A multi-hazard perspective on the São Sebastião-SP event in February 2023: What made it a disaster?

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A MULTI-HAZARD PERSPECTIVE ON THE SÃO SEBASTIÃO-SP EVENT IN FEBRUARY 2023: WHAT MADE IT A DISASTER?

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Abstract: The historical rainfall recorded at the coast of São Paulo State during the Carneval weekend of 2023, surpassing 600 mm in less than 24h, lead to 571 landslides, more than 1000 people displaced and 64 deaths in São Sebastião. Disaster impacts result from the interplay of hazard processes, exposure of human settlements and infrastructures, and their vulnerability; hence, disasters are not natural. In this paper, we present a first event report including an analysis of the rainfall amounts, the warning situation, and the growth of urban areas into hazard-prone areas.

Resumo: As chuvas históricas registradas no litoral do Estado de São Paulo durante o fim de semana do Carnaval de 2023, ultrapassando 600 mm em menos de 24 horas, provocaram 571 deslizamentos de terra, mais de 1.000 pessoas desalojadas e 64 mortes em São Sebastião. Os impactos causados por desastres resultam de uma interação entre ameaças, exposição de assentamentos humanos e infraestrutura, e as suas vulnerabilidades; portanto, desastres não são naturais. Neste trabalho, nós apresentamos um primeiro relatório incluindo a análise das intensidades de chuva, a situação das alertas durante o evento, e o crescimento de áreas urbanas em áreas de risco.

Keywords – extreme rainfall, landslides, multi-hazard risk

INTRODUCTION

In the night between the 18th and 19th of February 2023, the North Coast of São Paulo State was hit by heavy rain, surpassing 600 mm in less than 24h at several locations, according to the gauge network of the National Center for Natural Disaster Monitoring and Alerts (CEMADEN). This rainfall triggered extensive landslides. The most affected municipality was São Sebastião, which was afflicted by 571 active landslides (CENAD, 2023), where more than 1000 people were displaced, and where 64 out of the 65 fatalities of the disaster occurred[5]. Though triggered in the short term by a stationary cold front and prolonged, intense rainfall, the root causes of the disaster impacts can be traced back over several decades.

Here, we attempt to identify the factors that led to the disaster from a multi-risk perspective. In particular, we focus on the extremity of the rainfall at different temporal scales, the patterns of urban exposure and segregation, the existence and use of hazard maps, as well as early warnings of the event. In this study, we address each of these points, including their intersections and interactions.

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[5] https://www.saosebastiao.sp.gov.br/emergencia/boletins.asp

While many municipalities were affected, we focus our analysis on the most impacted location in the southern coast of São Sebastião. This includes, from west to east, the beaches of Juquehy, Barra do Sahy, Baleia, Camburi, Camburizinho, and Boiçucanga.

DATA AND METHODS

For the rainfall analysis, we adjusted radar data from the Salesópolis station using 10-min data from 78 automatic rain gauges (CEMADEN, 2023). Additionally, ERA5 reanalysis data (ECMWF, 2023) was used to assess the synoptic situation during the event. Next, we investigated the spatio-temporal characteristics of the rainfall event. The extremeness of the event was analyzed at sub-daily scale, using existing intensity-frequency-duration (IDF) curves (CPRM, 2017) and at daily scale conducting a return period analysis of the maximum daily rainfall per hydrological year. For this last analysis, the L-moment method (Hosking, 1990) was employed, using data (1970-1994) from the Boraceia station located in the eastern part of Bertioga. The historical data was supplemented with event data from the automatic station ("355070402A"), located in São Sebastião, less than 9 km away from Boraceia. The goodness of fit was evaluated by ranking the Root Mean Square Error (RMSE) to define the best fit probability distribution.

Information on the susceptibility to multiple flood and landslide hazards for the area were assessed using two different sources. The first one is the mapping of areas with landslide and flooding risk in the municipality of São Sebastião, a project carried out by the Geological Institute of São Paulo (IG) in 2005 (IG, 2006). The project used aerial photographs and field visits to identify critical risk areas based on criteria including terrain morphology, evidence of active processes, and observed levels of exposure. The results include 93 polygons with different levels of landslide and flooding risk. The second document is the regional assessment of susceptibility to landslides, flooding, debris flows and flash floods with maps at the scale of 1:25,000 from 2014 (IPT, 2014). The landslide susceptibility was computed using a weighting method that relates conditioning factors, including slope, curvature and density of structural lineaments, with landslide density, using the homogeneous terrain unit as the scale of analysis. The flood susceptibility map was creating using a Height Above Nearest Drainage (HAND) analysis. Finally, the debris flow and flash flood susceptibility were identified at the basin scale. The criteria for flash flood susceptibility include slopes, drainage area and susceptibility to flooding. Debris flow susceptibility also used these criteria, and additionally considered landslide susceptibility and ratio between relief to basin length for debris flow susceptibility.

Using post-event Planet satellite imagery (PLANET LABS PBC), we corrected the landslide extents mapped by CENAD (2023), who outlined 571 landslide areas. Additionally, we mapped the landslides and debris flow source points. We conducted a spatial analysis to assess the intersection between the landslide areas and initiation points with the hazard information described above.

To investigate how urban growth and segregation played a role on the disaster, we mapped all damage to buildings and to the Rio-Santos (BR-101) highway, which is the main road access to the area. We overlapped the damaged areas with historical urban footprint maps (DLR, 2023), and with the location of informal settlements (IBGE, 2019). Urban footprint maps were obtained from the World Settlement Footprint (WSF) evolution layer, which represents yearly urban changes from 1985 to 2015 at a 30-m of spatial resolution. Damage was mapped through the visual interpretation of very high-resolution images (0.1m) comparing pre- and post-disaster conditions. These images were obtained from the Geographic and Cartographic Institute of the State of São Paulo (ICG)[6]. We classified as damaged all buildings and road sections that intersected landslide areas, also using as a proxy the presence of mud or debris in the surroundings. Buildings were further classified into

[6] https://datageo.ambiente.sp.gov.br/app/

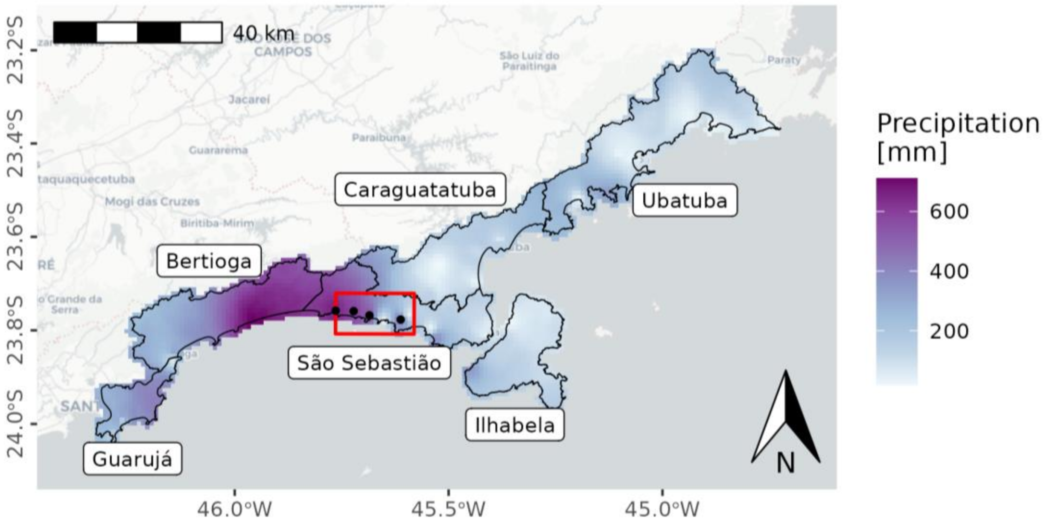
potentially damaged (when their structure remained intact, but they were still surrounded by landslide deposits) or completely destroyed (when their structure disappeared in the post-disaster image).

SYNOPTIC SITUATION, HEAVY RAINFALL AND EARLY WARNING

The heavy rainfall event has two main causes from a meteorological point of view: a remarkably stationary cold front, and an intensification of the precipitation due to the orography. The weather conditions in the region of São Sebastião are influenced by the South American Low Level Jet, which transports warm humid air masses from the northwest (Montini *et.al*, 2019). In the days leading up to the event, a far-northern low-pressure system with a surface pressure of below 970hpa developed west of Argentina, transporting cold-dry air northwards. The cold-dry and warm-humid air masses met over the Atlantic, forming a cold front that reached the mainland at the São Sebastião region. The remarkable stationarity of this cold front over the 18 hours of the event, led to extreme rainfall in the study area. Heavy rainfall directly at the coast was caused by the rotation of the wind direction due to the cold front. While the wind blew from the northwest before the event, the direction turned to east-southeast in the afternoon of 18 February, pushing the air masses back against the orography and causing a further lifting of the warm-humid air masses, thus intensifying the rainfall.

The cold front hit the coast of Guarujá around 16:00 h (local time), spreading eastward through the night, and reaching the highest intensity as it passed over the eastern part of Bertioga and western São Sebastião (Fig. 1). In that region, the total event rainfall was about three times higher than what was observed in Ilhabela, Ubatuba or Caraguatatuba, due to the intense rainfall being sustained for several hours. Thus, two-thirds of the total event rainfall, i.e. about 400 mm, fell during the first six hours (see Fig. 2).

Figure 1 – Distribution of total event rainfall in six affected municipalities. The four rain gauges in western São Sebastião depicted in Fig. 2 are indicated with black dots. The study area with the most affected settlements is denoted in red (Source: Weather radar corrected with CEMADEN stations).

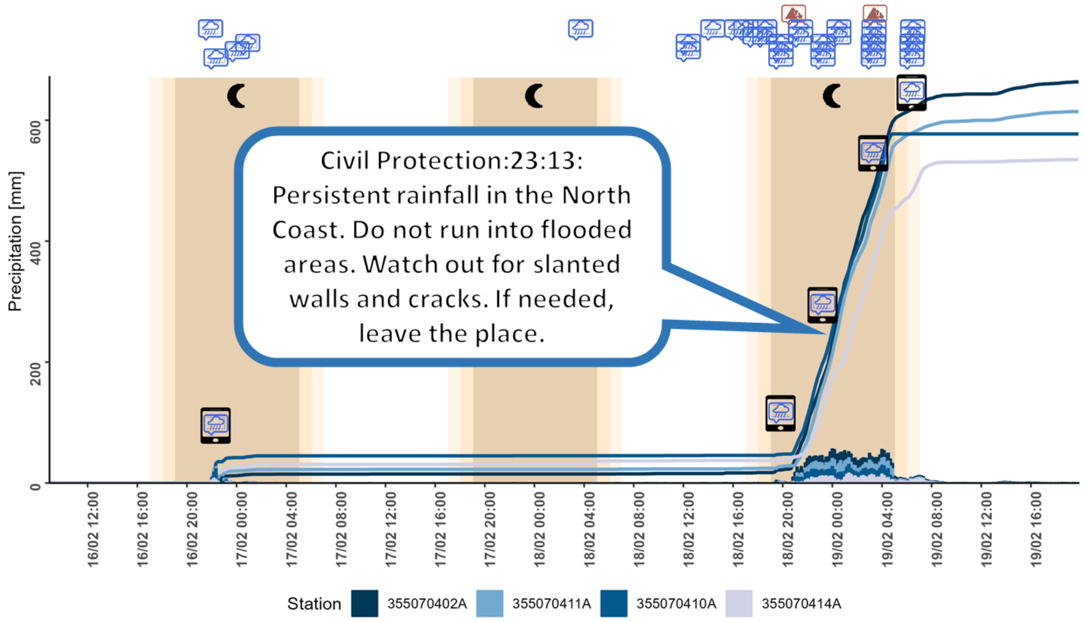


Two days before the event, CEMADEN forecasted intense rainfall and potentially “moderate” hydrological risks (on a scale of: “low”, “moderate”, “high” and “very high”) in the extended region. This was published in their daily bulletins and communicated to the national and state civil protection agencies (CPAs) (Palhares, 2023). One day before the event[7], a “very high” potential risk of both hydrological and geohazard risks was published, already indicating the risk of landslides. In contrast to risk forecast bulletins, the decision to issue a warning to the population is ultimately the responsibility of the municipal CPAs or assumed by higher levels in case of incapacity or impediment

[7] https://www.gov.br/cemaden/pt-br/assuntos/riscos-geo-hidrologicos/18-02-2023-previsao-de-riscos-geo-hidrologicos

(BRASIL, 2020). Fig. 2 shows the evolution of the event with the cumulative and 10-min rainfall together with the warnings issued to the population via SMS in the study area as well as nearby municipalities. Warnings issued to São Sebastião only indicated intense and/or prolonged rainfall, and only one studied municipality (Guarujá-SP, second-next neighbour city to São Sebastião-SP) received landslides warnings. Nonetheless, the warnings carried action recommendations, namely: (at 19:49 h) to stay alert; (at 23:13 h and later at 03:15 h) to avoid flooded areas and watch out for slanted walls or cracks, and leave the place if needed; and (at 06:23) to leave the place in case of "unusually" slanted walls. Accumulated rainfall surpassed 100mm between 22:00 h and 23:00 h, about 3 hours into the event.

Figure 2 – Cumulative rainfall in selected rain gauges and timeline of warnings issued. Icon next to the rainfall curve show warnings issued to São Sebastião. Icons on the top show warnings issued to nearby municipalities. The landslide warnings are isolated for readability only. Orange vertical bars denote night time (Source: ANATEL, 2023; CEMADEN, 2023).

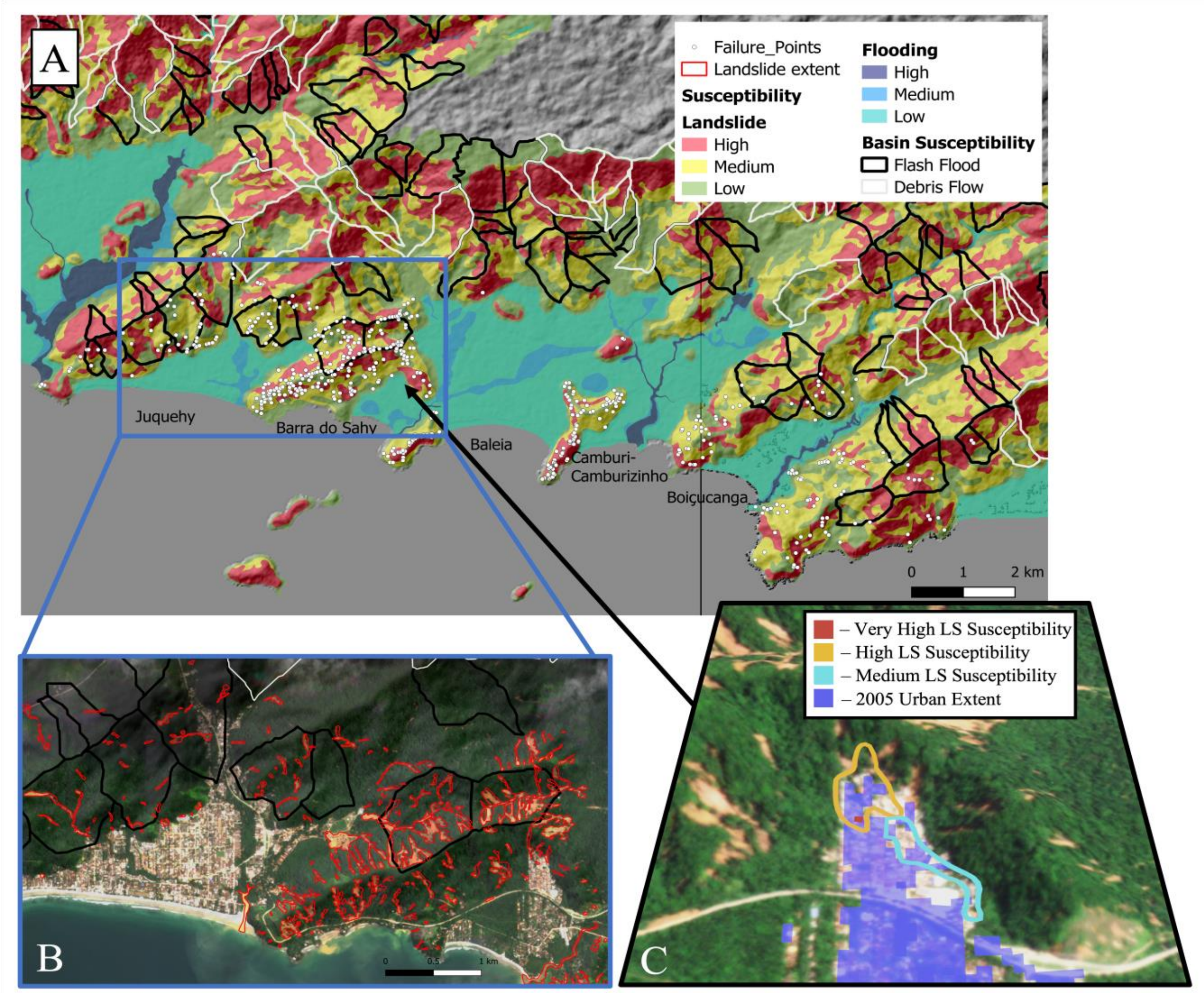


In the context of the maximum daily historical record, the event was extremely exceptional, particularly in the areas of highest rainfall during this event. A daily rainfall of ~ 633 mm has never been recorded since 1970 at the Boraceia station, and it is almost twice the highest recorded daily rainfall (i.e. 351 mm observed in 1991). When analyzing the return period of the maximum daily rainfall for the Boraceia station, it is estimated that the event in this area has a return period (RP) of over 430 years, based on the best-fitted theoretical curve. It is important to note that due to the limited data available in the area (25 years), there is some uncertainty in the estimation. However, this analysis highlights the exceptional nature of this event at a daily scale. On the sub-daily scale, the event was not exceptional in terms of short duration rainfall. The RP for the 10-min and 1-hour maximum rainfall intensity was < 20 years and < 60 years respectively for the São Sebastião rain gauges. What made the event truly exceptional was the fact that high rainfall intensities of > 50 mm/h was sustained for several hours. Thus, the estimated RP of 6-hour and 12-hour rainfall was far outside of the range of the IDF curves, i.e. >> 100 years.

HOW THE EVENT OVERLAPPED WITH KNOWN HAZARD ZONES

In addition to the rainfall, it is important to investigate the nature of the landslides themselves. Our comparison between the landslide initiation points and the landslide susceptibility map created by IPT indicates that 30% of the landslides originated from areas that were considered as highly susceptible, 42% in areas with medium susceptibility, and the remaining 28% in areas with low susceptibility. Critically, only 1.4% of the triggered landslides initiated inside debris flow susceptible basins, and 13.7% inside flash flood susceptible basins (Fig. 3A).

Figure 3 – Relationships between previous hazard and risk maps, extent of the event and urbanization of hazardous areas. (A) Landslide failure points and flooding, flash flood and debris flow susceptibility (IPT, 2014). (B) Urbanization of known landslide risk areas (IG, 2006) (Image © 2023 Planet Labs PBC). (C) Distribution of landslide affected area inside regions previously mapped as highly susceptible to flash floods.



Most of the damage was the result of landslide run out impact. We measured the area affected by landslides, and how it relates to the basins considered as susceptible to flash floods and landslides. We find that the landslides that occurred inside basins considered as susceptible to flash floods had larger areas than those that occurred in areas only susceptible to landslides (Fig. 3B). More than a third of landslides occurred in flash flood-prone basins, regardless of their landslide susceptibility level, with 36% in area of low, 35% in medium, and 42% in highly susceptibility areas. With a visual identification of those landslides, it is clear that the initiation areas of landslides inside flash flood prone areas are not larger, but instead they connect with each other in the deposition zones and channels.

The criteria to determine the basins' susceptibility to flash floods include being in morphological units of high slopes, difference between maximum and minimum elevation greater than 300 m, and a drainage area of less than 10 km^2. Such criteria were successfully identifying areas that can enhance the combination of processes. We stress that the combined flood and landslide hazards indicate the significant multi-hazard risk manifested during to this event. These multi-hazard phenomena created rapid flow-like bursts hyper-concentrated with debris material that could explain the significant and destructive impacts to roads and residential areas downstream of the flash flood basin outlets.

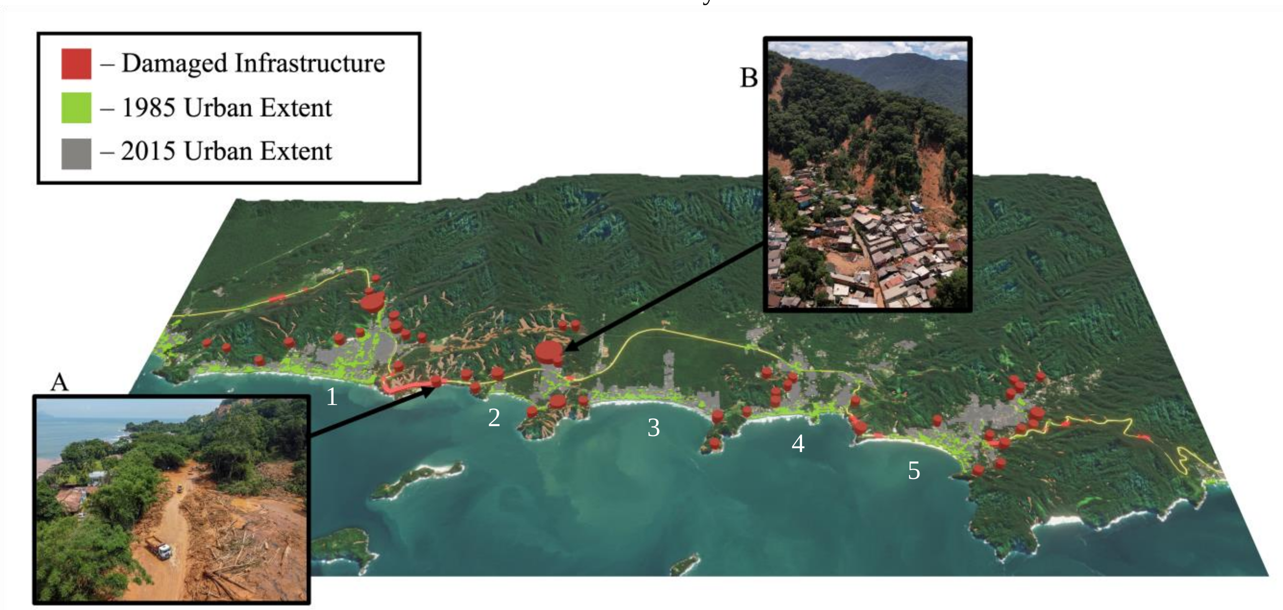
There are two key factors to analyze the relationship between knowledge of the hazard and the disaster impacts. The first is the assessment of potential areas where landslide failures can originate, and the second is its run out to possible areas that can be affected by deposition of the failed material. The critical saturation of the soils within these flash flood basins due to the intense rainfall enabled the debris of the landslides to join channelised flows downstream. As a consequence, the material impacted areas with low landslide susceptibility.

In addition, significant damage occurred in regions identified in a previous study as susceptible to landslide risk (Fig. 3C). Although these regions were identified already in 2006, significant urban expansion within these regions is visible between 2005 and 2023 (compare the blue area in Fig. 3C to the underlying satellite map). In fact, the manner in which urban areas grew in the decades preceding the disaster is a significant component in explaining its huge impacts.

THE EVOLUTION OF URBAN AREAS AND ITS IMPACTS ON EXPOSURE

The North Coast is a well-known tourism destination in the State of São Paulo, which has experienced rapid urban growth since the construction of the Rio-Santos highway at the second half of the 20th century (Rosemback *et al.*, 2010). An analysis from our companion submission (Moroz *et al.*, 2023) estimated that the extent of urban areas increased 4.5 times the study area between 1985 and 2015. However, this growth was even more extensive in informal settlements, which increased their area by 8.9 times in the same period. A damage map is presented in Fig. 4.

Figure 4 – Damage to infrastructure and evolution of urban areas from 1985 to 2015. The radius of the red cylinders indicates the density of damaged buildings, ranging from 1 (smallest circle) to 31 buildings (largest circle). The Rio-Santos highway is represented in yellow; (A) Rio-Santos (BR-101) highway, km 174.5; (B) Informal settlement in Barra do Sahy.



1. Juquehy | 2. Barra do Sahy | 3. Baleia | 4. Camburi/Camburizinho | 5. Boiçucanga

In total, an estimated number of 191 buildings were damaged, including 126 partially damaged and 65 completely destroyed. The most affected area was an informal settlement in Barra do Sahy (Fig. 4B), where 34 buildings were affected, of which 20 were completely destroyed. The second most affected region was another informal settlement in Juquehy, along the Rio-Santos highway. In total, 26 buildings were affected in this area, of which 17 were completely destroyed.

Overall, we observed that informal settlements were more affected by the disaster. Even though these settlements currently cover just 15% of the urban areas in the region, they represented 36.5% of all partially damaged and 66.2% of all completely destroyed buildings. These figures indicate that informal settlements are most probably more exposed to climate-related hazards than formal areas in the analyzed communities of São Sebastião. Combined with their higher physical (e.g. quality and resistance of building materials) and social (e.g. socioeconomic conditions, adaptive capacity, governmental support) vulnerabilities, these communities are at a considerably higher risk to disasters than formal urban areas.

When analyzing the temporal evolution of urban areas, we also observed that most of the damaged buildings were recently constructed. Roughly 77.5% of all buildings were constructed after the year 2000, and 45% after 2010. In 1985, the initial year of the WSF layer, less than 6% of the damaged buildings already existed (see Fig. 4 for a visual indication). The expansion of informal settlements was even more recent. No damaged buildings existed until 1996, and around 82.7% were only built after 2000.

Regarding the Rio-Santos highway, we identified a total of 15 disrupted sections, blocking almost 3.2 kilometers of the road. The most damaged section was between the beaches of Juquehy and Barra do Sahy (see Fig. 4A), where several landslides completely covered an extension of more than a kilometer with mud and debris. The disruption of the road traffic was one of the most critical factors for evacuation and rescue during (and after) the disaster, as the highway is the main (and sometimes only) access to the area. Therefore, the high number of blockages completely isolated some communities in the study area[8].

DISCUSSION

When discussing the key factors determining a disaster, it is essential to consider not only the hazard, but also the two other components of risk: exposure and vulnerability. The 2023 North Coast of São Paulo disaster is a clear illustration of this fact. Our analysis highlights that three factors were especially important in determining the severity of the impacts of this event: (1) the extremeness and multi-component nature of the hazard processes, (2) the exposure increasing in the decades leading up to the event due to urban expansion into critical areas, and (3) a gap in a multi-hazard forecast, warning and response system (i.e. hazard maps, landslide early warning alerts).

The analysis of landslide-affected areas shows that the damage caused by this event was amplified by connected hydrological processes resulting in landslides and floods. Risk assessments in this region are limited to susceptibility maps describing hazard-prone areas (IPT, 2014). The natural conditions of the coastal mountain range of Serra do Mar region, characterized by its steep slopes, rainfall regime and deep layers of weathered soils make it prone to the occurrence of multi-hazard events. Disastrous (multi-hazard) events are not unknown in the region, e.g. the Caraguatatuba disaster in 1967, where rainfall of 585 mm in 48h triggered more than 640 landslides and debris flows (Dias *et al.*, 2016). Therefore, while the 2023 event was an extreme and rare event with a return period of 420 years, it cannot be said that the event was entirely unprecedented. Thus, it is essential for hazard and risk assessments to evolve from independent evaluations to the inclusion of possible interactions in the face of increased intensity and frequency of extreme rainfall events under the influence of climate change. It is evident from the outcome of this event that prior knowledge of predisposition to hazards makes headway in the translation of susceptibility information to hazard maps in response to growing risk in dynamic environments.

Increasing urban exposure over the last decades played a decisive role in making the event more severe. More than three quarters of the damaged buildings were constructed over the last two

[8] https://www1.folha.uol.com.br/cotidiano/2023/02/litoral-norte-ainda-tem-2-interdicoes-totais-e-15-parciais-segundo-o-governo.html

decades. Substantial urban growth occurred into hazardous locations, despite the existence of knowledge and information about both flood and landslide susceptibility. This was specially the case of informal settlements such as the most impacted area of Barra do Sahy, which is evidence for the need for policies focused on the provision of safe and affordable housing. Also, susceptibility maps did not consider the potential impacts of landslide run out. For this reason, several buildings that had been located in areas of low susceptibility were impacted by large volumes of landslide run out during the event. This suggests that a greater connection between scientific knowledge of such events and urban planning may help to prevent and mitigate such disasters in the future.

Though hard to pinpoint without a field investigation, warnings, which have the potential to reduce both structural and human impacts, might have been insufficient. The CPAs' field operation was not covered in our study, the only preparation and response action observed were the issued warnings. It is important to distinguish alerts and warnings sent internally to the early warning system from warnings sent to the population, which in turn must be short, understandable, and necessarily contain recommendations for self-provision. As reported, messages warnings sent to São Sebastião did not warn about landslides. Currently, the "Public Alerts Dissemination Interface" (IDAP) uses the Common Alerting Protocol to disseminate warnings via SMS or messaging apps (currently: Telegram and WhatsApp), but only to registered users, i.e. those who requested to receive warnings from specific municipalities. Cell broadcast, i.e. the issuing of warning to all capable mobile phones within a geographical area, obviating the need for self-registration, reaching anyone e.g. tourists in the area, is still under study in Brazil (ANATEL, 2023). Furthermore, a detailed hazard assessment that includes more precise information about landslide-triggering rainfall thresholds in the region could provide key information for increased preparedness and response.

CONCLUSIONS

Under the current conditions of exposure and vulnerability, i.e. settlement expansion in risk areas along with informal settlements, disconnection between hazards in a multi-risk condition, it is foreseeable that such an extreme hazardous event could result in a disaster. Whilst we might infer that improved crisis management could have reduced the overall disaster impact. Given that mapped susceptible areas have been known for more than a decade and was updated nine years ago, the implementation of a long-term disaster risk management plan could have alleviated the situation greatly. This event highlights the critical importance of coupled multi-risk assessments and urban planning in disaster risk reduction.

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