

Urban growth and spatial segregation increase disaster risk: Lessons learned from the 2023 disaster on the North Coast of São Paulo, Brazil

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Point-by-point response letter to the editor

Dear Dr. Sven Fuchs,

*We would like to thank you for your attention and your consideration to publish our article in NHESS. First, we highly appreciate the proposed suggestion to consider reading the study of Papathoma-Köhle et al. (2021). Our discussion benefitted a lot from the study, and we now included two new paragraphs in the revised version, from **lines 492 to 508**, as follows:*

“These results reinforce the multiple complexities in the disaster management cycle, especially in the context of LMICs. The expansion of precarious urban settlements towards hazardous locations and their higher physical and social vulnerability to disasters are not only a consequence of competition for the urban space, as discussed by Maricato (2017), but also of several institutional vulnerabilities. Papathoma-Köhle et al. (2021) describe institutional vulnerability as “an attribute that reflects the degree to which institutions can reduce the capacity of a system to withstand, cope and recover from the impact of a natural hazardous process” (p. 03). This includes the socio-political dimension such as the population’s risk perception and public awareness, and legal-regulatory aspects of formal organizations such as the promulgation and (more importantly) consolidation of land use plans, building regulations, and others. Thus, urban development processes are intrinsically associated with the role of institutions.

In the Brazilian context, planning policies including city and urban land use plans are constitutionally compulsory for every municipality with at least 20 thousand inhabitants. Nevertheless, the present study highlights strong intraurban inequalities in the São Sebastião region, manifested in unequal exposure and vulnerability to the 2023 event. These patterns of spatial segregation indicate gaps in the effective consolidation of such policies, thus pointing out potential institutional vulnerabilities, as described by Papathoma-Köhle et al. (2021). These findings reiterate the need for instruments to reduce disaster risk taking into account the existing complexities and interrelations among institutions, the private sector, and society. From a quantitative research perspective, a potential path is the development of novel methods to integrate such dimensions into disaster risk assessments (e.g., through the use of agent-based models).”

Apart from this modification, we carefully evaluated the comments from the referees and the community, and prepared a revised version of our manuscript accordingly. Please, find below our point-by-point responses (in italics) for each reviewer independently (RC1, RC2, and CC1). The reference to the line numbers is associated with the track-changed file.

Referee comment (RC1) by Julio Cesar Pedrassoli

Global evidence indicates that ongoing climate change is already impacting, and will continue to impact in the future, urban populations and, furthermore, precarious urban occupations, especially in middle- and low-income countries in the global south, are likely to suffer the consequences of these impacts in a more direct and devastating way. In this way, this article, by analyzing the direct impacts of a recent extreme event in an extremely socially and spatially segregated Brazilian urban area, is of great scientific significance, especially as it demonstrates the disproportionality of the impacts on formal and informal urban areas.

As for the methods used and the general quality of the input data in the analytical model, the work follows the necessary rigor and presents the results clearly. As a caveat, the work would benefit from a better development of the concept of susceptibility. Vulnerability is developed in a substantial way, however, taking into account the idea that risk can be understood as the interface between susceptibility and vulnerability, characterizing the natural susceptibility of the São Sebastião region, especially due to its very steep topography, would be beneficial from a conceptual point of view.

Response 1: We would like to thank the reviewer Julio Cesar Pedrassoli for the interesting and positive comments on our paper. We are also grateful for the proposed suggestions and further references, which altogether improved the paper.

*In the revised version, we better developed the concept of susceptibility by including a more detailed characterization of the natural susceptibility of the São Sebastião region in Section 2, where the study area is described. We included the following paragraph from **lines 101 to 105**: “The large prevalence of small-sized drainage areas with steep slopes makes the region highly susceptible to multiple hazards. Existing studies of the São Sebastião region – the most impacted by the 2023 event – point out a considerable amount of areas classified as either susceptible to landslides, flash floods, or debris flows, or an intersection of them (Arango Carmona et al., 2023). The region is also characterized by a tropical climate, with an average annual precipitation of over 1,800 millimeters (CPRM, 2011), thus exacerbating the risks. Consequently, we address the event of 2023 as multi-hazard event.”*

In addition, it would be interesting to deal in a little more detail with some of the other layers of complexity of the specific event on which the article is based: there was also a failure in the risk communication process, as the local government had received official warnings of a large amount of rain forecast some time in advance (<https://agenciabrasil.ebc.com.br/geral/noticia/2023-02/centro-de-monitoramento-emitiu-alertas-tres-dias-antes-dos-temporais>) but chose not to take any action. In addition, the risk areas were previously mapped, according to a report by the São Paulo State Institute for Technological Research (https://www.sidec.sp.gov.br/map_risco/uploads/doc1637073821.pdf).

Response 2: We agree that considering other layers of complexity is essential to better comprehend the conditions that led to such devastating impacts. As mentioned by the reviewer, we also identified failures and communication gaps in early warning before and during the event and were aware of existing maps indicating risk areas in the region. We recently addressed these in a technical paper submitted to the XXV Brazilian Symposium on Water Resources (November 2023). You can find the paper through the link: <https://anais.abrhidro.org.br/job.php?Job=14954>. To better describe this in the manuscript, we have now included a few sentences addressing these layers of the disaster. We opted to present a brief introduction to such layers while referring to our more complete study on the topic. Thus, the following modifications were made in the revised version:

- **Lines 101 to 105:** we discussed the existence of susceptibility maps that point out the region’s high susceptibility to flash floods, debris flows, and landslides. We also referred to our previous study so that the reader can get further information if desired. It now reads as follows: “The large prevalence of small-sized drainage areas with steep slopes makes the region highly susceptible to multiple hazards. Existing studies of the São Sebastião region – the most impacted by the 2023 event – point out a considerable amount of areas classified as either susceptible to landslides, flash floods, or debris flows, or an intersection of them (Arango Carmona et al., 2023). The region is also characterized by a tropical climate, with an average annual precipitation of over 1,800 millimeters (CPRM, 2011), thus exacerbating the risks. Consequently, we address the event of 2023 as multi-hazard event”.
- Regarding the reference to communication gaps in early warning, we opted to not include it in the manuscript. We agree with the relevance of early warning systems for an efficient response to such events and especially to prevent human losses. However, our study is focused on the physical damage to buildings and historical urban development processes in the region. While we attempted to incorporate the discussion on communication gaps into our manuscript, we could not find a proper way of connecting both dimensions of the disaster

cycle (historical urban processes and early warning) without deviating too much from the main topic.

Overall, the paper is presented clearly with appropriate language, figures, and references, and its conclusions have great potential for applying better tools to public policies for monitoring and assessing risks related to extreme events in cities in the global south.

We thank Julio Cesar Pedrassoli very much again for his time to review the paper.

Referee comment (RC2) (Anonymous)

Here is a review of “Urban growth and spatial segregation increase disaster risk: Lessons learned from the 2023 disaster on the North Coast of São Paulo, Brazil”. The authors have presented some perspectives on how urban growth and inequalities influence disaster risk in terms of exposure and vulnerability. In this case, rain-triggered landslide.

Here are some suggestions:

The authors used a more generalized term, disaster. I suggest that the authors consider being more specific as to which disaster is being studied here. Readers can get easily confused from reading the abstract as to which rainfall-triggered event is being studied for the 2023 event. One disaster that could come to mind would be flooding which is also very common to Sao Paulo, Brazil. Although the 2023 events included both flooding and landslides, the authors only considered landslides in their analysis.

Response 3: *We would like to thank the reviewer for the interesting comments about our paper. We agree that the 2023 disaster was characterized by a multi-hazard event combining landslides, mudflows, and flash floods. In most cases, we could not delineate crisp boundaries between these processes as there were several areas of spatial intersection. However, the comparison of very high-resolution pre- and post-disaster images was adequate for mapping the physical damage to buildings. We conducted a few modifications in the revised version to be clear about such limitations. The following modifications were made in the revised version:*

- **Line 8:** *we replaced “hazardous event” with “multi-hazard event”;*
- **Line 125:** *we replaced “most landslides” with “most of the damage”;*
- **Table 1:** *we replaced “landslides and/or mudflow deposits” with “evidence of disaster damage”, and provided examples of such evidence (e.g., debris, tree trunks, and garbage piles);*
- **Lines 151 to 156:** *we added a short paragraph to explain limitations on the identification of the hazardous events: “It is important to mention that the 2023 disaster on the NCSP was characterized as a multi-hazard event, combining different rainfall-triggered hazards including landslides, mudflows and flash floods (Arango Carmona et al., 2023). In most cases, we could not identify crisp boundaries separating these hazards as there were several areas of spatial intersection. However, these limitations did not influence our mapping of the physical damage to buildings since we did not focus on distinguishing hazardous processes. Thus, the comparison of very high-resolution pre- and post-disaster aerial images was adequate for our purposes.”*
- **Lines 308 to 309:** *we replaced “triggered multiple landslides and mudflows” with “triggered a severe multi-hazard event”;*
- **Lines 328 to 359:** *in this part of the study, we maintained the explicit reference to landslides when describing Figures 6 and 7 since they refer to a local assessment of the disaster damages supported by in-site evidence during the field visit (conducted together with experts in landslide mapping and members of the local Civil Defense).*

Line 25 - For example, the authors cited “Tellman et al. (2021) demonstrated that the proportion of the global population occupying areas exposed to large riverine floods has increased by 20% from 2000 to 2015”. Literature reviews on floods and landslides could be misleading to readers. I’ll suggest the authors consider stating which disaster their work focuses on in the context of disaster risk and the 2023 event.

Response 4: *While we focused on specific hazards, the major topic of our study remains the association between exposure to hazardous processes and urban growth. For this reason, we believe that presenting previous research such as Tellman et al. (2021) is still important to contextualize our study. In any case, we adjusted the text as stated in Response 3, aiming to better describe the hazards that are being investigated in our study.*

Line 470 - Could this be a typo? “450%” or 45%?

Response 5: *The numbers are correct. The total urban area grew by 4.5 times (450%) from 1985 to 2015, according to information from the World Settlement Footprint evolution layer (as illustrated in Figure 4 of the paper).*

Question - Has there been a history of landslides in the study location? That could expressly indicate some level of exposure to landslides and could be accounted for in the analysis.

Response 6: *There is no evidence of a history of landslides in the study area. To the best of our knowledge, the 2023 event in São Sebastião was an unprecedented event, both regarding the extreme rainfall and the large number of landslides. The only case of a similar event in the region happened in 1967 in the neighboring city of Caraguatatuba (not the same location, but nearby). We now included this information from lines 63 to 65, as follows: “The 2023 disaster was classified as an unprecedented event in the São Sebastião region. To the best of our knowledge, the only event of similar magnitude in the region was the 1967 disaster in Caraguatatuba, one of the cities that are part of the NCSP (Dias, Dias, & Vieira, 2016).”*

In section 3.3 Understanding the patterns and drivers of urban growth and spatial segregation, you identified the factors driving urban development processes and how they are associated with disaster exposure and vulnerability. By extension, some of these factors also influence landslide occurrence, so maybe relating drivers of urban growth and spatial segregation to landslide factors could provide more context to exposure in the study area.

Response 7: *We agree that urban development processes are not only associated with exposure and vulnerability but also with hazard processes and can cause feedbacks. We now acknowledge this in the Introduction section, lines 50 to 53:*

“... urban growth, especially the construction of irregular housing and settlements, can increase the probability of hazard occurrence due to human modifications of the physical environment. These modifications impact slope stability through processes such as vegetation deforesting, slope cutting, and inadequate drainage systems.”

However, quantifying this influence would require the development of models to investigate temporal changes in hazard processes. Modeling such “what-if” scenarios to investigate where landslides would have occurred if areas were not urbanized is beyond the scope of our study. It also involves uncertainties that we would not be able to quantify without a proper multi-temporal hazard inventory. In this paper, we focused exclusively on the 2023 disaster, thus using this specific hazardous event as a reference for our analysis.

In the result section, I suggest authors focus on facts from their analysis and less citation of literature. A bulk of geospatial analysis and some statistical analyses have been done and efforts need to be placed on interpreting them for ease of readability.

Response 8: *We included citations from the literature because we combined the results and discussions in the same section. We would like to keep the merged section since it better connects our findings with the discussions in the literature. However, we carefully assessed the results and discussion section when revising the paper, aiming to identify potential paragraphs with limited readability. Most of our text is composed of the description of our main findings, which is followed by their interpretation. The inclusion of the literature throughout this section is only adopted in relevant cases, as when important findings were stated (or contradicted) in previous research, thus supporting the conclusions of our study.*

Generally, the authors have done very fine-scale work on improving our understanding of the risk increased urbanization and inequality pose to exacerbate exposure and vulnerability to disaster.

We thank the reviewer again for all remarks and suggestions.

Community comment (CC1) by Lorraine Trento Oliveira

This paper shows important evidence of hazard exposure in secondary LMIC cities and shed light in the disparities on the level of exposure and vulnerability of low-income neighborhoods. It adds to the body of knowledge with the spatial and temporal analysis of urban growth and the influences to disaster risk.

The manuscript can have minor revisions: (1) the introduction would benefit from more literature review on urban growth (spatially explicit) factors as well as a methodological flowchart figure;

Response 9: *We would like to thank Lorraine Trento Oliveira for her interesting comments about our paper. We carefully evaluated the proposed suggestions and revised the paper accordingly. We agree that a more complete literature review on the factors driving urban growth would be beneficial for our study. However, we believe that the reference to the systematic review of Allan et al. (2022) (line 242) provides a good theoretical background to support our selection of the spatial factors of growth (Table 2), given the purposes of our study. Regarding the methodological flowchart, we opted to not include an additional figure given the large number of existing figures and tables and the current length of our manuscript (which is almost exceeding the limits). However, we carefully reviewed this section to improve the readability and interpretability of our methodology. For example, all methodological steps are now explicitly integrated in the title of the sub-sections, and the visual demonstration of our analyses with figures (e.g., Figures 2 and 3).*

(2) more details on the processing and analysis should be provided e.g. choice of cell size, intersection of FUC's shapefile with WSF layer, handling of collinearity of factors etc;

Response 10: *We included more details on the processing and analysis of our data in the revised version. To do so, we added the following paragraph from lines 226 to 230: "We did it by intersecting the vector of SAs with the WSF map. To perform this analysis, we first converted the vector of SAs into a raster layer, adopting an overlap of at least 50% as a minimum threshold to classify a raster cell as an SA. The raster was generated at the same spatial resolution (30 meters) and extent as the WSF layer. We opted to use the spatial configurations of the WSF layer as a baseline to ensure the finest possible resolution for our analysis given the limitation of the datasets". We did not address the issue of collinearity at this stage of our research since we are only conducting an univariate exploratory analysis, which is not influenced by the existence of collinearity among factors.*

(3) future research should use this as baseline for prediction on exposure of the same study area, considering different land use change scenarios, as well as the inclusion of more contextual factors (such as distance to CBD).

Response 11: *Thank you for the suggestions for future research. We are currently working on the development of modeling approaches to simulate scenarios of urban growth and spatial segregation in the region. We will certainly consider other contextual factors in this next stage of our research (followed by a literature review, as indicated in Response 9).*

Response 12: *In addition to the main comments, we also addressed minor issues pointed out by the reviewer throughout the paper. The following modifications were made:*

- **Lines 6 to 7:** *as mentioned by the reviewer, the influence of urban processes on disaster risk is already acknowledged, but the main uncertainties are more on the extent of such influence. We updated the sentence to be more clear regarding this issue. It now reads as follows: "Urban growth and the increase in urban poverty are important drivers of disaster risk. However, to what extent these processes influence the dynamics of exposure and vulnerability remains uncertain".*

- **Line 13:** we replaced the term “historical urban growth” with “historical built-up land use changes”;
- **Lines 30 to 31:** we eliminated the examples of urban challenges;
- **Lines 34 to 43:** we rephrased the paragraphs to emphasize the challenge of intraurban inequalities in a global context (and not exclusively in Brazilian cities); it now reads:

“Projections from the World Cities Report 2022 (UN-Habitat, 2022) estimate that the global population living in cities is expected to increase further to 68% by 2050, with new urban residents mostly concentrated in low- and middle-income countries (LMICs).

Urban exposure to disaster risk is even more expressive among the urban poor (IPCC, 2022). Worldwide, it is estimated that around 1.6 billion people live in inadequate housing and 1 billion in informal settlements (UN-Habitat, 2022). These intraurban inequalities are often led by a complex system of competition between the housing market and the “informal city” (Maricato, 2017). As a result, the urban poor are driven towards areas that are less desirable to the market, frequently confined to hazardous locations such as floodplains and hillslopes (Maricato, 2017; UN-Habitat, 2022)”.

- **Line 49:** we replaced the phrase “Apart from changing trends in exposure” with “In addition to their associations with exposure”;
- **Line 55:** we replaced “a few factors” with “key factors”;
- **Lines 72 to 73:** we replaced the term “gated condominiums of second homes” with “gated communities for vacation purposes”;
- **Line 95:** we eliminated the phrase comparing the population of the study region with the entire population of the São Paulo State;
- **Lines 115 and 482:** we replaced the term “second homes” with “summer houses”;
- **Lines 169 to 179:** we corrected our definition of precarious urban settlements. Favelas and urban communities are official criteria to define substandard urban settings that were only promulgated by the Brazilian Institute of Geography and Statistics (IBGE) in 2024. Thus, the dataset adopted in our analysis still refers to the former definition of precarious urban settlements, previously referred to as substandard agglomerates;
- **Lines 181 to 183:** we replaced “... organized in irregular layouts, and connected via narrow and unpaved streets, thus indicating the lack or precarity of public infrastructure” with “... densely and irregularly arranged, with narrow distances between buildings and unpaved streets”. As commented by the reviewer, the lack or precarity of public infrastructure is not per se a morphological characteristic of precarious settlements.
- **Lines 225 to 230:** we replaced the term “favelas and urban communities” with “subnormal agglomerates”, and also included a short sentence to explain the method adopted to convert the vector into a raster file: “To perform this analysis, we first converted the vector of SAs into a raster layer, adopting an overlap of at least 50% as a minimum threshold to classify a raster cell as an SA. The raster was generated at the same spatial resolution (30 meters) and extent as the WSF layer. We opted to use the spatial configurations of the WSF layer as a baseline to ensure the finest possible resolution for our analysis given the limitation of the datasets”.
- **Lines 277 to 278, and lines 471 to 472:** we replaced the term “favelas and urban communities” with “precarious urban settlements”;
- **Line 281:** we replaced “evidences” with “indicates”;
- **Line 342:** we added a reference to the phrase (Hallegatte et al., 2020);
- **Line 344:** we replaced “large number of densely packed buildings” with “built-up density”;
- **Lines 483 to 484:** we added references to the phrase (Daunt & Silva, 2019; Daunt et al., 2021; Rosembach et al., 2010);
- **Line 526:** we replaced “orientating the expansion of urban settlements” with “pushing the expansion of urban settlements”. The verb “to push” better represents the process that often happens with the growth of precarious urban settlements.

We would like to thank Lorraine Trento Oliveira again for her interesting comments which were of great help to improve the paper.