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Citizen-generated data, a climate adaptation complement: A case study in Brazil

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Abstract. Flooding is the most prevalent type of disaster globally with stronger impacts in low-developed areas, where the collection of up-to-date, high-quality, and representative data for flood risk management remains a challenge. Citizen science and participatory mapping methods have the potential to contribute to data acquisition to better inform flood scenario description and grassroots civic engagement and advocacy, overcoming the shortcomings of the lack of data. This paper aims to understand how citizen science can contribute to climate adaptation in Brazil. Factors affecting adaptation to extreme flooding events, i.e. I) official monitoring (presence of weather stations and historical numbers of flooding); II) proportion of municipalities' urban areas mapped as in risk of flooding; III) existence of educational strategies in disaster risk prevention; and IV) citizen engagement with local data production are analysed to check if interactions between them may indicate where participatory adaptation could be more inclusive. This is done through an exploratory analysis that combines numerical analysis with geoprocessing techniques using official and citizen-generated data from the Waterproofing Data project. Despite the existing data gaps, results show that adaptation resources tend to be more abundant in bigger cities and municipalities that have historically been affected by floods. The study concludes that citizen-generated data can provide valuable insights into adaptation and resilience while complementing official data.

Submission Type. Case study.

BoK Concepts. [GS4] Geospatial citizenship; [TA12] EO for societal and environmental challenges.

Keywords. Flooding vulnerability; Adaptation; Urban Analytics; Participatory citizen science

1 Introduction

Over the last 30 years, reports by the Intergovernmental Panel on Climate Change (IPCC) have indicated a tendency for increasing magnitude and frequency of extreme weather events (Debortoli et al., 2017). Such events can raise the risk of disasters like floods, landslides, heat waves and droughts. Urban areas are considered the most vulnerable to potential disasters, as globally more than half of the population resides in areas of accelerated urbanisation and growing disaster risk-related issues (Ribeiro et al., 2022).

Flooding is the prevalent type of disaster around the world (Sy et al., 2019), accounting for 44% of climate-related disasters between 2000 and 2019 (Marengo et al., 2023). It also causes a considerable share of direct impacts, being responsible for 9% of fatalities, 23% of damages and 49% of displacements since 2008 (Sauer et al., 2024).

Flood-exposed population in low and middle-income countries are estimated around 1.6 billion people (Porto de Albuquerque et al., 2023). These countries (mainly located in the Global South) often concentrate higher levels of inequality, and research has shown that more people are killed by floods in countries where inequality is greater (Sauer et al., 2024). In Brazil, hydro-meteorological disasters (such as landslides and floods) were responsible for the most damage and deaths in the period 1991 to 2012 (Debortoli et al., 2017). More recently, the country was hit by what has been called 'the worst climate catastrophe in its history', when floods and landslides caused by heavy rainfall between April and May 2024 displaced over 400,000 people and killed 175 in the state of Rio Grande do Sul (ReliefWeb, 2024).

Global South countries face challenges when collecting updated, high quality and representative data for flooding risk management and vulnerability mapping (Porto de Albuquerque et al., 2023). Citizen science and participatory methods have been used in attempts to overcome these shortcomings. Citizen science is a collaborative research approach that involves active participation of local communities in scientific projects, where volunteers can provide insights into science and governance (Sy et al., 2019).

This paper conducts a data-driven exploratory analysis to comprehend how citizen-generated data might contribute to flood adaptation in Brazilian municipalities. Through a selection of variables from different official government sources, combined with data from a participatory citizen science project (the Waterproofing Data (WPD) project), we hope to contribute to advancing the knowledge on participatory citizen science methods as a potential complementary data source to official data on flood risk mapping in a Global South context. This contribution is relevant since there has been limited progress in global reduction of vulnerability to flood impacts over the first two decades of the 21st century, with considerably higher levels of vulnerability in less-developed areas (Sauer et al., 2024).

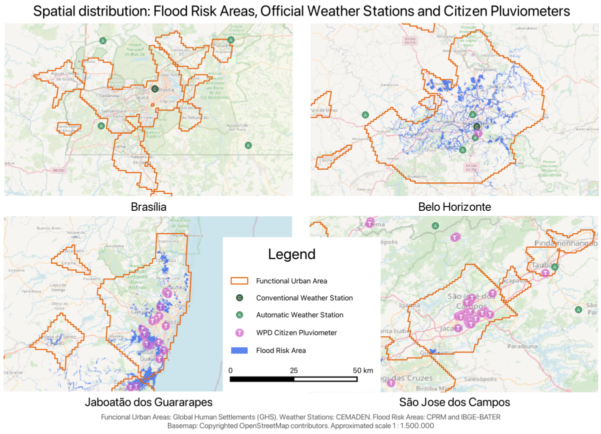

Figure 1. Maps for four of the municipalities included in the study, showcasing the spatial distribution of some of the datasets used in the analysis.

2 Literature Review

To provide just environmental strategies for climate adaptation, there is a need to address the unequal representativeness of data available for analysis (Galimberti et al., 2023). Data innovations are suggested as promising tools with potential for social transformations, including strengthening resilience among communities. However, data serving privileged socioeconomic groups are often more detailed and abundant when compared to data for marginalised communities. The data available for those communities also contain biases and assumptions derived from unequal accessibility to digital technologies for the numerous social groups (Porto de Albuquerque et al., 2023).

Traditional flood hazard assessments normally encompass a similar framework that requires the use of classical tools such as ground measurements, remote sensing and hydrological modelling to acquire data for defining flooding scenarios. Nevertheless, some features and limited context can hamper the use of those tools, leading to attempts to incorporate citizen science into flood assessments in recent years. According to Sy et al. (2019), citizen science approaches can be classified in two categories: direct and online. The first involves observation or mapping activities through active surveys, participatory mapping and participatory GIS. As for the latter, citizen participation takes place through web platforms or social media in the form of crowdsourced data or volunteered geographic information.

There are examples in the literature of approaches to participatory citizen science that have proven to be effective. Porto de Albuquerque et al. (2023) developed a dialogical participatory mapping methodology based on Paulo Freire's dialogic pedagogy. This approach adopts Freire's principle of situationality, which poses concrete situations lived by a community as a problematic scenario in which they are invited to not only respond intellectually but also to act. Rivera-Flórez et al. (2024) adopted a similar dialogical participatory mapping approach to fill the lack of data related to the risk of disasters in El Pacifico neighbourhood in Medellín, Colombia, with an additional specific methodology for analysing territorial context based on Milton Santos' definitions from Espaço e Método ('Space and Method' in free translation). In this work, Santos proposes that four definitions determine a territory: form, function, process, and structure. Taking these elements into account, the researchers aimed to understand which of those were important to the community whilst also co-defining the data variables that would guide the mapping process.

Despite the demonstrated potential of participatory citizen science methods to fill data gaps in the context of flood risk assessment, some concerns are also raised. One of them is the quality and reliability of the data produced, and how to assess and deal with its uncertainties. Recommendations to deal with this challenge include the use of survey protocols and training for participants volunteering; statistical approaches to collect and treat the data together with a well-defined project structure; and to compare results with traditional and trusted providers of data (Sy et al., 2019).

Additionally, communication skills, as well as designing and presenting the project in a manner that participants are convinced of the relevance of their contribution to benefit themselves and their community, are essential to maintain engagement. Researchers should also aim to have a good relationship with community leaders or local associations representing citizen groups (Sy et al., 2019).

3 Data and Methods

3.1 Data

Citizen-generated data was obtained from the Waterproofing Data (WPD) research project led by the Urban Big Data Centre (UBDC) at the University of Glasgow. The project's aim was to reconsider how flood-related data is produced by engaging citizens to monitor rainfall and report local flooding events and integrating these novel types of data with official flood data (Urban Big Data Centre, 2022). The data was collected from 2022 to 2024 across sixteen Brazilian states and 105 municipalities. There were about 15,000 observations from participants with variables such as the type of observation (e.g., pluviometer, rainfall measurement, rain event, flooded zones or river floods) and the location. Some location features were diffused to preserve participant's privacy.

Official data about *weather stations* was obtained from the National Meteorology Institute's (INMET in the Portuguese acronym). The monitoring infrastructure and the presence of a station in a municipality inform of the institutional adaptation capacity in that territory since official weather forecasts will consider the conditions in that location.

Another indicator of adaptation capacity comes from *official education strategies on disaster risk prevention* based on the presence of institutions affiliated to Cemaden Educação, an educational programme from the National Centre for Natural Disaster Monitoring and Alerts (Cemaden) that aims to engage schools and other institutions in disaster risk prevention. A dataset with spatial points for the location of institutions part of the network of Cemaden Educacação was used.

To analyse *vulnerability to flooding*, two datasets were used. First, the risk areas mapping assessment from the Geological Survey Service of Brazil (CPRM) showed 872 municipalities with critical vulnerability to floods and landslides. Second, historical flood data showing the occurrences in Brazilian municipalities between 2003 and 2015 from the National Water Agency (ANA).

Finally, the administrative boundaries for municipalities in Brazil from the Brazilian Institute of Geography and Statistics (IBGE) and the functional Urban Areas (FUA) of Urban Centres - i.e., spatial entities representing commuting areas to the closest urban centre (Schiavina et al., 2019) - from the European Commission served as the general geographic framework. These two last geospatial data sources served to frame the results to administrative boundaries and make them comparable with other sources.

Fig. 1 shows FUA boundaries, official weather stations, flood risk areas and WPD pluviometers for four municipalities in this study: Brasília, Belo Horizonte, Jaboatão dos Guararapes and São José dos Campos.

3.2 Methods

The research method in this work adopts an approach that combines numerical analysis with geoprocessing techniques. Accordingly, two streams of analysis can be identified (Fig. 2): the first adopts points as the spatial analysis unit (i.e., WPD pluviometers, official weather stations and

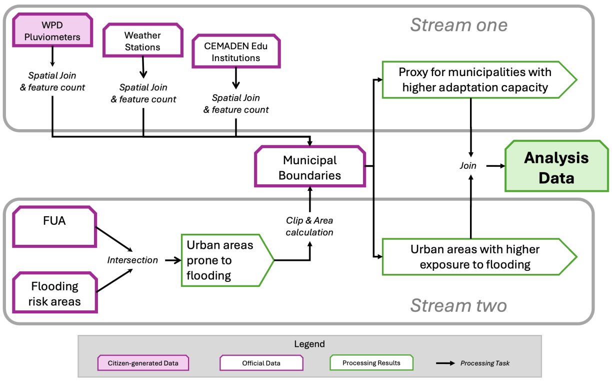

Figure 2. Diagram summarising the methodology adopted in the study.

Cemaden institutions) from which numerical variables are calculated through feature count and spatial joints.

The second stream uses a spatial unit based on FUA and the administrative boundaries for municipalities to calculate geographic measures such as the proportion of urban risk areas (Eq. (1)). That is, using tools such as *Clip* and *Intersect* from ArcGIS to extract areas susceptible to flooding within the urban areas of each municipality. Afterwards, the results from the first stream are joined based on the municipal identifiers. Thus, the final dataset for analysis has the municipalities as the basic spatial unit. Data processing was conducted using R scripts and ArcGIS Pro.

$$Prop.Risk.Area = \frac{CPRM.Risk.Area}{Urban.Area} \tag{1}$$

The process of analysis involves exploring data visualizations, to identify spatial concentrations, relations or patterns, and cross-comparison between variables using various plots. Constant reviews and discussions ground a critical review of the findings against the existing theory identified in the literature. The indicators (i.e., number/location of WPD volunteers, official weather stations and Cemaden Educação network institutions) for adaptation and resilience to flooding are estimated by combining citizen-generated data with official data and contrasting them with flood vulnerability variables.

The adoption of a quantitative approach in this research is justified by the lack of studies attempting to quantify adaptation and resilience to flooding in Brazil. The complex relationship of social, economic and environmental factors that can influence adaptation and resilience capabilities, together with limitations in accessing highly detailed data that reflects local conditions in some contexts are some of the challenges for this type of method. Therefore, this study offers an innovative and site-specific approach for analysis.

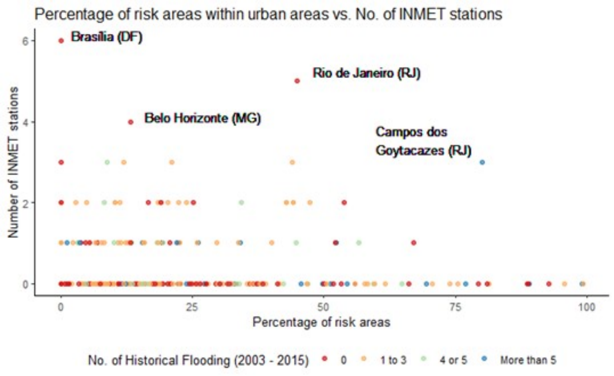

Figure 3. Scatter plot of municipalities according to percentage of urban risk areas vs. count of INMET stations per municipality.

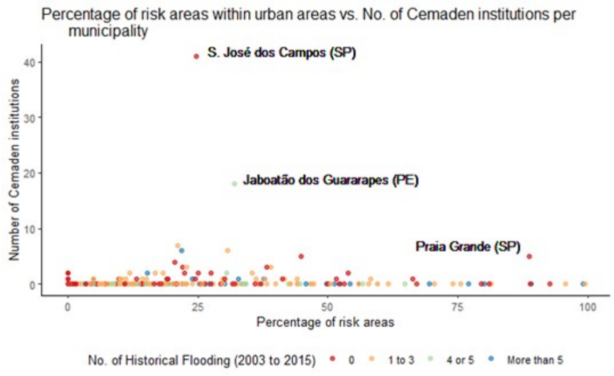

Figure 4. Scatter plot of municipalities according to percentage of urban risk areas vs. count of Cemaden institutions per municipality.

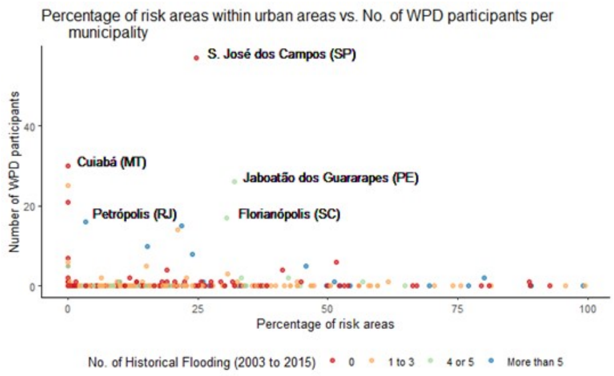

Figure 5. Scatter plot of municipalities according to percentage of urban risk areas vs. number of WPD participants per municipality.

3.3 Data and Software Availability

The final version of the source code used for the analysis and the corresponding dataset will be made available as an open repository under a permissive Apache License 2.0 license at github.com/urbanbigdatacentre/wpd-adaptation-br-paper.

4 Analysis and Results

Participatory citizen science methods can be an alternative tool to co-produce local data for historically underrepresented territories and strengthen their resilience and adaptation capabilities (Porto de Albuquerque et al., 2023). Here, the number of participants in the WPD project per municipality is considered a proxy measurement of adaptation, as it can indicate higher awareness of potential flooding risks and engagement with local data production.

The count of official weather stations (INMET stations) and Cemaden institutions per municipality are also considered as a proxy indication of adaptation. They indicate the presence of a sensing network of weather conditions (INMET stations) and, when having the presence of education initiatives (Cemaden institutions), a measure of local knowledge exchange about disaster risk prevention.

Fig. 3 compares how the number of official weather stations per municipality locate in comparison with the risk areas within their FUA and the historical record of flooding between 2003 and 2015. Brasília, the federal capital located in the midwest, has the most stations, with six in total. Rio de Janeiro follows with five stations and Belo Horizonte with four stations. Both cities are located in the southeast and are capitals of their respective states (Rio de Janeiro and Minas Gerais). None of the three municipalities has flooding records between 2003 and 2015, whilst Brasilia and Belo Horizonte have less than 25% of risk areas in their urban areas and Rio nearly 50%. In contrast, Campos dos Goytacazes in the north of Rio de Janeiro state has recorded seven flooding events and over 75% of its urban area is prone to flooding but has only three weather stations. Many municipalities have consistent reports of historical flooding and extensive flood-prone areas with no stations.

Considering arbitrary thresholds of seven or more historical floods as a reference to frequent flooding events (i.e., seven or more in a period of 13 years) and a proportion of more than 75% of urban risk areas indicating widespread flooding risk, only Campos dos Goytacazes is among the most physically vulnerable municipalities. The other three municipalities in the graph (i.e., Brasilia, Belo Horizonte and Rio de Janeiro) do not face widespread flooding risk or recurrent flooding events. However, they have the highest number of stations among all 846 municipalities analysed. Reasons for that may be related to the political and socioeconomic importance as some of the biggest urban centres in Brazil. However, the most physically vulnerable municipalities (with 75% or more of the urban risk areas) do not have official stations at all, which reduces their adaptation capacity.

Fig. 4 shows an uneven distribution of the interventions per municipality led by Cemaden with two outliers – São

José dos Campos in São Paulo (southeast) and Jaboatão dos Guararapes in Pernambuco (northeast region). When analysing the proportion of flood risk areas and historic flooding, São José dos Campos has less than 25% and no records of historical flooding, yet 41 institutions take part in the Cemaden Educação network. As for Jaboatão dos Guararapes, the city has 35% and five flooding events as well as 18 institutions engaged with Cemaden Educação activities. In contrast, Praia Grande in São Paulo is the only municipality with more than 75% flood-risk areas that has institutions engaged with Cemaden Educação.

A reason for such a high number of partner institutions in São José dos Campos can be attributed to the headquarters of Cemaden being based in the municipality, as noted from the institution's official website. Apart from that, the proportions of urban risk areas and the number of floods indicate the city is not among the most physically vulnerable.

In the case of Jaboatão dos Guararapes, Coutinho et al. (2020) point out that the municipality has implemented non-structural institutional measures for disaster risk reduction, including educational programs in 19 schools. Likely, those are the same partner institutions referred to Cemaden, which is responsible for monitoring disaster risks of over a thousand municipalities, one of them being Jaboatão (Coutinho et al., 2020). The paper also stresses that it would be significant to expand the program to cover more schools since most of them are in risk areas prone to landslides or flooding.

Overall, both figs. 3 and 4 depict that most municipalities with a high proportion of urban risk areas, according to the CPRM mapping, do not have a weather station nor Cemaden partner institutions. Considering the 37 municipalities with 50% or more of urban risk areas in this analysis, 32 have no institution working with Cemaden, and 31 have no INMET station. Twenty-seven do not have a station nor an institution. Among these, three municipalities have a high record of historical floods (Forquilhinha and Navegantes with seven and Ilhota with eight, all in Santa Catarina state).

In this scenario, projects like WPD can provide insights into community engagement activities happening in the most vulnerable municipalities. Fig. 5 shows the municipality with the highest number of WPD volunteers, São José dos Campos with 57 people. This is expected as the city also holds the highest number of Cemaden institutions, which was one of the project's research partners (Porto de Albuquerque et al., 2023). A similar situation is observed for Jaboatão dos Guararapes, that hosts 18 Cemaden institutions and has a total of 26 WPD volunteers. Cuiabá in the state of Mato Grosso (midwest) accounts for 30 volunteers, despite only hosting two Cemaden partner institutions and not having any urban risk areas (due to not being included in the CPRM mapping) and zero records of historical floods.

The other two municipalities highlighted are Florianópolis (capital city of Santa Catarina state) and Petrópolis in Rio de Janeiro, with 17 and 16 volunteers respectively. Florianópolis has 30% of its urban area considered risk area and four records of floods in the historical period, with two institutions in the Cemaden network. Additionally, previous works have indicated a tendency to increase vulnerability in the south region where the municipality is located (Debortoli et al., 2017). Avila et al. (2016) mention the floods that happened in Santa Catarina in 2008 as one of the second worst tragedies in southern Brazil until the paper was published.

In the case of Petrópolis, only 3.5% of risk areas are within its urban area but the municipality has six records of flooding events. There are no Cemaden institutions and there is one INMET station. For the wider public in Brazil, the city is known for being hit by past extreme climate events which received great coverage by news agencies, like the landslides and flash floods that killed over a hundred people in 2022 (BBC, 2022).

Overall, it appears that the WPD project was mainly run in municipalities that had Cemaden Educação partner institutions and/or a considerable history of past flooding events (observed in the case of Florianópolis and Petrópolis but also through other green and blue points in the plots with more than one WPD participants). According to WPD's methodology (Porto de Albuquerque et al., 2023), 'pollinators' (i.e., people in charge of steering participation within school teachers and schools) were responsible for reaching out to potential users of the WPD app. That is, local facilitators supported expanding the project to nine cities in five states in Brazil (each in a different region of the country): Acre, Mato Grosso, Pernambuco, Santa Catarina and São Paulo. Such facilitation seems to confirm the higher number of participants in the highlighted municipalities, with the exception of Petrópolis, located in Rio de Janeiro.

5 Discussion and Conclusions

The present paper explored data from different sources in an attempt to investigate the potential of citizen science to contribute to climate adaptation in Brazilian municipalities. Indicators used included location of official weather stations, number of historic floods, mapping of risk areas and institutions implementing educational strategies on disaster risk prevention. It also considered community engagement through citizen-generated data collected in the WPD project.

The analysis of the official weather stations (INMET stations) revealed monitoring infrastructure in Brazil is not deployed in areas where major risk areas are mapped. Instead, we see infrastructure concentrated, as in the national capital (Brasília) and state capitals (e.g., Belo Horizonte, Rio de Janeiro, and São Paulo). Among the nine municipalities with three or more stations six are state capitals. Despite the high population density, which implies typically a greater number of people in vulnerable areas (Membele et al., 2022), weather stations locations should also consider the proportion of risk areas and historical occurrence of flooding in municipalities.

Similarly, the network of Cemaden Educação partner institutions should aim to expand to other municipalities considering the same criteria. At the moment, Cemaden covers most of the densely populated areas, and Cemaden Educação institutions are mainly in municipalities with less than 50% risk areas.

The analysis of number of WPD participants per municipality seems to indicate there is a greater number of participants in municipalities that had registers of disasters before. Participatory citizen science approaches like the WPD project can provide complementary data to flood risk assessment (Sy et al., 2019). Therefore, we can affirm that the WPD offers an alternative to reaching municipalities where monitoring infrastructure is not dense or inexistent. The project should consider future partnerships with other organisations to expand its reaching potential and coverage of vulnerable municipalities.

Limitations of this study regard different levels of aggregation, completeness and currentness of the datasets used, which posed challenges to the analysis. Some data are only available aggregated per state, whereas municipal-level data often does not cover all municipalities in the country. An example of the latter is Cemaden's monitoring work, which currently covers 1,038 municipalities (Ribeiro et al., 2022), approximately 19% of all municipalities in the country. Furthermore, the study relies on many data sets from the IBGE census 2010 since data from the census 2022 were not yet completely available by the time of the analysis.

Despite these shortcomings, the research has contributed to advancing the understanding of the role of participatory citizen science in flooding adaptation by using a novel dataset (from the WPD project) together with official data. Studies of how citizen data is contributing to data inequalities are not very frequent and relevant to guide policy. Future studies on this topic can explore specific regions, states or municipalities in the country for a more in-depth cross-comparison of trends, considering specific contexts of those areas. Furthermore, studies using the WPD dataset could explore other variables available (e.g., rainfall measurement, rain events, flooded zones) in their analyses.

Declaration of Generative AI in writing

The authors declare that they have not used Generative AI tools in the preparation of this manuscript. Specifically, the AI tools were utilized for language editing, improving grammar, and sentence structure, but not for generating scientific content, research data, or substantive conclusions. All intellectual and creative work, including the analysis and interpretation of data, is original and has been conducted by the authors without AI assistance.

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