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The impacts of extreme weather events: a comprehensive analysis of the 2024 floods in Rio Grande do Sul

Felipe Caleffi
Universidade Federal de Santa Maria (UFSM) – Cachoeira do Sul – Rio Grande do Sul – Brasil
ORCID: https://orcid.org/0000-0002-7370-3327

Cláudia Viviane Viegas
Universidade Federal do Rio Grande do Sul (UFRGS) – Porto Alegre – Rio Grande do Sul – Brasil
ORCID: https://orcid.org/0000-0002-7602-9366

Karina Bruno Lima
Universidade Federal do Rio Grande do Sul (UFRGS) – Porto Alegre – Rio Grande do Sul – Brasil
ORCID: https://orcid.org/0009-0008-3492-9746

Samuel Vinícius Bonato
Universidade Federal do Rio Grande (FURG) – Rio Grande – Rio Grande do Sul – Brasil
ORCID: https://orcid.org/0000-0002-2486-4909

Abstract
This paper presents a comprehensive analysis of the 2024 floods in Rio Grande do Sul, Brazil, exploring their extensive impacts on populations, infrastructure, and the environment. The study emphasizes the significant increase in rainfall and its correlation with the catastrophic floods, which affected 478 out of 497 municipalities, resulting in 182 fatalities and displacing over 580,000 individuals. Methodologically, the study employs a systematic literature mapping, synthesized from 16 studies published after May 2024, to categorize and assess existing research on the flood impacts, trends, gaps, and patterns. The analysis highlights the economic repercussions, with severe damage to agriculture and infrastructure, leading to estimated losses exceeding 3 billion Brazilian reais. The public health impact is also discussed, noting a rise in waterborne diseases and psychological stress among the affected populations. Furthermore, the paper examines the immediate disaster response and long-term mitigation strategies, including infrastructure improvements, enhanced weather prediction models, comprehensive watershed management, resilient agricultural practices, and robust public health infrastructure. The study underscores the need for inclusive governance and policy integration to enhance disaster responsiveness and community resilience. By implementing these strategies, Rio Grande do Sul can build a more resilient future, better prepared to face the challenges posed by extreme weather events and climate

change. This comprehensive review provides valuable insights and practical recommendations for policymakers, researchers, and practitioners involved in disaster management and environmental sustainability.

Keywords: Extreme weather events. Climate change. Food. Rio Grande do Sul.

Os impactos de eventos climáticos extremos: uma análise abrangente das enchentes de 2024 no Rio Grande do Sul

Resumo
Este artigo apresenta uma análise abrangente das enchentes de 2024 no Rio Grande do Sul, Brasil, explorando seus extensos impactos sobre as populações, infraestruturas e o meio ambiente. O estudo enfatiza o aumento significativo das chuvas e sua correlação com as enchentes catastróficas, que afetaram 478 dos 497 municípios, resultando em 182 mortes e deslocando mais de 580.000 indivíduos. Metodologicamente, o estudo emprega um mapeamento sistemático da literatura, sintetizado a partir de 16 estudos publicados após maio de 2024, para categorizar e avaliar a pesquisa existente sobre os impactos das enchentes, tendências, lacunas e padrões. A análise destaca as repercussões econômicas, com sérios danos à agricultura e infraestrutura, levando a perdas estimadas superiores a 3 bilhões de reais. O impacto na saúde pública também é discutido, observando um aumento nas doenças transmitidas pela água e no estresse psicológico entre as populações afetadas. Além disso, o artigo examina a resposta imediata ao desastre e as estratégias de mitigação a longo prazo, incluindo melhorias na infraestrutura, modelos aprimorados de previsão do tempo, gestão abrangente de bacias hidrográficas, práticas agrícolas resilientes e uma infraestrutura robusta de saúde pública. O estudo ressalta a necessidade de uma governança inclusiva e integração de políticas para melhorar a resposta a desastres e a resiliência comunitária. Ao implementar essas estratégias, o Rio Grande do Sul pode construir um futuro mais resiliente, mais bem preparado para enfrentar os desafios impostos pelos eventos climáticos extremos e pelas mudanças climáticas. Esta revisão abrangente fornece insights valiosos e recomendações práticas para formuladores de políticas, pesquisadores e profissionais envolvidos na gestão de desastres e sustentabilidade ambiental.

Palavras–chave: Eventos climáticos extremos. Mudança climática. Alimentos. Rio Grande do Sul.

Los impactos de los eventos climáticos extremos: un análisis exhaustivo de las inundaciones de 2024 en Rio Grande do Sul

Resumen
Este artículo presenta un análisis exhaustivo de las inundaciones de 2024 en Rio Grande do Sul, Brasil, explorando sus extensos impactos en las poblaciones, infraestructuras y el medio ambiente. El estudio enfatiza el aumento significativo de las lluvias y su correlación con las inundaciones catastróficas, que afectaron a 478 de los 497 municipios, resultando en 182 muertes y desplazando a más de 580,000 individuos. Metodológicamente, el estudio emplea un mapeo sistemático de la literatura, sintetizado a partir de 16 estudios publicados después de mayo de 2024, para categorizar y evaluar la investigación existente sobre los impactos de las inundaciones, tendencias, brechas y patrones. El análisis destaca las repercusiones económicas, con graves daños a la agricultura e infraestructura, que conducen a pérdidas estimadas superiores a 3 mil millones de reales brasileños. También se discute el impacto en la salud pública, observando un aumento en las enfermedades transmitidas por el agua y el estrés psicológico entre las poblaciones afectadas. Además, el artículo examina la respuesta

inmediata al desastre y las estrategias de mitigación a largo plazo, incluidas las mejoras en la infraestructura, modelos mejorados de predicción meteorológica, gestión integral de cuencas hidrográficas, prácticas agrícolas resilientes y una infraestructura robusta de salud pública. El estudio subraya la necesidad de una gobernanza inclusiva e integración de políticas para mejorar la respuesta a desastres y la resiliencia comunitaria. Al implementar estas estrategias, Rio Grande do Sul puede construir un futuro más resiliente, mejor preparado para enfrentar los desafíos impuestos por eventos climáticos extremos y el cambio climático. Esta revisión exhaustiva proporciona conocimientos valiosos y recomendaciones prácticas para los responsables de la formulación de políticas, investigadores y profesionales involucrados en la gestión de desastres y la sostenibilidad ambiental.

Palabras clave: Eventos climáticos extremos. Cambio climático. Alimentos. Rio Grande do Sul.

1 Introduction

Climate change is one of the most pressing issues of our time, requiring immediate action and collaboration on a global scale. The ever-growing impact of human activities on natural processes has led to a multitude of changes in global climate patterns, with an observed increase in global average temperatures and changes in rainfall distribution and intensity (WASKO et al., 2021; HO et al., 2023). These shifts are indicative of the intricate relationship between human actions and natural processes, and their consequences on the environment, which require an integrated assessment of hydroclimate, socioeconomic, and land use aspects (CHANG; FRANCZYK, 2008). The warming effect disrupts climatic patterns, resulting in more frequent and severe weather events, such as heavy precipitation, droughts and heatwaves (DEBORTOLI et al., 2017; IPCC, 2021). Similarly, changes in rainfall patterns have resulted in more frequent and severe natural disasters such as floods and droughts, causing devastating effects on human livelihoods and disrupting ecosystems. The repercussions of climate change extend beyond environmental degradation, impacting biodiversity, agricultural productivity, and human health, thereby posing a serious challenge to sustainable development and human well-being (HESHMATI, 2021; PECL et al., 2017).

Climate change has significantly impacted the southern region of Brazil, notably altering rainfall patterns and increasing extreme weather events (ALVALÁ et al., 2024; ÁVILA et al., 2016). According to Marengo (2008), evidence of changing patterns in rainfalls were clear already in the 4th Intergovernmental Panel of Climate Change (IPCC) report launched in 2007, with warnings on the increasing intensity and frequency of rainfall in the Plata Basin (Southern Brazil) expected up to 2040. Wasko et al. (2021) recently recommended integrating climate change aspects in rainfall forecasting, which corroborates the idea of integrated assessment already proposed by Chang and Franczyk (2008).

Climate patterns disruption has profoundly affected agriculture, a key economic sector, while also intensifying soil erosion and degradation (SANCHES et al., 2019). In the state of Rio Grande do Sul (Brazil), studies highlight increased rainfall variability and extreme events, resulting in more frequent floods and landslides impacting urban and rural areas (MARENGO, 2008). Additionally, rising global temperatures and shifting rainfall patterns have disrupted local flora and fauna, potentially altering species distribution and ecosystems (ALVALÁ et al., 2024; BRASIL, 2022; SANCHES et al., 2019).

From 1991 to 2022, Rio Grande do Sul recorded a high frequency of disaster events, ranking as the second-most affected state in Brazil. During this period, the state endured 3,913 hydro-geo-meteorological disasters, resulting in 100 fatalities, displacing over 700.000 individuals, and incurring economic losses exceeding 6 billion Brazilian reais (BRASIL, 2022). These climate change effects in southern Brazil demand urgent attention to mitigate environmental and economic impacts.

Between April 29 and May 6, 2024, Rio Grande do Sul experienced unprecedented extreme rainfall, leading to catastrophic floods. These events, the most significant disasters in the state's history, affected 478 out of 497 municipalities, resulted in 182 fatalities, and impacted over 2,3 million people, displacing over 580,000 individuals. According to estimation based on the number of affected municipalities, the size of the hit land reaches 272,374.481 km^2 (CNN, 2024), which corresponds to 96.7% of the whole State area (281,707.156 km^2).

These disasters have far-reaching consequences, significantly affecting both the economy and society. Damage to key infrastructure imposes substantial financial burdens on recovery and reconstruction efforts, hindering economic progress and the delivery of essential services, which entail the mobilization of large amounts of human and financial resources to restore the critical infrastructures as energy, transport, digital communications, and water (PANT et al., 2018). This disruption affects local economic activities, while the loss of human lives and displacement of communities intensify the vulnerability of marginalized populations. Consequently, these events exacerbate social inequalities and undermine community resilience (CARONE et al., 2019).

This paper aims to present the context of the 2024 floods and address the research question: What are the immediate social, economic and environmental impacts of the 2024 floods in Rio Grande do Sul? It discusses recovery measures and innovative solutions for disaster management and environmental sustainability, emphasizing strategies for disaster recovery and prevention. The analysis will focus on the early published impacts of floods in the affected municipalities.

2 Study area

Rio Grande do Sul stands as one of the 27 states of Brazil, a country situated in the mid-latitude region of South America. Located at the southern extremity of Brazil, the state covers a vast area of 281,707 square kilometers. Its territory is divided into 497 municipalities, and it is home to over 10 million residents, making up approximately 5,4 % of the total Brazilian population. This places Rio Grande do Sul as the sixth most populous state in Brazil, a significant demographic ranking. In terms of population density, the state records a figure of 38.62 inhabitants per square kilometer, placing it as the thirteenth most densely populated state in the country (BERTÊ et al., 2021).

Rio Grande do Sul boasts diverse vegetation, including remnants of the Atlantic Forest and grassland ecosystems. The Atlantic Forest, a biodiversity hotspot, is rich in flora and fauna, supporting a variety of species that rely on this habitat for survival (SANTOS; SILVA; FARIA, 2023). Grasslands in Rio Grande do Sul, known as the

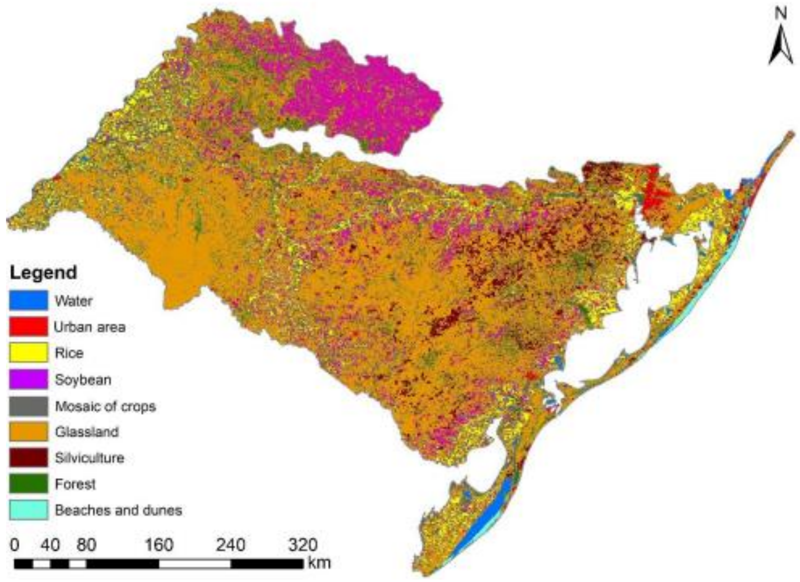
Pampa biome, are equally significant, providing unique habitats for many endemic species (ROESCH et al., 2009).

Pampa, or Southern fields, has an extension of 176,496 km², which comprises 2% of the Brazilian territory. Regardless its limited extension compared with larger biomes as Amazon forest, it is characterized by one of the most diverse herbaceous species of the world, comprising parts of the Argentina and Uruguay territories (ROVANI et al., 2020). The yearly average temperatures of the State are historically around 18°C, and the region is under subtropical climate. Nonetheless, the State has experienced diverse extreme events – 68 intense floods episodes in 2010, and 49 in 2015 – years of intense El Niño influence (RIO GRANDE DO SUL, 2022). The most affected municipalities by floods in Rio Grande do Sul, from 2003 and 2021, were Uruguaiana, in the border of the State, close to Uruguay, in the West region (5,806 displaced persons); Estrela (4,128 displaced persons), Montenegro (3,043) and Roca Sales (2,241) – these last three in Taquari Valley, once again hit in 2024 – and Alegrete (2,100 displaced) (RIO GRANDE DO SUL, 2022).

In the last decades, Pampa biome has been significantly modified, with reduction of agricultural areas in the Northest portion in 2001 compared with 1991, attributed to the rural exodus (ROVANI et al., 2020). With more recent field data, Mengue et al. (2019) analyzed land use and land cover (LULC) in the Pampa, from 2000 to 2014, using environmental variables that included geomorphometric data, landscape metrics and climate data, and socioeconomic variables. They found a reduction of around 25% of grassland class in 15-year interval, from 10,252.740 ha to 7,676.208 ha. In the same period, the cultivation of soybean increased 145.56%, reaching 2,099.837 ha in 2014, and the silviculture presented an even higher increase – over 167% of its total area of cultivation compared to 2000. According to the same study, forested areas declined 22,25%, from 2,2226,523 ha to 1,731,016 ha, while urbanized areas increased 22.3% from 2000 to 2014 (Mengue et al., 2019). Considering four Brazilian biomes (Amazon, Cerrado, Pantanal, and Pampa), this last one is the most impacted by agricultural and livestock activities, with 80% of degraded land (DICK et al., 2021).

Specifically in Porto Alegre, Kaiser et al. (2022) found that the vegetation removal in four neighborhoods (Hípica, Campo Novo, Aberta dos Morros, and Restinga) represented a reduction of 51% to 7% in grassland, and 14.4% to 0.6% in forest from a whole area of 534.61 hectares where live an average of 120,000 persons. This study covered the years 1985 to 2018. Comparing the first decade with the last within this period, the land surface temperature has risen 4.18°C (KAISER et al., 2022). Although there are no studies correlating these land changes in Rio Grande do Sul and in Porto Alegre with the recurring flood and drought episodes recorded from 2003 to 2021 (RIO GRANDE DO SUL, 2022), it is probable that the more recent climate disaster embeds consequences of these changes. Figure 1 presents the classification of land use in Pampa biome considering the evolution of LULC from 2000 to 2014 according Mengue et al. (2019).

Figure 1. Land use in Pampa Biome from 2000 to 2014



(MENGUE et al., 2019).

3 Methods

The main steps for this review include defining the research question, establishing the review protocol (e.g., search terms, digital libraries), selecting eligible studies based on inclusion and exclusion criteria, extracting and categorizing relevant data, and interpreting and reporting the findings.

To answer the research question of what are the immediate social, economic and environmental impacts of the 2024 floods in Rio Grande do Sul? This paper employs a systematic literature mapping (SLM). Salam, Bahsoon and Bencomo (2017) observe that a systematic mapping is a type of study that aims at identifying, categorizing, and analyzing the existing literature with respect a given topic. Axelson and Skoglun (2016) highlight that SLM helps to formulate research agendas, while Soaita, Serin and Preece (2019) argue that this type of review is useful for both academic and policy purposes.

A systematic mapping study provides a structure of the type of research reports and results that have been published by categorizing and assessing existing research. Unlike systematic literature reviews, which aim to answer specific research questions by synthesizing evidence from selected studies, systematic mapping studies focus on identifying trends, gaps, and patterns within a broader field of study (PETERSEN et al., 2008).

The literature search was carried out in: Web of Science, Scopus, PubMed and Google Scholar. Sources of gray literature were systematically explored via Google Scholar. The last search was conducted on July 5th, 2024.

3.1. Study selection and inclusion/exclusion criteria

The terms included in the search strategy were divided into two categories: (i) term related to the geographical area, and (ii) terms related to disaster/extreme climate events. For the final search string, (i) and (ii) were grouped. The complete list of search terms is shown in Table 1.

Table 1. Search terms.

	Terms	Keywords
(i)	Geographical area	(“Rio Grande do Sul”)
(ii)	Disaster/extreme climate events	(“Flood*” OR “Climate Tragedy” OR “Extreme Event” OR “Catastrophic Event” OR “Disaster” OR “Extreme Climate”)
(iii)		#(i) AND #(ii)

The selection process was performed in different steps: (1) search query design (Table 1); (2) screening based on title, abstract and keywords; and (3) study selection based on full text. Duplicates were removed during the elimination process.

To be included in this review, a study must meet the following inclusion criteria:

- Published in Portuguese or English-language journal, conference proceedings, or academic-style report (e.g., governmental reports).
- Published after the extreme flood event of May 2024.
- Clearly presents impacts of the flood event.

Studies were excluded if:

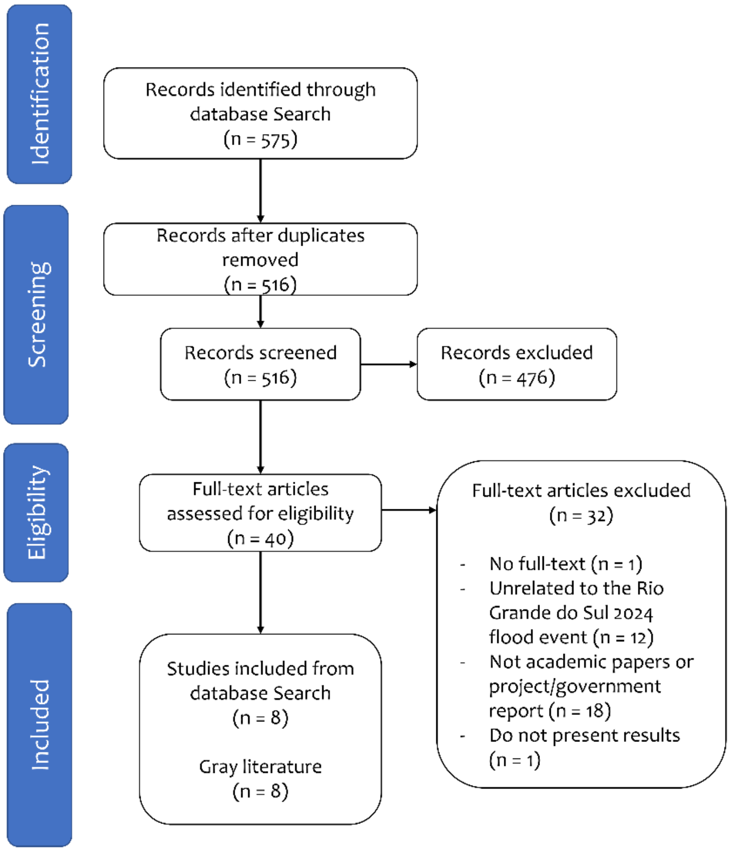
- Are not accessible in full text from standard research libraries or other means.
- Are unrelated to the Rio Grande do Sul 2024 flood event.
- Do not present results or methodology.
- Are not academic papers or project/government reports.

3.2. Data extraction

Data were extracted and documented in a standardized data extraction form. Paper's publication venue, objective/addressed problem, results, discussion/conclusion, and proposed future research directions were extracted. The systematic process of literature search, the criteria of inclusion and the records per step are presented in an adapted version of the PRISMA protocol (PAGE et al., 2021) in Figure 2.

The electronic database search yielded 575 results. After the removal of duplicates, 516 studies remained which were screened based on title and abstract. A total of 40 studies were considered to meet the inclusion criteria, and full-text versions were read to assess eligibility. This process resulted in the exclusion of 32 studies, leaving 8 for the full-text review process (see Figure 2 for reasons of exclusion). Furthermore, 8 publications were curated from gray literature sources, predominantly comprising reports from governmental bodies and academic institutions.

Figure 2. Systematic literature search process.



The predominant factor contributing to the exclusion of numerous records from this review is their non-academic nature. Most of these records are magazine or news site reports or coverage of flood events. Additionally, many records were unrelated to the 2024 flood event.

4 Results

The analysis of the immediate flood impact studies is divided into four key areas: impacts on populations and public health, climate and precipitation impacts, economic and infrastructural impacts, and disaster response and mitigation. The first category examines the effects of the floods on human health and community well-being. The second focuses on the meteorological data and precipitation patterns associated with the flood event. The third area assesses the economic consequences and damage to infrastructure. Finally, the fourth category explores the strategies and measures implemented for disaster response and mitigation.

4.1. Impacts on populations and public health

The 2024 floods in Rio Grande do Sul have profound implications for populations and public health, as elucidated by several studies. These studies explore diverse impacts ranging from immediate health emergencies to long-term public health challenges. According to the state's government, the extreme events affected

478 out of 497 municipalities, resulted in 182 fatalities, and impacted over 2,3 million people, displacing over 580.000 individuals.

The study of Henkes and Henkes (2024) emphasizes the disruption to daily life, including a significant displacement of individuals, property loss, human deaths and psychological stress. Additionally, it highlights the increased vulnerability to infectious diseases due to compromised living conditions and sanitation systems. Complementing these findings, Martins-Filho et al. (2024) reveals that the floods affected over 2 million people, exacerbating public health issues. The research points out that the floods led to a significant rise in waterborne and vector-borne diseases, stressing the urgent need for robust public health interventions to mitigate these health crises. Floodwaters contaminated by fecal matter and rodent urine pose severe health risks, facilitating the spread of diseases such as hepatitis A, typhoid fever, and leptospirosis. Martins-Filho et al. (2024) reports 29 cases of leptospirosis and two fatalities associated with the floods as of May 22, 2024.

Neris et al. (2024) further elaborates on the public health emergency caused by the floods, detailing the surge in waterborne diseases, respiratory infections, and mental health issues. Between April 30 and May 10, over 500 mm of rainfall was recorded in Porto Alegre, the state capital, leading to stagnant floodwaters and overcrowded shelters, creating conditions conducive to disease spread and straining healthcare systems. The study reports a significant increase in leptospirosis cases, with 281 confirmed cases in the Porto Alegre region from April to June 2024, a fourfold increase compared to the same period in previous years.

Silva, Silva and Molin (2024) discusses the role of risk and disaster management in response to the floods. This paper underscores the significant impact on public health infrastructure, emphasizing the increased incidences of diseases due to the disruption of health services. Castro (2024) investigates the meteorological and hydrological causes of the floods. It highlights how the extreme weather overwhelmed existing infrastructure, leading to widespread water supply contamination and severe public health risks.

Lastly, EMATER/RS (2024) conducted by a state public company providing technical assistance and rural extension services to farmers and rural communities, offers a comprehensive analysis of the 2024 floods' impacts on public health and infrastructure. This study details how the extreme weather event led to widespread infrastructure damage, including the destruction of homes, roads, and health facilities. The resultant displacement of thousands of individuals exacerbated public health challenges, with significant increases in waterborne and vector-borne diseases due to disrupted sanitation and water supply systems. This severe disruption in water supply has led to significant public health risks and necessitated urgent intervention. They report contamination of 4,570 water sources left 34,519 families without access to potable water.

In Rio Grande do Sul, there are four officially recognized indigenous peoples: Charrua, Guarani, Kaingang, and Xokleng, with villages in 72 municipalities across the state. According to Decree No. 57,614 of May 21, 2024 (GOVERNO DO ESTADO DO RIO GRANDE DO SUL, 2024), 92% of the indigenous villages (147 villages across the four peoples) in the state declared a state of calamity or emergency due to the climatic events, affecting 62 municipalities. The EMATER/RS (2024) survey identified three primary impact areas: (i) 80% of indigenous villages suffered material damage to housing, possessions, and personal belongings; (ii) 60% experienced damage to food production, affecting crops, gardens, livestock, and rural infrastructure; and (iii) 100% faced damage, directly or indirectly, to their primary income source, the sale of handicrafts. Additionally, 88% of quilombola communities in Rio Grande do Sul were also directly affected.

4.2. Climate and precipitation impacts

The 2024 floods in Rio Grande do Sul have prompted early research to understand the underlying climatic and precipitation factors contributing to this catastrophic event. This section aims to synthesize findings from studies that examine the extreme precipitation levels, the extent of the flooded areas, and the meteorological conditions that precipitated the floods.

The extreme precipitation event analyzed by Rocha, Reboita, Crespo (2024) provides a comprehensive assessment of the rainfall patterns that contributed to the 2024 floods in Rio Grande do Sul. The research identifies a significant increase in precipitation levels during the period of the event, attributing this anomaly to specific climatic conditions. Some locations, such as Segredo, Fontoura Xavier, and Lagoa Bonita receiving 812.6 mm, 778.0 mm, and 749.2 mm of rain respectively over ten days. This is about 280% more than the expected precipitation for the entire period of April to May. The study also emphasize that the Guaíba Lake reached a record height of 5.35 meters, surpassing the previous historical record of 4.76 meters set in May 1941 – the most important flood of the entire State until then.

Additionally, Rizzatti and Batista (2024) mapped the flooded areas across municipalities, illustrating the spatial extent of the flood impacts. The data reveals a substantial inundation of urban and rural areas (Municipalities of Agudo, Dona Francisca, Paraíso do Sul and Restinga Sêca) between April 29 and May 6, highlighting the severity of the event. The most affected municipalities studied were Restinga Sêca and Agudo, with more than 20% of their territory inundated. The study also estimated the number of residences impacted by the flooding. Restinga Sêca had the highest number of affected residences (505), followed by Agudo (307), Paraíso do Sul (57), and Dona Francisca (29).

The attribution report by Clarke et al. (2024) analyzes two event windows: the 4-day capturing the most intense rainfall event (29th April – 2nd May) and the 10-day capturing a succession of 3 rainfall events (26th April – 5th May). The main findings are that El Niño played a major role, increasing for the 4-day event by a factor of 2-5 the likelihood and 3-10% the intensity, and for the 10-day event by a factor of 2-3 the likelihood and 4-8% the intensity.

Furthering the understanding of precipitation impacts, Alcantara et al. (2024) delves into the unprecedented flooding in the Porto Alegre metropolitan area, presenting detailed rainfall data and its correlation with the flooding extent. The study underscores the extreme precipitation levels that surpassed historical records registered in 1941, prompting a reevaluation of existing flood management infrastructure. The meteorological analysis provided in Nachtigall and Sias (2024) focuses on the extreme rainfall conditions that triggered the floods, detailing the specific atmospheric phenomena that led to such intense precipitation. The findings indicate a convergence of meteorological factors that collectively intensified the rainfall, contributing to the unprecedented flooding.

Anthropogenic climate change also had a major influence on both events increasing for more than a factor of 2 the likelihood and intensifying them by 6-9%. The study also cites reduced investment in adaptation measures, lack of maintenance of the flood protection system in Porto Alegre, non-compliance with environmental legislation and warnings that did not reach all affected population and were not clear to the public (Clarke et al., 2024).

Faria et al. (2024) characterizes the hydrographic basins of Rio Grande do Sul, which are pivotal in understanding the regional water flow and flood dynamics. The research identifies the complex interplay between various basins and their role in exacerbating flood conditions during extreme weather events.

Table 2 summarizes key rainfall measurements in various locations in Rio Grande do Sul.

Table 2. Key rainfall measurements (EMATER/RS, 2024; NACHTIGALL; SIAS, 2024; RIZZATTI; BATISTA, 2024; ROCHA; REBOITA; CRESPO, 2024).

Municipality	**Rainfall (mm) (between April 27 and May 2)**	**Rainfall (mm) (between April 27 and May 6)**	**Rainfall (mm) (between April 30 and May 10)**	**Rainfall (mm) (May)**
Agudo			582	
Bento Gonçalves	537		609	
Campo Bom	335		316	
Canela			527	
Canoas	407			
Caxias do Sul	561		346	
Cruzeiro do Sul	409			
Faxinal do Soturno	576			
Fontoura Xavier	657	778		
Lagoa Bonita		749.2		
Lajeado	408			
Porto Alegre	343		340	+500
Restinga Sêca			560	
Rio Pardo	329		346	
Santa Maria	501		467	
Soledade	487		591	
Segredo		812.6		
Serafina Corrêa	335		486	
Teutônia	438			

The hydrographic basins of Rio Grande do Sul, comprising the Guaíba Basin, the Coastal Basin, and the Uruguay River Basin, exhibit distinct environmental, urban, and rural characteristics that influence water behavior during droughts and floods. The Guaíba Basin features significant forest cover with diverse vegetation and varied topography, whereas the Uruguay and Coastal Basins have less forest cover and are characterized by steppe areas and pioneer formations. Land use varies, with the Guaíba Basin experiencing intense agricultural activities, particularly in cereal farming, and substantial forested areas in river headwaters. In contrast, the Uruguay and Coastal Basins show similar agricultural intensity, impacting natural vegetation, especially in the southern Uruguay Basin. Urban areas in these basins differ, with high population density and industrial activity in the Guaíba Basin, significant urban growth in the Coastal Basin, and a mix of larger cities and smaller towns in the Uruguay Basin. Rural areas exhibit diverse agricultural practices, with family farms predominating in the Guaíba Basin and a mix of cereal farming and other activities in the Uruguay Basin. The 2024 floods exacerbated these regional disparities, affecting vast areas and generating significant waste, particularly from construction debris, underscoring the urgent need for enhanced waste management infrastructure (FARIA et al., 2024).

4.3. Economic and infrastructural impacts

The 2024 floods in Rio Grande do Sul have caused remarkable economic and infrastructural damage, as detailed in the following research papers. These studies offer an early analysis of the impacts and the contributing factors that have worsened the situation.

According to Henkes and Henkes (2024), the floods caused substantial economic losses due to the destruction of homes, businesses, and infrastructure. The paper reports that the agricultural sector suffered significant losses, with estimates of damages reaching 3 billion Brazilian reais. Surveys conducted by EMATER/RS (2024) across 12 administrative regions revealed that 405 municipalities reported soil fertility losses due to water erosion over 2,706,683 hectares. Further analysis in Melgarejo (2024) explores the economic implications through the lens of disaster capitalism. The editorial discusses how the crisis not only disrupted local economies but also presented opportunities for certain sectors to capitalize on the disaster. This phenomenon often leads to inequitable recovery efforts, where marginalized communities suffer the most significant losses without adequate support for rebuilding their lives and livelihoods. The crisis affected approximately 75% of the state's population and the entire regional economy. It compromised 47,000 industries employing around 800,000 people and devastated 200,000 agricultural properties, leading to massive losses in crops and livestock (HENKES; HENKES, 2024; MELGAREJO, 2024).

Rizzatti and Batista (2024) provides a detailed mapping of the flooded areas, revealing that the inundation extensively damaged critical infrastructure, including roads, bridges, and public facilities. The study presents the absolute and percentage numbers of residences in flooded or isolated areas in four municipalities as of May 6, 2024 (Agudo, Dona Francisca, Paraíso do Sul e Restinga Sêca). Table 3 summarizes the flooded areas number of residences impacted.

Table 3. Flooded areas number of residences impacted, as of May 6, 2024 (RIZZATTI; BATISTA, 2024).

Municipality	Number of residences in flooded and/or isolated areas	Total number of residences in the municipality	Percentage (%) of residences in flooded and/or isolated areas	Percentage (%) of the municipality's area covered with water
Agudo	307	10,118	3.03	21.78
Dona Francisca	29	2,007	1.44	16.55
Paraíso do Sul	57	5,449	1.05	11.48
Restinga Sêca	505	10,349	4.88	23.60

Given the state's heavy reliance on the agricultural sector, four publications focus on the severe impact of the floods on agricultural productivity (EMATER/RS, 2024; LAMPERT et al., 2024; POSSAMAI; SERIGATI; BASTOS, 2024). Possamai, Serigati and Bastos (2024) discusses the extensive impact on agricultural productivity due to the flooding, that not only destroyed farmlands but also resulted in significant losses of livestock, threatening food security and economic stability in the region. Significant losses were reported, with over 12,000 pigs and 300,000 poultry lost, primarily in the Vale do Taquari region. The floods further strained the already struggling dairy sector, which had endured three consecutive years of drought. The dairy sector experienced substantial losses, with 1,464,335 liters of milk not collected daily, resulting in a total uncollected volume of 9,625,918 liters. This affected 7,450 producers, further exacerbating the challenges faced by the dairy industry (EMATER/RS, 2024; POSSAMAI; SERIGATI; BASTOS, 2024).

Further, Lampert et al. (2024) highlights the substantial damage to the cattle population in the affected areas. The study details the loss of over 15,000 bovines and the destruction of extensive pasturelands, which severely compromised cattle feeding and productivity.

In addition, EMATER/RS (2024) provides a detailed account of the losses across various crops, including rice, wheat, corn and soybeans. The reports reveal that despite some resilience in the rice sector, significant portions of the wheat and soybean harvests were lost. The report explores the broader economic and infrastructural impacts of the floods, highlighting the extensive damage to transportation networks, which impeded the distribution of agricultural products. The study points out that the destruction of roads and bridges not only delayed the delivery of critical supplies but also increased production costs.

During the extreme rainfall and flooding, 9,158 locations in Rio Grande do Sul were significantly impacted, with disruption or collapse of buildings and roads. Transportation and access issues arose in 4,548 communities due to damaged roads. Additionally, 19,190 rural families reported damage to homes (14,029), warehouses (8,402), silos (738), and other agricultural structures. Contamination of 4,570 water sources left 34,519 families without access to potable water (EMATER/RS, 2024).

Regarding grains, the losses primarily affect planted areas and stored products such as rice, corn, soybeans, and beans. Winter crop losses are localized and involve newly sown areas that will need replanting. A total of 48,674 grain producers were impacted (EMATER/RS, 2024). Table 4 presents the state's affected area and grain production losses.

Table 4. Affected area and grain production losses (EMATER/RS, 2024).

Culture	Losses in affected area (t)	Affected producers	Affected area (ha)
Soybeans	2,714,151	15,661	1,490,505
Corn for silage	721,336	7,963	32,681
Rice	160,664	1,581	89,931
Corn	354,189	28,339	113,700
Beans	18,244	2,697	14,402
Canola/Oats	132	14	310

Regarding soybeans, the 2023 estimate indicated a productivity of 3,329 kg/ha. However, after accounting for the flood-related losses, the new state production estimate is expected to reduce productivity to 2,923 kg/ha. Regarding corn, the pre-flood productivity estimate was 6,401 kg/ha. The new projection indicates that post-flood production will be 4,848,786 tons, reducing state productivity to 5,966 kg/ha. In November 2023, the state's bean production was estimated at 79,743 tons across two subsequent harvests. With an estimated loss of 18,244 tons, production will decrease to 61,499 tons, representing a 22.88% decline from the previous estimate (EMATER/RS, 2024).

The period of extreme rainfall and flooding coincided with the final fruiting phase of key citrus varieties, particularly tangerines, whose harvest season was ongoing, thereby intensifying the losses. In many orchards, the soil was soggy not only due to river overflow and rain runoff but also because of several days of high-volume precipitation. This adverse climatic context reduced soil oxygen availability, causing hypoxia in the root systems. Consequently, this led to the formation of abscission layers, inducing ethylene production and triggering physiological damage such as fruit drop. Additionally, the abrupt temperature drop exacerbated these production losses (EMATER/RS, 2024). Table 5 presents the state's affected area and fruit crop losses.

Due to its proximity to the Metropolitan Region, the area most affected by the floods plays a crucial role in supplying vegetables to large urban populations nearby. Leafy greens and legumes were the most impacted crops. Overall, 8,049 producers experienced losses in vegetable production, significantly affecting the supply chain and the state economy (EMATER/RS, 2024; POSSAMAI; SERIGATI; BASTOS, 2024).

A vast expanse of pastures has been impacted. In addition to native grasslands, producers rely on forage crops, whose losses in both area and percentage will directly affect milk and meat production in the months following the event. Silage experienced a 67.04% loss over 7,548.80 hectares, cultivated pastures underwent a 48.84% loss over 249,809 hectares, and native pastures faced a 45.02% loss over 430,848 hectares. The number of affected producers is also substantial, totaling 32,409, highlighting the severity of the situation. This combination of losses will seriously compromise livestock sustenance, negatively impacting the local economy and the supply of animal products (EMATER/RS, 2024; POSSAMAI; SERIGATI; BASTOS, 2024).

Table 5. Affected area and fruit crop losses (EMATER/RS, 2024).

Activity	Losses in affected area (t)	Planted area in affected municipalities (ha)	Affected area (ha)	Affected producers
Tangerine	620,530	7,540	6,694	3,825
Orange	40,986	9,195	5,276	3,474
Banana	2,695	7,124	6,477	1,257
Apple	2,700	2,625	120	24
Pecan	1,194	2,691	1,848	566
Lemon	2,524	563	441	121
Strawberry	4,900	259	194	428
Maracuja	676	207	155	95
Fig	609	184	76	28
Pineapple	300	340	300	120
Guava	227	69	36	34
Dragon Fruit	51	20	18	17
Avocado	48	37	20	34
Persimmon	980	1,092	146	135
Peach	15	15	15	20
Other Fruits	52	43	13	23

The extreme events caused significant damage to forestry production, affecting both commercial plantations and native riparian forests due to landslides. The losses include 438,880 erva-mate plants, impacting current and future economic conditions for producers; 571,655 eucalyptus plants, affecting commercial wood production and firewood supply; 84,050 acacia plants, impacting the production of sawn wood, charcoal, tannin, and other derived forest products; and 32,102 pine plants, further exacerbating the forestry sector's challenges (EMATER/RS, 2024).

4.4. Disaster response and mitigation

Disaster response and mitigation strategies are crucial for addressing the immediate and long-term challenges posed by extreme weather events.

Martins-Filho et al. (2024) emphasizes the catastrophic nature of the floods and evaluates the initial response strategies implemented by local and federal authorities. The study highlights the importance of coordinated efforts among different governmental levels and emergency services to ensure efficient evacuation, provision of relief supplies, and restoration of essential services. In a complementary analysis, Neris et al. (2024) discusses the public health emergency response during the floods. This paper outlines the deployment of medical teams and the establishment of temporary healthcare facilities to address the surge in health-related incidents, such as injuries, waterborne diseases, and mental health issues.

Rizzatti and Batista (2024) provides an in-depth examination of the mapping and monitoring techniques used to assess the flooded areas. The paper underscores the role of geospatial technologies and remote sensing in identifying the extent of the floods and guiding emergency response operations. It highlights that accurate mapping is vital for resource allocation, risk assessment, and planning of mitigation measures.

Lampert et al. (2024) focuses on the agricultural sector, detailing the implementation of the "*Recupera Rural RS*" plan, which aims to restore agricultural productivity and support affected farmers. This initiative includes actions such as financial aid, technical assistance, and the introduction of more resilient agricultural practices to mitigate future risks. The study emphasizes that collaborative efforts between government agencies, research institutions, and the private sector are essential for successful recovery and long-term sustainability of the agricultural economy.

Finally, Schabbach and Ramos (2024) provides a detailed examination of the shelters established for individuals displaced and offers valuable insights into the effectiveness and challenges of the shelter system during the disaster. The study outlines that the floods resulted in the displacement of a significant portion of the state's population. The primary aim of the research was to describe the demographic and social profiles of the sheltered individuals, assess the adequacy of the shelter facilities, and evaluate the support services provided. The research highlights that most of the shelters were temporary structures set up in schools, community centers, and other public buildings, which were quickly adapted to accommodate the influx of displaced persons. While the shelters provided immediate relief by offering safety and basic necessities, there were significant challenges related to overcrowding, sanitation, safety, and access to healthcare services. The study points out that many shelters lacked sufficient medical supplies and personnel to handle the health needs of the displaced population, including those suffering from chronic illnesses, injuries, and mental health issues resulting from the trauma of the floods.

As of May 16, 2024, 875 shelters were mapped across 103 municipalities, accommodating 78,185 people. 57% of these shelters were in the Metropolitan Region of Porto Alegre (RMPA), 23% in the Vale do Rio dos Sinos, and the remainder distributed across 20 other regions. The municipalities with the highest number of shelters were Porto Alegre (160), São Leopoldo (92), Canoas (76), and Guaíba (67). Canoas has the highest number of sheltered individuals (18.246), followed by Porto Alegre (14,685) and São Leopoldo (13,907). Shelters were mostly provided by religious or spiritual institutions (30%), private companies, universities, or schools (21%), and various government entities (18%) (SCHABBACH; RAMOS, 2024).

5. Discussion

The devastating floods in Rio Grande do Sul in 2024 not only caused immediate damage but also highlighted significant vulnerabilities in the region's disaster preparedness and response systems. Studies show that while emergency responses were timely, there were critical crashes in infrastructure resilience and public health readiness, which exacerbated the flood's impact on affected communities. This disaster underscores the necessity for a systemic overhaul in both infrastructure planning and emergency preparedness. Future strategies must focus on enhancing the adaptive capacities of both human settlements and agricultural systems to withstand extreme weather events.

Public health challenges post-flood includes increased risks of waterborne diseases and psychological impacts due to displacement and loss. The need for robust public health infrastructure and preparedness plans that can quickly adapt to emergency situations has never been more evident. The reviewed studies collectively highlight the need for enhanced disaster preparedness, resilient public health infrastructure, and comprehensive long-term health strategies to mitigate future risks and make the population more prepared. These insights underscore the critical importance of integrating public health considerations into disaster response and urban planning, especially in the municipalities master plans. Also, long-term health strategies must prioritize community health and well-being to mitigate the impacts of future floods.

Comparing the 2024 floods to previous events in similar ecosystems, such as the 2023 floods in the same state, and the 2011 floods in the Amazon basin, it is possible to realize a recurring pattern of inadequate infrastructural resilience and poor adaptive strategies in response to extreme weather events in Brazil (ALVALÁ et al., 2024; HESHMATI, 2021). These comparisons help to underline the repeated failures and highlight successful strategies that could be adapted and implemented in Rio Grande do Sul. Emphasizing historical context allows for a better understanding of the evolutionary trajectory of disaster management practices in Brazil. Emphasizing historical context allows for a better understanding of the evolutionary trajectory of disaster management practices in Brazil.

The socio-economic repercussions of the floods are profound, impacting numerous sectors but most notably agriculture, which is a cornerstone of the regional economy. The floods disrupted markets, destroyed crops, and placed considerable strain on the food supply chains, significantly affecting rural communities. This event has enhanced the critical need for economic policies that not only address immediate relief efforts but also support sustainable economic resilience and recovery in the long term. The reviewed studies highlight the urgent need for integrated disaster management approaches, encompassing strategic environmental management, advanced planning, robust infrastructure, and equitable recovery policies to mitigate the adverse effects of such natural calamities.

Environmentally, the 2024 floods have caused significant degradation of critical habitats, affecting biodiversity and the ecological balance of the region. The alteration of landscapes and loss of biodiversity may have long-term consequences for ecological stability and the provision of ecosystem services (PECL et al., 2017). Effective environmental management and restoration strategies are essential to mitigate these impacts and promote ecological resilience. The floods generated large amounts of debris, prompting discussions on waste management and environmental protection.

There is a crucial need for improved governance structures that can enhance disaster responsiveness. Integrating scientific research with policymaking, particularly in terms of climate change adaptation strategies, can significantly reduce disaster risk and enhance community resilience. Policies need to be inclusive, considering the socio-economic diversity of affected populations to ensure equitable and effective disaster response and recovery.

The recurring nature of significant flood events in this region calls for an integrated approach to disaster management that encompasses not only immediate response mechanisms but also long-term planning that includes infrastructure resilience, environmental management, public health preparedness, and socio-economic recovery strategies. The lessons learned from the 2024 floods should guide future policies to better prepare for and respond to natural disasters, ensuring that resilience becomes a core component of regional policies, plans and programs. Effective coordination, advanced technology, comprehensive healthcare, and resilient agricultural practices form the backbone of a robust strategy to combat the challenges posed by natural disasters like the recent floods in Rio Grande do Sul.

6. Mitigation proposals

Effective mitigation strategies are critical to reducing the impact of extreme weather events such as the 2024 floods in Rio Grande do Sul. These strategies must address immediate relief and long-term resilience, encompassing infrastructure, public health, agriculture, and environmental management. This section outlines existing proposals and introduces new mitigation methods to enhance regional resilience.

6.1. Infrastructure improvements and adaptive strategies

To address future climate extremes, significant improvements in infrastructure are essential. Current research emphasizes the need for robust infrastructure capable of withstanding extreme weather events. This includes reinforcing buildings, roads, and bridges, particularly in flood-prone areas. Integrating adaptive strategies such as elevating structures and using flood-resistant materials can significantly mitigate damage. Upgrading drainage systems and constructing flood barriers are also critical to managing water flow and preventing urban flooding.

6.2. Enhanced weather prediction models

Improving weather prediction models is crucial for early warning and disaster preparedness. Enhanced meteorological monitoring and predictive analytics can provide accurate forecasts, enabling timely evacuation and resource allocation. Advanced geographic information systems (GIS) should be integrated for real-time flood mapping and response, allowing authorities to better anticipate and manage flood impacts. As advocated by Nachtigall and Sias (2024), more comprehensive meteorological monitoring and predictive analytics can help to better anticipate and respond to similar future events.

Furthermore, the current meteorological monitoring system, in both atmosphere and rivers (pluviometry sensors), has been proved insufficient and/or outdated, which arises needs for increasing technologies and capacity building in terms of climatological knowledge integration.

6.3. Comprehensive watershed management

Effective watershed management practices are pivotal for mitigating flood risks. This includes maintaining natural vegetation cover in watershed areas to absorb rainwater and reduce runoff. Implementing measures such as reforestation and wetland restoration can enhance the region's capacity to manage excess water. Additionally, strategic planning for land use in floodplains can prevent the construction of vulnerable infrastructure in high-risk areas.

6.4. Resilient agricultural practices

Agricultural resilience can be improved through diversified cropping systems and the adoption of flood-resistant crop varieties. Providing financial aid and technical assistance to farmers can support the transition to more resilient agricultural practices. Implementing soil conservation techniques and improving irrigation infrastructure can also help protect agricultural productivity against extreme weather events.

6.5. Public health infrastructure and preparedness

Investing in public health infrastructure is essential to prevent health crises during disasters. This includes establishing mobile health units and stockpiling essential medical supplies. Training healthcare professionals in disaster response and integrating health services into emergency frameworks can ensure comprehensive care during and after such events. Regular public health drills and community education programs can also enhance preparedness.

The report from EMATER/RS (2024) emphasizes the need for immediate and long-term interventions to rebuild and strengthen public health infrastructure to prevent future health crises. It also highlights the importance of integrating public health resilience into urban planning and disaster response strategies to better prepare for such catastrophic events.

6.6. Emergency relief and long-term rebuilding strategies

Immediate relief efforts must be complemented by long-term rebuilding strategies. These strategies should focus on restoring critical infrastructure and supporting affected communities in rebuilding their lives. Financial assistance programs for rebuilding homes and businesses, coupled with mental health support services, can facilitate recovery. Moreover, policies that promote equitable recovery efforts are crucial to addressing the needs of marginalized populations.

6.7. Community-based disaster risk management

Community involvement in disaster risk management can enhance resilience. Establishing local disaster response teams and engaging communities in planning and preparedness activities ensures that local knowledge and resources are utilized effectively. Community-based initiatives such as disaster education programs and volunteer training can empower residents to respond swiftly and effectively during emergencies.

Moreover, Schabbach and Ramos (2024) emphasizes the need for improved planning and infrastructure for emergency shelters. Recommendations include the establishment of pre-designated shelter locations with adequate facilities, regular training for shelter management staff, and the integration of healthcare services within the shelter system to ensure comprehensive care for the affected individuals. The study also calls for better coordination between local authorities, non-governmental organizations, and community groups to enhance the overall effectiveness of the disaster response.

6.8. Governance and policy integration

Improving governance structures to integrate scientific research with policymaking can significantly enhance disaster responsiveness. Policies must be inclusive, considering the socio-economic diversity of affected populations. Collaborative efforts between government agencies, research institutions, and the private sector are essential for developing comprehensive disaster management strategies. Regular policy reviews and updates based on the latest scientific findings can ensure that disaster management practices remain effective and relevant.

7. Conclusion

To present the context of the 2024 floods in Rio Grande do Sul, this paper considerate, through a systematic literature mapping, the last publication exploring the immediate social, economic and environmental impacts of the 2024 floods in Rio Grande do Sul, highlighting the impacts on populations and public health, Climate and precipitation impacts, Economic and infrastructural impacts, Disaster response and mitigation.

From this perspective, it was possible to observe the severity of this extreme climate event and all the implications it brought to a large part of the population of the state of Rio Grande do Sul, both in terms of structural issues and physical and emotional health. It also points to a large economic, social and environmental gap whose impacts will be more deeply felt in the coming months and years. However, there is no way to guarantee that new events like this will occur at any time, requiring a rapid response both in terms of reconstruction and the defense system of the cities.

In conclusion, effective mitigation of the impacts of extreme weather events requires a diversified approach that includes infrastructure improvements, advanced predictive models, comprehensive watershed management, resilient agricultural practices, robust public health infrastructure, and inclusive governance. Implementing these strategies can significantly enhance the resilience of Rio Grande do Sul to future climatic challenges.

7.1 Future studies and research agenda

With respect to health effects, it is recommended to improve means for capacity building and training health agents enabling a better integration between these agents (public or private) and the Civil Defence teams. The recent disaster has shown how important is the preparedness for tackling physical and mental health diseases in short, middle, and long terms.

In terms of climate and precipitation, there are several lessons to be learnt. First, public managers and business leaders must be more tunned with scientific forecasting on climate patterns, providing public and private policies to adequately prepare and respond to sudden changes. The infrastructure of sensors and other meteorological devices must be reviewed and updated to deliver accurate data for refining decision making of governments and firms. Also, the use and integration of artificial intelligence and machine learning in all governmental instances and in impact assessment of all types of business should become a routine and be accessible for all citizens through the use of interactive media.

Economic activities and infrastructure must be developed to the point of models and tools adoption to reduce its environmental and social impacts mirroring solutions already found in the natural systems, for instance, biomimetics and industrial symbiosis, increasing circular thinking, and sponge-cities models for coastal territories. Finally, it is noteworthy to learn from initiatives already adopted in countries where natural hazards are routinary – for instance, in the United States, the Federal Emergency Agency (FEMA) constantly works in population training with the aim to better prepare citizens for all types of undesirable events, from natural to cybernetic disasters.

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Felipe Caleffi. Doutor. Universidade Federal de Santa Maria. Professor Adjunto. E-mail: felipe.caleffi@ufsm.br

Cláudia Viviane Viegas. Doutora. Universidade Federal do Rio Grande do Sul (UFRGS). Programa de Pós -graduação em Administração (PPGA). Escola de Administração. Professora Adjunta. E-mail: cldviegas@gmail.com

Karina Bruno Lima. Doutoranda. Universidade Federal do Rio Grande do Sul (UFRGS). Programa de Pós-Graduação em Geografia (POSGEA). E-mail: karina.blima@yahoo.com.br

Samuel Vinícius Bonato. Doutor. Universidade Federal do Rio Grande (FURG). Instituto de Ciências Econômicas, Administrativas e Contábeis (ICEAC). Programa de Pós-graduação em Administração (PPGA). Professor Adjunto. E-mail: svbonato@gmail.com

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CONTRIBUIÇÃO DE CADA AUTOR

Conceituação (Conceptualization): Felipe Caleffi; Cláudia Viviane Viegas; Karina Bruno Lima; Samuel Vinícius Bonato.

Curadoria de Dados (Data curation): Felipe Caleffi; Cláudia Viviane Viegas; Karina Bruno Lima; Samuel Vinícius Bonato.
Análise Formal (Formal analysis): Felipe Caleffi; Cláudia Viviane Viegas; Karina Bruno Lima; Samuel Vinícius Bonato.
Investigação/Pesquisa (Investigation): Felipe Caleffi; Cláudia Viviane Viegas; Karina Bruno Lima; Samuel Vinícius Bonato.
Metodologia (Methodology): Felipe Caleffi; Cláudia Viviane Viegas; Karina Bruno Lima; Samuel Vinícius Bonato.
Administração do Projeto (Project administration): Felipe Caleffi.
Supervisão (Supervision): Felipe Caleffi.
Validação (Validation): Felipe Caleffi; Cláudia Viviane Viegas; Karina Bruno Lima; Samuel Vinícius Bonato.
Visualização (Visualization): Felipe Caleffi; Cláudia Viviane Viegas.
Escrita – Primeira Redação (Writing – original draft): Felipe Caleffi.
Escrita – Revisão e Edição (Writing – review & editing): Felipe Caleffi; Cláudia Viviane Viegas; Karina Bruno Lima; Samuel Vinícius Bonato.