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DEVELOPING A SPATIOTEMPORAL MODEL TO INTEGRATE LANDSLIDE SUSCEPTIBILITY AND CRITICAL RAINFALL CONDITIONS. A PRACTICAL MODEL APPLIED TO RIO DE JANEIRO MUNICIPALITY

Pedro Lima[1], Mateo Moreno[2,6], Stefan Steger[2], Pedro Ivo Camarinha[3], Luiz Carlos Teixeira Coelho[4,5], Felipe C. Mandarino[5], Thomas Glade[1]

[1]Department of Geography and Regional Research, University of Vienna, Vienna, Austria, [2]Institute for Earth Observation, Eurac Research, Bolzano, Italy, [3]National Center for Monitoring and Early Warning of Natural Disasters (CEMADEN), Ministry of Science, Technology and Innovation of Brazil (MCTI), São José dos Campos, São Paulo, Brazil, [4]Department of Cartographic Engineering, University of Rio de Janeiro (UERJ), Rio de Janeiro, Brazil, [5]Instituto Pereira Passos, Prefeitura da Cidade do Rio de Janeiro, Brazil, [6]Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, Enschede, The Netherlands

Despite being a landscape evolution element, landslides pose a significant threat to infrastructure, property, and human life around the globe. In Brazil, this has been a major source of concern for many years. Over the last decades, especially in the humid areas of Brazil, landslide occurrences have become more frequent and catastrophic (Pelech et al., 2019). Especially in large and medium-sized cities, poorly-regulated living conditions and a progressing global warming scenario will likely increase the frequency, magnitude, and possibly damage caused by landslides (Marengo et al., 2021). On the other hand, despite the efforts of local authorities to forecast and mitigate the phenomena, not enough is currently being done in terms of preparedness for future events, especially concerning research (Dias et al., 2021).

Due to the geomorphological and climatic settings, the municipality of Rio de Janeiro (~1,200 km²) is often affected by landslides (Coelho Netto et al., 2007; 2009). According to the Brazilian Institute of Geography and Statistics (IBGE, 2021), the municipality has 6.7 million inhabitants, of which circa 20-25% lives in the favelas. These communities, usually located on hill slopes, face diverse challenges such as poor basic infrastructure, lack of sanitation systems, and high criminality, which tend to diminish the inhabitants' awareness of potential landslide hazards. On the other hand, the municipality of Rio de Janeiro has systematically tracked rainfall data for the last decades. Such data comprises 33 stations, recording measurements every 15 minutes. Rainfall data is available for a few decades and comprise 33 stations recording measurements every 15 minutes. Also, the availability of high-resolution DTM and DEM (obtained through LiDAR with a 15 cm resolution), orthoimagery updated quasi-yearly, and a suitable landslide inventory, turns Rio de Janeiro into a promising real-life laboratory for suggesting and enhancing modeling solutions that may provide valuable tools for landslide emergency preparedness, management, and response.

Building upon the findings of Steger et al, 2022, the present research represents a joint effort to suggest a methodological framework to develop a dynamic landslide model that integrates static predisposing factors with dynamic rainfall conditions. Data-driven methods (e.g., Generalized Additive Models) will be used to establish statistical relationships between the static factors, the dynamic rainfall conditions prior to a potential landslide, and the landslide occurrence in space and time. The outcomes may be used by stakeholders to strategically prepare for potential rainfall events leading to landslides and possibly to improve early warning systems. Data collection and preparation are currently happening, and the analysis will follow. Partial results will be presented at the 6th World Landslide Forum.

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Developing a spatiotemporal model to integrate landslide susceptibility and critical rainfall conditions. A practical model applied to Rio de Janeiro municipality.

Pedro Henrique Muniz Lima[1], Mateo Moreno[2,3], Stefan Steger[2], Pedro Ivo Camarinha[4], Luiz Carlos Teixeira Coelho[5,6], Felipe C. Mandarino[5], Thomas Glade[1]

[1]University of Vienna, Department of Geography and Regional Research, Vienna, Austria;
[2]Institute for Earth Observation, Eurac Research, Bozen/Bolzano, Italy;
[3]ITC Faculty Geo-Information Science and Earth Observation, Enschede, Netherlands;
[4]Centro Nacional de Monitoramento e Alertas de Desastres Naturais, Ministry of Science, Technology and Innovation of Brazil, São José dos Campos, Brazil;
[5]Instituto Municipal de Urbanismo Pereira Passos - IPP, Rio de Janeiro, Brazil;
[6]Universidade do Estado do Rio de Janeiro, Department of Cartographic Engineering, Rio de Janeiro, Brazil.

I Introduction & Study area

Rio de Janeiro municipality & landslides

- Circa **1,200Km²** and is often affected by landslides (Coelho Netto et al., 2007; 2009).
- **6.2 million inhabitants, of which 22.7% reside in favelas.** These communities are usually located at the hillslopes and often have a poor infrastructure.
- 583 of the 1664 landslides occur in Favelas.
- The **city is highly susceptible to the occurrence of landslides** due to complex geomorphological and climatic settings.
- The city is closely monitored through rainfall records (**33 stations, recording measurements every 15 minutes**). Rainfall data is freely available for a few decades.
- There is an **urgent need to increase awareness and preparedness for future events (**Dias et al., 2021).
- Especially when considering climate change scenarios, which are **expected to increase the frequency and magnitude of catastrophic events** (Pelech et al., 2019; Marengo et al., 2021).

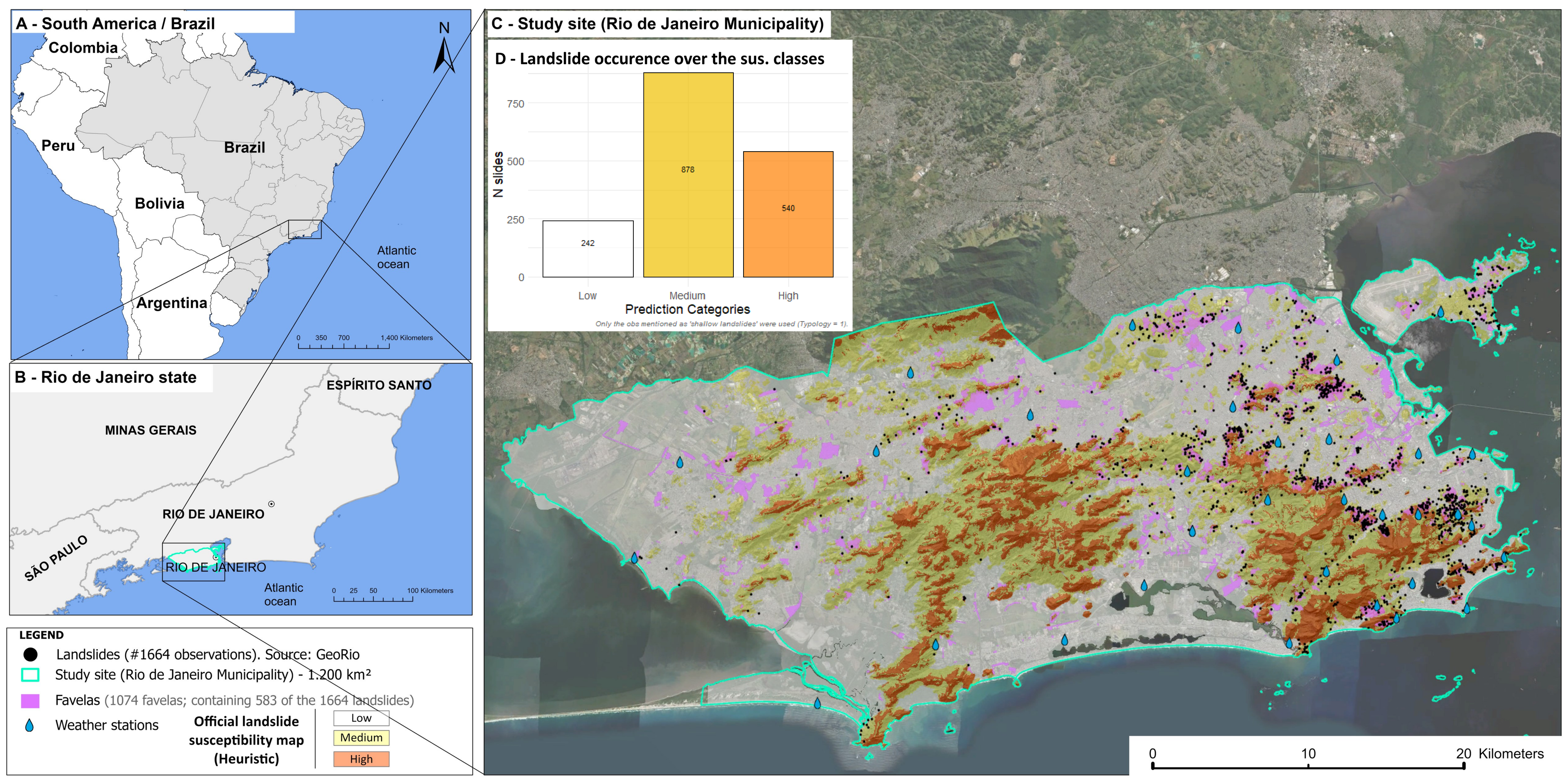

Fig. 1: Study site and official Landslide Susceptibility for Rio de Janeiro Municipality. **A)** Showcases the location of Brazil within South America, with a focus on Rio de Janeiro state. **B)** Zooms in on the state of Rio de Janeiro, highlighting its capital. **C)** Detailed satellite image of Rio de Janeiro Municipality, overlaid with data points indicating recorded landslide occurrences and the heuristic landslide susceptibility classes. The pink areas shows the distribution of informal settlements known as favelas. **D)** Landslide occurence over the susceptibility classes (https://www.data.rio/apps/PCRJ::suscetibilidade-a-deslizamentos/explore).

II Data & Methods

Landslide inventory

Fig. 2: Geotechnical occurrence report example. Source: Rio de Janeiro Geological Survey (Geo-Rio).

Table 1: Number of reports and actual landslides per year.

Year	Number of reports	Actual landslides	Landslides with date Information
2009	NA	2	167
2010	1080	909	408
2011	959	162	24
2012	582	80	11
2013	949	196	69
2014	542	111	6
2015	410	78	12
2016	509	123	3
Total	**5031**	**1664**	**700**

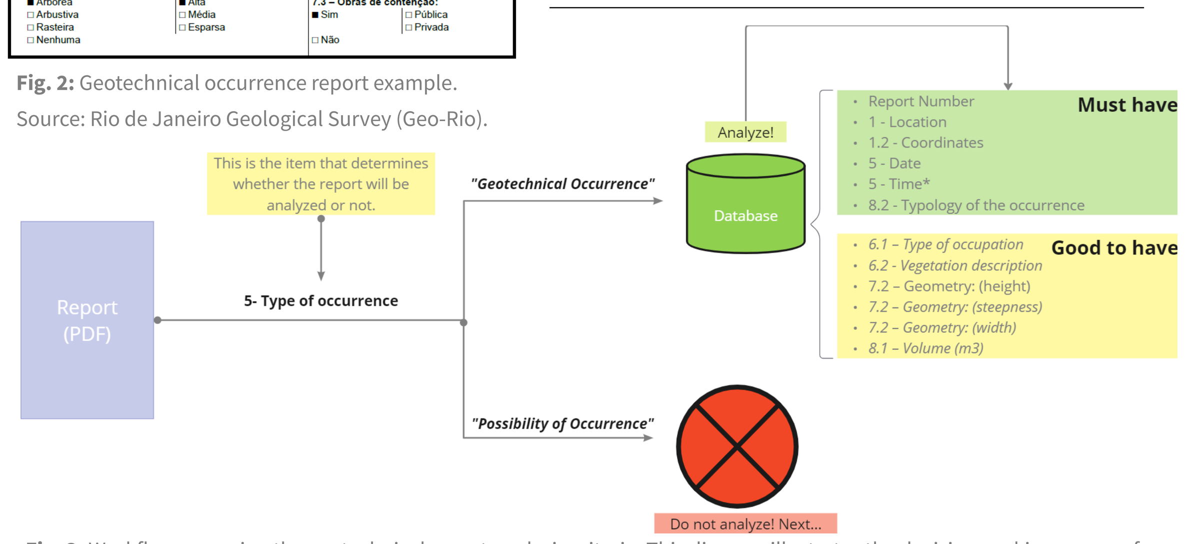

Fig. 3: Workflow assessing the geotechnical report analysis criteria. This diagram illustrates the decision-making process for the analysis of geotechnical reports based on predefined criteria.

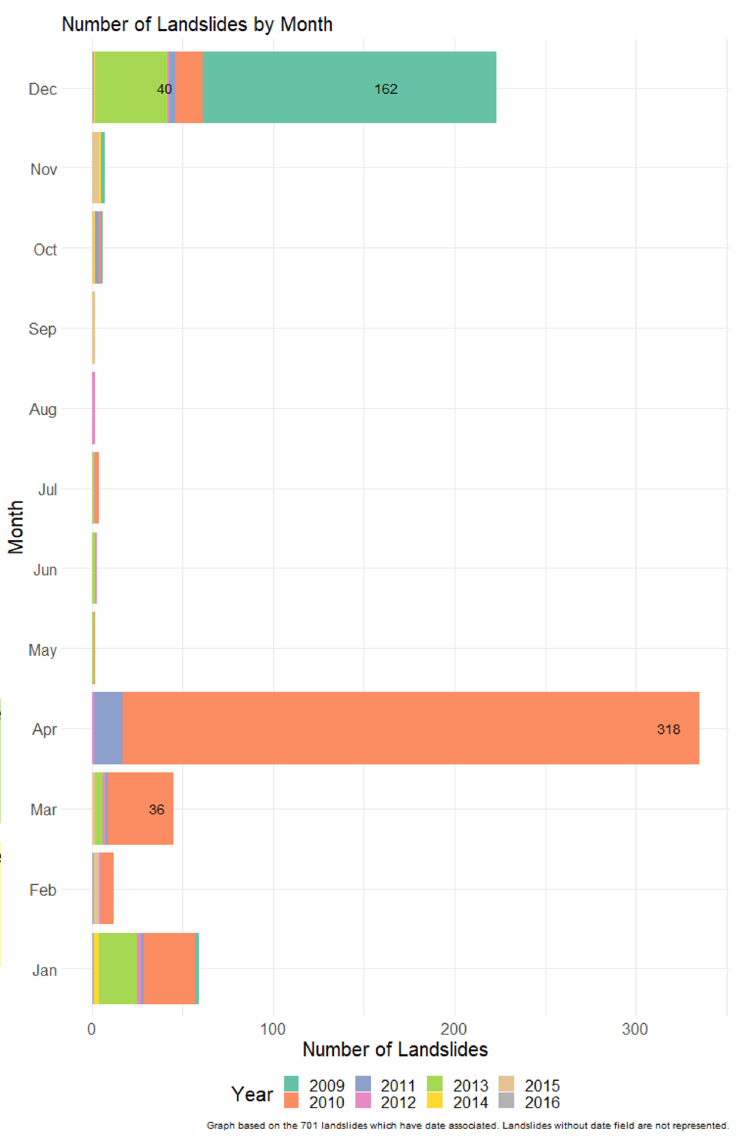

Fig. 4: Temporal (monthly) distribution of the landslides.

Summarized Work Plan

Data collection and preparation

Stage 1

Landslide inventory
- GeoRio inventory
- Coelho Netto et al. (2009), Coelho Netto et al. (2007), Silva (2000) e Negreiros et al. (2012).
- NASA global landslide inventory (Kirschbaum et al. (2015))

Predictors
- Digital Elevation Model (IPP/RJ)
- Geomorphological Variables
- Land Cover Map
- Geology
- Geomorphological map

Rainfall data
- Rainfall data, with a 15-minute temporal resolution. [Available from 1997 - 2023].

Available at: http://alertario.rio.rj.gov.br/download/dados-pluviometricos/

Modelling

Stage 2

Landslide Susceptibility Map (static map)
Statistical models and/or machine learning for the creation of spatial prediction models of landslides.

Integration with pluviometric data (dynamic map)
Identification of critical rainfall that triggered landslides and integration with the terrain susceptibility model.

Visualization of results and product availability

Stage 3

The products (static and dynamic maps) will be made available in the form of:
- Online dashboard?
- Provision of the code for modeling reproduction (e.g., GitHub).

Fig. 5: Three-stage workflow, detailing data collection, modeling techniques, and dissemination methods. Current stage: Stage 2.

III Preliminary results & perspectives

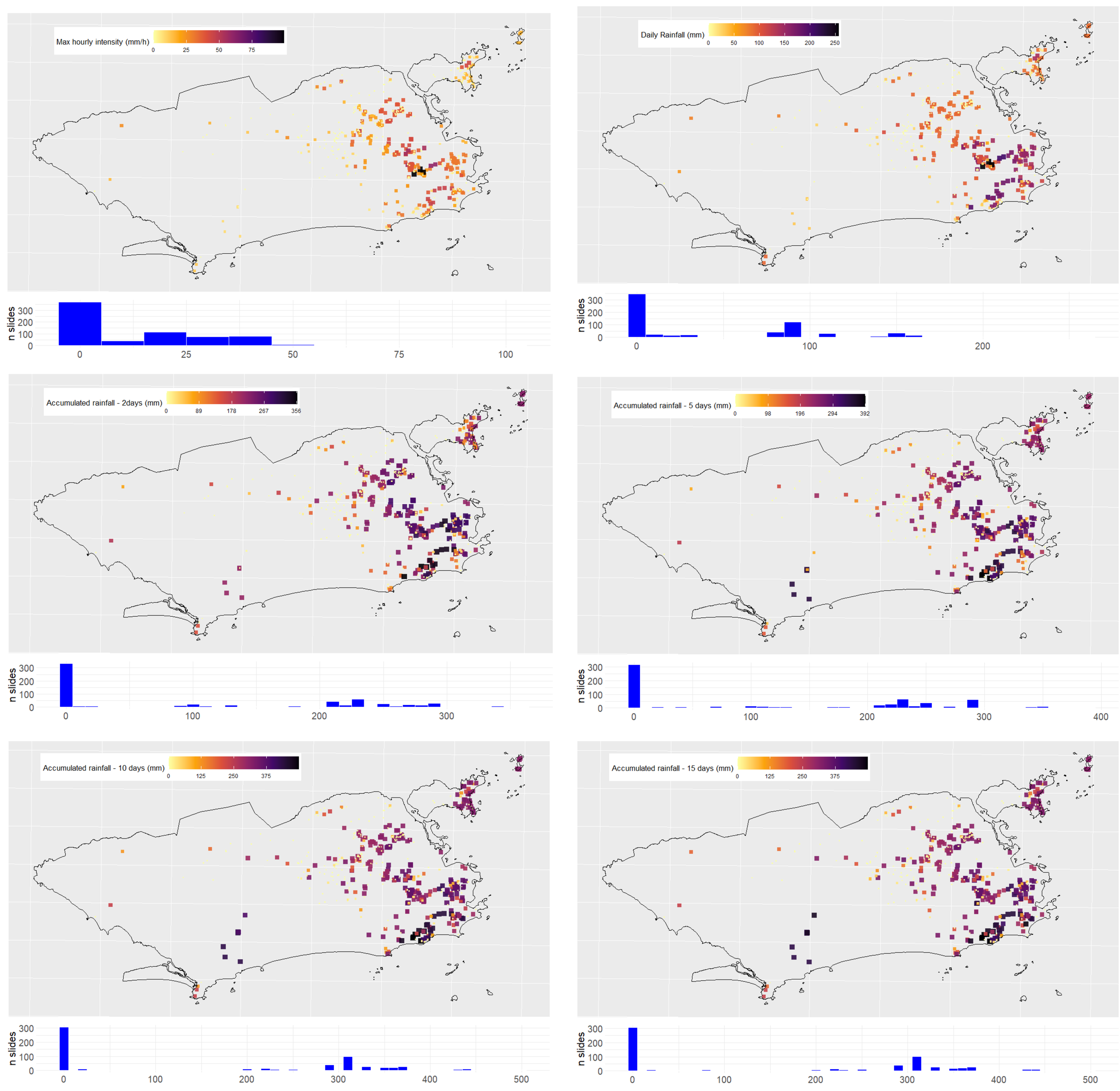

Fig. 6: Distribution and precipitation patterns related to landslides occurences (max hourly intensity, daily totals, and accumulated rainfall over 3-, 5-, and 10-day periods).

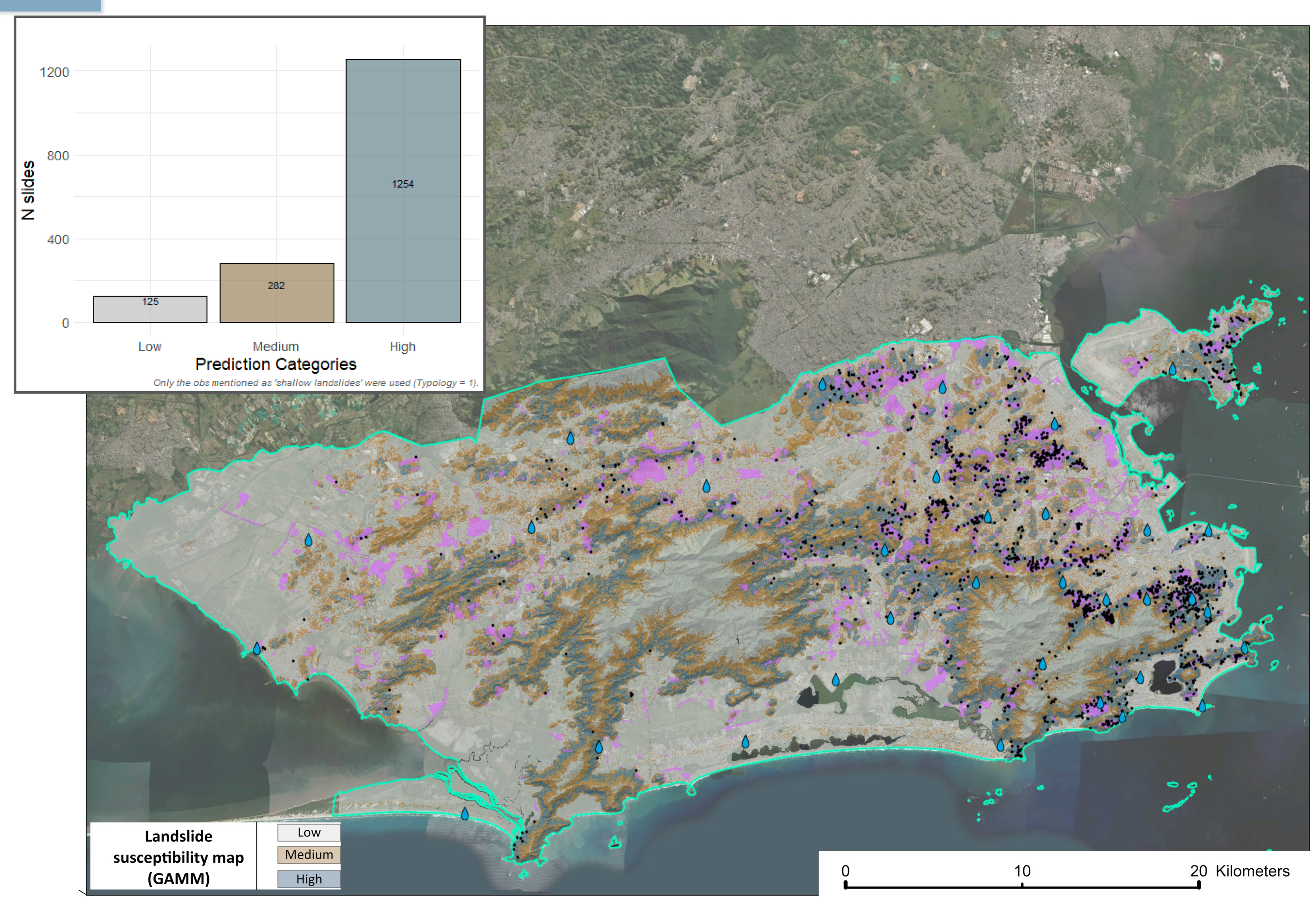

Fig. 7: Data-driven landslide susceptibility map. Model created using GAMM: *fo1 <- slide ~ s(dtm) + s(prof_curv) + s(slope) + geomorph_rec + geol_rec + fav_res* . The "*fav_res*" was introduces as a random intercept.

Moving towards...

Alternative mapping unit –> Slope unit.

Sampling strategy adaptation -> In terms of time balance and excluding non-landslide observations in trivial terrain.

Bias handling -> Mixed effects. Given the high number of occurrences (reports) in the favelas, these were added (together with the residential areas) as random intercept.

Landslide occurrences x Rainfall patterns -> Still needs to be better comprehended.

Space-time prediction -> Similar as performed in Steger et al., 2023 and Moreno et al., 2023.

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Contact
Pedro H. M. Lima
pedro.lima@univie.ac.at
Department of Geography and Regional Research
Universitätsstraße 7 | A-1010 Vienna | Austria