, V. Masson-Delmotte, M. Meinshausen, K. Mintenbeck, A. Mokssit, F.E.L. Otto, M. Pathak, A. Pirani, E. Poloczanska, H.-O. Pörtner, A. Revi, D.C. Roberts, J. Roy, A.C. Ruane, J. Skea, P.R. Shukla, R. Slade, A. Slangen, Y. Sokona, A.A. Sörensson, M. Tignor, D. van Vuuren, Y.-M. Wei, H. Winkler, P. Zhai, Z. Zommers, J.-C. Hourcade, F.X. Johnson, S. Pachauri, N.P. Simpson, C. Singh, A. Thomas, E. Totin, A. Alegría, K. Armour, B. Bednar-Friedl, K. Blok, G. Cissé, F. Dentener, S. Eriksen, E. Fischer, G. Garner, C. Guivarch, M. Haasnoot, G. Hansen, M. Hauser, E. Hawkins, T. Hermans, R. Kopp, N. Leprince-Ringuet, J. Lewis, D. Ley, C. Ludden, L. Niamir, Z. Nicholls, S. Some, S. Szopa, B. Trewin, K.-I. van der Wijst, G. Winter, M. Witting, A. Birt, M. HaIPCC, Climate change 2023: synthesis report, in: H. Lee, J. Romero (Eds.), Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, IPCC, Geneva, Switzerland, 2023 https://doi.org/10.59327/IPCC/AR6-9789291691647, 2023.

[2] CRED - EM-DAT, 2022 Disasters in Numbers, 2023.

[3] L.O. Anderson, G. Ribeiro Neto, A.P. Cunha, M.G. Fonseca, Y. Mendes de Moura, R. Dalagnol, F.H. Wagner, L.E.O. e C. de Aragão, Vulnerability of Amazonian forests to repeated droughts, Phil. Trans. Biol. Sci. 373 (2018) 20170411, https://doi.org/10.1098/rstb.2017.0411.

[4] J.A. Marengo, C.M. Souza, K. Thonicke, C. Burton, K. Halladay, R.A. Betts, L.M. Alves, W.R. Soares, Changes in climate and land use over the Amazon region: current and future variability and trends, Front. Earth Sci. 6 (2018), https://doi.org/10.3389/feart.2018.00228.

[5] J.C. Jimenez, J.A. Marengo, L.M. Alves, J.C. Sulca, K. Takahashi, S. Ferrett, M. Collins, The role of ENSO flavours and TNA on recent droughts over Amazon forests and the Northeast Brazil region, Int. J. Climatol. 41 (2021) 3761–3780, https://doi.org/10.1002/joc.6453.

[6] S.S.B. Brito, A.P.M.A. Cunha, C.C. Cunningham, R.C. Alvalá, J.A. Marengo, M.A. Carvalho, Frequency, duration and severity of drought in the Semiarid Northeast Brazil region, Int. J. Climatol. 38 (2018) 517–529, https://doi.org/10.1002/joc.5225.

[7] A. Ávila, F. Justino, A. Wilson, D. Bromwich, M. Amorim, Recent precipitation trends, flash floods and landslides in southern Brazil, Environ. Res. Lett. 11 (2016) 114029, https://doi.org/10.1088/1748-9326/11/11/114029.

[8] J.A. Marengo, L.M. Alves, T. Ambrizzi, A. Young, N.J.C. Barreto, A.M. Ramos, Trends in extreme rainfall and hydrogeometeorological disasters in the Metropolitan Area of São Paulo: a review, Ann. N. Y. Acad. Sci. 1472 (2020) 5–20, https://doi.org/10.1111/nyas.14307.

[9] J.A. Marengo, T. Ambrizzi, L.M. Alves, N.J.C. Barreto, M. Simões Reboita, A.M. Ramos, Changing trends in rainfall extremes in the metropolitan area of São Paulo: causes and impacts, Frontiers in Climate 2 (2020) 1–13, https://doi.org/10.3389/fclim.2020.00003.

[10] J. Pinos, A. Quesada-Román, Flood risk-related research trends in Latin america and the caribbean, Water (Switzerland) 14 (2022), https://doi.org/10.3390/

w14010010.
[11] CNM, Desastres obrigam mais de 4,2 milhões de pessoas que foram negligenciadas pelas políticas públicas a buscarem alternativas de moradia nos últimos dez anos, https://cnm.org.br/storage/noticias/2023/Links/27072023_Estudo_Habita%C3%A7%C3%A3o_Desastre_revisado_area_publica%C3%A7%C3%A3o.pdf, 2021. (Accessed 10 January 2024).
[12] E. Alcântara, J.A. Marengo, J. Mantovani, L.R. Londe, R.L.Y. San, E. Park, Y.N. Lin, J. Wang, T. Mendes, A.P. Cunha, L. Pampuch, M. Seluchi, S. Simões, L.A. Cuartas, D. Goncalves, K. Massi, R. Alvalá, O. Moraes, C.S. Filho, R. Mendes, C. Nobre, Deadly disasters in southeastern South America: flash floods and landslides of February 2022 in Petrópolis, Rio de Janeiro, Nat. Hazards Earth Syst. Sci. 23 (2023) 1157–1175, https://doi.org/10.5194/nhess-23-1157-2023.
[13] J.A. Marengo, E. Alcantara, A.P. Cunha, M. Seluchi, C.A. Nobre, G. Dolif, D. Goncalves, M. Assis Dias, L.A. Cuartas, F. Bender, A.M. Ramos, J.R. Mantovani, R.C. Alvalá, O.L. Moraes, Flash floods and landslides in the city of Recife, Northeast Brazil after heavy rain on May 25–28, 2022: causes, impacts, and disaster preparedness, Weather Clim. Extrem. 39 (2023), https://doi.org/10.1016/j.wace.2022.100545.
[14] J.A. Marengo, M.E. Seluchi, A.P. Cunha, L.A. Cuartas, D. Goncalves, V.B. Sperling, A.M. Ramos, G. Dolif, S. Saito, F. Bender, T.R. Lopes, R.C. Alvala, O.L. Moraes, Heavy rainfall associated with floods in southeastern Brazil in November–December 2021, Nat. Hazards 116 (2023) 3617–3644, https://doi.org/10.1007/s11069-023-05827-z.
[15] Defesa Civil Estadual do Rio Grande do Sul, Boletim Defesa Civil Rio Grande Do Sul, 2023.
[16] UNISDR, Sendai framework for disaster risk reduction 2015-2030, https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030, 2015.
[17] B. Wisner, I. Davis, T. Cannon, P. Blaikie, At Risk: Natural Hazards, People's Vulnerability and Disasters, second ed., Routledge, London, 2004, https://doi.org/10.4324/9780203974575.
[18] W.N. Adger, Social and ecological resilience: are they related? Prog. Hum. Geogr. 24 (2000) 347–364, https://doi.org/10.1191/030913200701540465.
[19] J. Birkmann, Measuring Vulnerability to Natural Hazards — towards Disaster Resilient Societies, United Nations University Press, 2013.
[20] UNDRR, Report of the Open-Ended Intergovernmental Expert Working Group on Indicators and Terminology Relating to Disaster Risk Reduction, 2016. http://www.preventionweb.net/drr-framework/open-ended-working-group/.
[21] S.L. Cutter, K.D. Ash, C.T. Emrich, The geographies of community disaster resilience, Global Environ. Change 29 (2014) 65–77, https://doi.org/10.1016/j.gloenvcha.2014.08.005.
[22] A.M. Sadri, S.V. Ukkusuri, S. Lee, R. Clawson, D. Aldrich, M.S. Nelson, J. Seipel, D. Kelly, The role of social capital, personal networks, and emergency responders in post-disaster recovery and resilience: a study of rural communities in Indiana, Nat. Hazards 90 (2018) 1377–1406, https://doi.org/10.1007/s11069-017-3103-0.
[23] S.L. Cutter, C. Finch, Temporal and Spatial Changes in Social Vulnerability to Natural Hazards, vol. 105, 2008, pp. 2301–2306.
[24] E.A. Goto, S.J. Domingue, S. Kalafatis, R.G. Ramos, S. Şalap-Ayça, Do the type of impact and vulnerability dimension matter when assessing natural hazard vulnerability? Int. J. Disaster Risk Reduc. 98 (2023), https://doi.org/10.1016/j.ijdrr.2023.104069.
[25] M.W. Beck, C.C. Shepard, Coastal environments and risk reduction, in: World Risk Report 2012, Alliance Development Works, Berlin, 2012, pp. 32–41.
[26] UNISDR, Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters, 2005.
[27] J. Birkmann, O.D. Cardona, M.L. Carreño, A.H. Barbat, M. Pelling, S. Schneiderbauer, S. Kienberger, M. Keiler, D. Alexander, P. Zeil, T. Welle, Framing vulnerability, risk and societal responses: the MOVE framework, Nat. Hazards 67 (2013) 193–211, https://doi.org/10.1007/s11069-013-0558-5.
[28] M.L. Carreño, O.D. Cardona, A.H. Barbat, New methodology for urban seismic risk assessment from a holistic perspective, Bull. Earthq. Eng. 10 (2012) 547–565, https://doi.org/10.1007/s10518-011-9302-2.
[29] D.F. Ribeiro, S.M. Saito, R.C.S. Alvalá, Disaster vulnerability analysis of small towns in Brazil, Int. J. Disaster Risk Reduc. 68 (2022) 102726, https://doi.org/10.1016/j.ijdrr.2021.102726.
[30] R.C.S. Alvalá, M.C. Dias, S.M. Saito, C. Stenner, C. Franco, P. Amadeu, J. Ribeiro, R.A.M. Souza, C.A. Nobre, Mapping characteristics of at-risk population to disasters in the context of Brazilian early warning system, Int. J. Disaster Risk Reduc. 41 (2019) 101326, https://doi.org/10.1016/j.ijdrr.2019.101326.
[31] F.E.A. Horita, J.P. de Albuquerque, V. Marchezini, Understanding the decision-making process in disaster risk monitoring and early-warning: a case study within a control room in Brazil, Int. J. Disaster Risk Reduc. 28 (2018) 22–31, https://doi.org/10.1016/j.ijdrr.2018.01.034.
[32] M. Kabenge, J. Elaru, H. Wang, F. Li, Characterizing flood hazard risk in data-scarce areas, using a remote sensing and GIS-based flood hazard index, Nat. Hazards 89 (2017) 1369–1387, https://doi.org/10.1007/s11069-017-3024-y.
[33] P.P. Santos, S. Pereira, J.L. Zêzere, A.O. Tavares, E. Reis, R.A.C. Garcia, S.C. Oliveira, A comprehensive approach to understanding flood risk drivers at the municipal level, J. Environ. Manag. 260 (2020), https://doi.org/10.1016/j.jenvman.2020.110127.
[34] S. Pereira, P.P. Santos, J.L. Zêzere, A.O. Tavares, R.A.C. Garcia, S.C. Oliveira, A landslide risk index for municipal land use planning in Portugal, Sci. Total Environ. 735 (2020), https://doi.org/10.1016/j.scitotenv.2020.139463.
[35] M. del M. Garro-Quesada, M. Vargas-Leiva, P.O. Girot, A. Quesada-Román, Climate risk analysis using a high-resolution spatial model in Costa Rica, Climate 11 (2023), https://doi.org/10.3390/cli11060127.
[36] A. Quesada-Román, Flood risk index development at the municipal level in Costa Rica: a methodological framework, Environ. Sci. Pol. 133 (2022) 98–106, https://doi.org/10.1016/j.envsci.2022.03.012.
[37] A. Tasnuva, M.R. Hossain, R. Salam, A.R.M.T. Islam, M.M. Patwary, S.M. Ibrahim, Employing social vulnerability index to assess household social vulnerability of natural hazards: an evidence from southwest coastal Bangladesh, Environ. Dev. Sustain. 23 (2021) 10223–10245, https://doi.org/10.1007/s10668-020-01054-9.
[38] BRASIL, Atlas Digital de Desastres no Brasil, Ministério do Desenvolvimento Regional. Secretaria de Proteção e Defesa Civil. Universidade Federal de Santa Catarina. Centro de Estudos e Pesquisas em Engenharia e Defesa, Brasília, 2022. https://atlas.ceped.ufsc.br/paginas/index.xhtml.
[39] A.M. Bertê, A.P. Cargnin, B. de O. Lemos, C.R. da Silva, G. da S. Ferreira, L. da S. Mieres, M.S.L. Pereira, S.B. de Oliveira, J. Marcon, Atlas socioeconômico do Rio Grande do Sul. Secretaria de Planejamento, Governança e Gestão, 6th ed., Porto Alegre, 2021. https://atlassocioeconomico.rs.gov.br/inicial.
[40] M.C. Peel, B.L. Finlayson, T.A. McMahon, Updated world map of the Köppen-Geiger climate classification, Hydrol. Earth Syst. Sci. 11 (2007) 1633–1644, https://doi.org/10.5194/hess-11-1633-2007.
[41] IBGE - Instituto de Geografia e Estatística, Censo Demográfico 2022, IBGE, 2022.
[42] J.R. Rozante, D.S. Moreira, L.G.G. de Goncalves, D.A. Vila, Combining TRMM and surface observations of precipitation: technique and validation over south America, Weather Forecast. 25 (2010) 885–894, https://doi.org/10.1175/2010WAF2222325.1.
[43] G.W. Brunner, HEC-RAS river analysis system. Hydraulic Reference Manual, 1995.
[44] US Army Corps of Engineers, HEC-RAS river analysis system. Version 6.1.0. User's manual, Hydrologic Engineering Center (2021).
[45] US Army Corps of Engineers, HEC-RAS River Analysis System, 2D Modeling User's Manual, Hydrologic Engineeering Center, 2016 Version 5.0.
[46] Y. Lee, Social vulnerability indicators as a sustainable planning tool, Environ. Impact Assess. Rev. 44 (2014) 31–42, https://doi.org/10.1016/j.eiar.2013.08.002.
[47] S.L. Cutter, The landscape of disaster resilience indicators in the USA, Nat. Hazards 80 (2016) 741–758, https://doi.org/10.1007/s11069-015-1993-2.
[48] A. Asadzadeh, T. Kötter, P. Salehi, J. Birkmann, Operationalizing a concept: the systematic review of composite indicator building for measuring community disaster resilience, Int. J. Disaster Risk Reduc. 25 (2017) 147–162, https://doi.org/10.1016/j.ijdrr.2017.09.015.
[49] H. Cai, N.S.N. Lam, Y. Qiang, L. Zou, R.M. Correll, V. Mihunov, A synthesis of disaster resilience measurement methods and indices, Int. J. Disaster Risk Reduc. 31 (2018) 844–855, https://doi.org/10.1016/j.ijdrr.2018.07.015.
[50] J.-M. Cariolet, M. Vuillet, Y. Diab, Mapping urban resilience to disasters – a review, Sustain. Cities Soc. 51 (2019) 101746, https://doi.org/10.1016/j.scs.2019.101746.
[51] W. LOPES, D.M. F HENRIQUE (Eds.), Cidades médias e pequenas: reflexões sobre os desafios no estudo dessas realidades socioespaciais, Cidades Médias e Pequenas: Teorias, Conceitos e Estudos de Caso, 2010, p. 250.
[52] F.H. Norris, S.P. Stevens, B. Pfefferbaum, K.F. Wyche, R.L. Pfefferbaum, Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness, Am. J. Community Psychol. 41 (2008) 127–150, https://doi.org/10.1007/s10464-007-9156-6.

[53] K. Sherrieb, F.H. Norris, S. Galea, Measuring capacities for community resilience, Soc. Indicat. Res. 99 (2010) 227–247, https://doi.org/10.1007/s11205-010-9576-9.
[54] S.M. Saito, M.C. Assis Dias, D.F. Ribeiro, R.C.S. Alvalá, D.B. Souza, R.A.S.M. Santana, P.A. Souza, J.V.M. Ribeiro, C. Stenner, Disaster risk areas in Brazil: outcomes from an intra-urban scale analysis, Int J Disaster Resil Built Environ 12 (2021) 238–250, https://doi.org/10.1108/IJDRBE-01-2020-0008.
[55] S.L. Cutter, B.J. Boruff, W.L. Shirley, Social vulnerability to environmental hazards, Soc. Sci. Q. 84 (2003) 242–261, https://doi.org/10.1111/1540-6237.8402002.
[56] I. Kotzee, B. Reyers, Piloting a social-ecological index for measuring flood resilience: a composite index approach, Ecol. Indicat. 60 (2016) 45–53, https://doi.org/10.1016/j.ecolind.2015.06.018.
[57] B.M.L. Hummell, S.L. Cutter, C.T. Emrich, Social vulnerability to natural hazards in Brazil, International Journal of Disaster Risk Science 7 (2016) 111–122, https://doi.org/10.1007/s13753-016-0090-9.
[58] D.J. Roncancio, A.C. Nardocci, Social vulnerability to natural hazards in São Paulo, Brazil, Nat. Hazards 84 (2016) 1367–1383, https://doi.org/10.1007/s11069-016-2491-x.
[59] H. Abdi, L.J. Williams, Principal component analysis, Wiley Interdiscip Rev Comput Stat 2 (2010) 433–459, https://doi.org/10.1002/wics.101.
[60] G1, Chega a 100 o número de cidades atingidas por ciclone no RS (2023). Https://G1.Globo.Com/Rs/Rio-Grande-Do-Sul/Noticia/2023/09/13/Chega-a-100-o-Numero-de-Cidades-Atingidas-Pelo-Ciclone-Do-Rs.Ghtml.
[61] WMO, State of the Global Climate 2020, 2021 Geneva.
[62] WMO, State of the Global Climate 2022, 2023 Geneva.
[63] W. Cai, M.J. McPhaden, A.M. Grimm, R.R. Rodrigues, A.S. Taschetto, R.D. Garreaud, B. Dewitte, G. Poveda, Y.-G. Ham, A. Santoso, B. Ng, W. Anderson, G. Wang, T. Geng, H.-S. Jo, J.A. Marengo, L.M. Alves, M. Osman, S. Li, L. Wu, C. Karamperidou, K. Takahashi, C. Vera, Climate impacts of the El niño–southern oscillation on south America, Nat. Rev. Earth Environ. 1 (2020) 215–231, https://doi.org/10.1038/s43017-020-0040-3.
[64] C. Funk, P. Peterson, M. Landsfeld, F. Davenport, A. Becker, U. Schneider, D. Pedreros, A. McNally, K. Arsenault, L. Harrison, S. Shukla, Algorithm and data improvements for version 2.1 of the climate hazards center's InfraRed precipitation with stations, Data Set (2020) 409–427, https://doi.org/10.1007/978-3-030-24568-9_23.
[65] Cptec, CPTEC, Monitoramento Precipitação, Http://Clima1.Cptec.Inpe.Br/Monitoramentobrasil/Ptacumulado). (n.d.).
[66] Defesa Civil do Estado do Rio Grande do Sul, Após identificação de mais uma vítima, chega a 54 o número de mortos nas enchentes no Vale do Taquari, 2024.
[67] R. Davies, Brazil – Rains and Floods Wreak Havoc in Santa Catarina as Emergency Declarations Escalate (2023). Https://Floodlist.Com/America/Brazil-Floods-Santa-Catarina-October-2023.
[68] R. Davies, Brazil – Hundreds Displaced, 4 Dead After Storms and Floods in Rio Grande Do Sul, Https://Floodlist.Com/America/Brazil-Floods-Riograndedosul-September-2023 (n.d.).
[69] Brasil, Plano de Contingência - Livro Base, http://www.integracao.gov.br/images/stories/ArquivosDefesaCivil/ArquivosPDF/publicacoes/II---Plano-de-Contingencia---Livro-Base.pdf, 2017.
[70] R.S. Ganem, Gestão de desastres no brasil, Biblioteca Digital da Câmara dos Deputados, http://www.bibliotecaflorestal.ufv.br/handle/123456789/10029, 2012. (Accessed 21 June 2023).
[71] V. Marchezini, S. Saito, L.D.R. Londe, A.S. Viana, Diagnóstico de capacidades e necessidades municipais em proteção e defesa civil: Brasil, 2021.
[72] Ministério do Desenvolvimento Regional, GIRD+10: caderno técnico de gestão integrada de riscos e desastres, DF, Brasilia, 2021.
[73] PNUD, Índice de Desenvolvimento Humano Municipal Brasileiro, Brasília, 2013.
[74] D.F. Ribeiro, S.M. Saito, R.C. dos, S. Alvalá, Community disaster resilience in Brazilian small urban centers, Int. J. Disaster Risk Reduc. 100 (2024) 104200, https://doi.org/10.1016/j.ijdrr.2023.104200.
[75] IBGE, Perfil dos Municípios Brasileiros, IBGE, Coordenação de População e Indicadores Sociais, Rio de Janeiro, 2021 2020.
[76] A.G. Akaishi, Desafios do planejamento urbano-habitacional em pequenos municípios brasileiros, Risco Revista de Pesquisa Em Arquitetura e Urbanismo (Online) 14 (2011) 41–50, https://doi.org/10.11606/issn.1984-4506.v0i14p41-50.
[77] V. Sandoval, J.P. Sarmiento, A neglected issue: informal settlements, urban development, and disaster risk reduction in Latin America and the Caribbean, Disaster Prev. Manag. 29 (2020) 731–745, https://doi.org/10.1108/DPM-04-2020-0115.