Comprehensive multi-hazard risk assessment in data-scarce regions. A study focused on Burundi

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Abstract. The increased occurrence of multiple cascading and compounding hazards underlines the importance of integrated- and multi-hazard-based assessment approaches for the development of thorough strategies towards disaster resilience. To this purpose, a national-scale multi-hazard risk assessment was conducted between September 2020 and December 2021 for Burundi, focusing on the natural hazards flooding, torrential rains, landslides, earthquakes, and strong winds. This integrated multi-hazard assessment resulted in comparable nationwide provincial and commune-scale Annual Average Loss (AAL) values, further aggregated to provide a preliminary estimate of the resulting overall risk. Historical climatology (1990-2019) was computed, and a preliminary evaluation of the potential effects of climate change in the future period (2020-2049) was carried out. Data availability and reliability were challenging throughout the whole assessment and were tackled by integrating local authoritative sources with international and global resources. An up-to-date exposure model was implemented and complemented by an indicator-based socioeconomic vulnerability assessment. Furthermore, a data-driven statistical susceptibility model for shallow landslides has been derived at national scale. The consequent multi-hazard risk assessment provides an approximate picture of the expected nationwide risk distribution in economic terms. The results should support the identification of priority areas and actions for disaster risk management.

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...the authors propose a research that aims to tackle a lot of issues on different
hazards, their vulnerability, and climate change related aspects. This is a very ambitious work.
However, lack of (i) methodological justification, (ii) use of local knowledge, (iii) discussion with
respect to previous work, and (iv) absence of state of the art literature are factors that weakens the quality of this work. In addition, the research shows a lack a connection with its assume target audience. Per say, that is an point that one could understand, especially with respect to the constraint of going in the field (COVID restriction) and connecting with the local experts and institutions. Nevertheless, one would then have assumed a more elaborate discussion on those aspects.

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The references of Paul et al., (2022); and Paul and Silva, (2025) are missing. are missing. These
studies contain valuable references that should be contrasted with the authors' findings.
There has been no thorough bibliographic revision concerning multi-hazard risk. I fully agree
with Reviewer 1 on this point.

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Jess - check references

REVIEWER COMMENTS ON STRUCTURE AND LANGUAGE

1 Introduction

'Understanding disaster risk' is the first of the four 'priorities of action' of the Sendai Framework for Disaster Risk Reduction 2015-2030. This priority emphasises that "policies and practices for disaster risk management should be based on an understanding of disaster risk in all its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment." (UNISDR, 2015). Hazard risk assessments are a crucial component leading to an understanding of disaster risk and generating knowledge required for disaster risk reduction

(European Commission. Joint Research Centre., 2021). The increased occurrence of multiple cascading and compounding hazards underlines the importance of integrated and multi-hazard-based assessment approaches for the development of thorough strategies towards disaster resilience (Choi et al., 2021; Schneiderbauer et al., 2017; Zebisch et al., 2023). The scientific community has increasingly invested in research to untangle the interactions and cascades between different hazards (Owolabi and Sajjad, 2023) considering their interdependencies, spatial and temporal overlaps, and compounding effects, also challenging conventional assessment approaches and demanding more sophisticated models and interdisciplinary collaboration, with notable applications (e.g., Stalhandske et al., 2024; Ward et al., 2020) also fuelled by the soaring consequences of global warming (IPCC, 2022). Despite these advances, translating this understanding into actionable, integrated risk assessments poses its own set of obstacles (Kappes et al., 2012), and multi-hazard risk analysis remains fraught with important challenges, particularly from the perspective of local and regional stakeholders (Rözer et al., 2023; Šakić Trogrlić et al., 2024). At the same time, a consistent analysis of risk arising from multiple hazards on an assumption of

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Considering the final results the paper intends to convey, the structure of the submitted manuscript requires revision. Numerous sub-sections lack sufficient detail (e.g., the approaches followed for hazard-specific vulnerabilities) and surface late in the document. It would be beneficial to consolidate sections by creating "chunks" for each hazard-related physical risk.
This means having risk as a header, with hazard and physical vulnerabilities (the adopted methods) presented together. Such an organization would harmonize text that currently mixes these components (e.g., lines 173-175 & 235-240) in the "Hazard" section, while exposure and social vulnerability could be presented separately.

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The current arrangement of having discussion as Section 9 (after Section 8: Results) and then Section 10 on 'Climate Change' is not appealing. I advise revising this structure

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The SEVA and Climate Change analyses were not integrated into the final results and therefore feel distracting. I suggest either completely removing them or presenting them as an Appendix, treating them as auxiliary an ... [1]

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Commented [MP12R11]: As stated in the conclusions, due to the short timeframe of the project and its extensive requiremen ... [7]

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independence in an integrated and comparable framework is often missing, while this provides a pragmatic and useful baseline upon which to base more sophisticated approaches tackling cascade and compound effects. A major difficulty lies in the scarcity and variability of reliable data, particularly in regions where record-keeping and technological infrastructure are limited. Discrepancies between datasets from various sources, and the absence of consistent, long-term observational records, can introduce significant uncertainty into hazard assessments. Efforts to harmonise data or work with proxies only partially offset these limitations, often requiring careful methodological adaptation and transparency regarding the resulting uncertainties (Gallina et al., 2016). Moreover, institutional and resource constraints can hinder the implementation of comprehensive risk analyses and management strategies. In many settings, especially where capacity is developing, integrated assessments must be designed not only to be scientifically robust but also operationally feasible and directly relevant to policymakers (Cocuccioni et al., 2022). As such, initial assessments often serve as a baseline to be incrementally refined as better data and expertise and models become available.

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Furthermore, a critical challenge in advancing Disaster Risk Management (DRM) lies in the establishment of robust, context-sensitive risk metrics that extend beyond the quantification of physical damages. Metrics based solely on recorded fatalities further underrepresent the true burden of disasters, as accurate fatality data may be scarce, inconsistently reported, or insensitive to chronic, low-impact events that cumulatively erode well-being. Moreover, the spectrum of hazards relevant to DRM manifests over contrasting temporal and spatial scales: floods and landslides for instance are significantly more frequent than earthquakes, albeit potentially less damaging. Economic losses offer an essential perspective, although they tend to omit critical dimensions such as disruption of livelihoods and long-term community resilience. Therefore, the development and adoption of comprehensive, DRM-friendly metrics—capable of reflecting not only direct but also indirect losses, and sensitive to the diverse temporal dynamics of hazards—are fundamental to effective risk prioritisation, resource allocation, and the promotion of holistic disaster resilience strategies. The 2015 Global Assessment Report on Disaster Risk Reduction (GAR[1]) , for instance, adopted an approach based on probabilistic multi-hazard risk assessment using the Average Annual Loss (AAL) metrics to provide analytical results and achieve comparability across different types of phenomena (UNISDR, 2015). A more qualitative approach based on the use of a composite index has been followed instead to identify countries at risk from humanitarian emergencies and disasters that could overwhelm current national response capacity (European Commission. Joint Research Centre., 2017). The activities presented here were funded by the International Organization for Migration (IOM) in the context of a larger European Union development program focused on Disaster Risk Reduction (DRR), with the aim of conducting a multi-hazard assessment and risk mapping of all 18 provinces and 119 communes of Burundi, with a more refined focus on five particularly vulnerable localities in the country. The five hazards prioritized by IOM and local authorities were flooding, torrential rains, landslides, earthquakes and strong winds.

[1] https://www.undrr.org/gar

The results of the assessment were aimed at decision makers, civil protection authorities and other stakeholders at national and sub-national levels to support planning, decision-making and prioritisation of Disaster Risk Management (DRM) investments and activities. Local experts and scientists were also involved to discuss specific topics and potential contributions.

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As stated in lines 40-42: "The results of the assessment were aimed at decision makers, civil protection authorities and other stakeholders at national and sub-national levels to support planning, decision-making and prioritisation of Disaster Risk Management (DRM) investments and activities.", the motivation of this research is to provide assessments for a specific audience. In that context, I find it a bit strange that the involvement of researchers from local institution is not considered. Usually, as expert, we are usually pleased to be invited to take part to a research were we can bring our own expertise. That would also have been a better strategy to try to overcome this gap between science and policy where the stakeholders are usually barely listened (Gill et al., 2021). Local scientists are certainly better at making stakeholders aware of the problems of natural hazards.

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The paper appears to be more of a project report rather than a scientific manuscript, evident from its general structure and specific phrasing (e.g., lines 36, 43, 352, etc.). The scope of the study seems directed towards a specific audience, distinct from the scientific community, which is acceptable.
However, the basics of the various methodologies and assumptions should be clearly stated, even if only in a supplementary section.
Below are some related suggestions

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The multi-hazard risk assessment was conducted between September 2020 and December 2021. It faced multiple challenges and disruptions related to the COVID-19 pandemic, including travel restrictions and staff illness. A significant limitation was the lack of availability of observed data and the lack of reliability of some datasets (Campalani et al., 2023). Concerns regarding the reliability of datasets stemmed from discrepancies between similar datasets collected from different international sources. These data and research gaps necessitated an assessment approach based on proxies with the aim of providing an approximate nationwide disaster impact distribution, which was applied for torrential rains, strong winds and landslides. This integrated multi-hazard assessment resulted in comparable nationwide provincial and commune-scale Annual Average Loss (AAL) values for the five hazards under consideration.

Several scientific studies have studied natural hazards in Burundi (Delvaux et al., 2017; e.g., Jacobs et al., 2018; Monsieurs et al., 2019; Nsabimana et al., 2023), while seismic risk has been also assessed probabilistically within a continental scale model (Paul and Silva, 2025). Most of these contributions focus on specific combinations of hazards and regions or locations. The Global Assessment Report (GAR) in 2015 provided a multi-hazard risk assessment of the Burundi within a global assessment (UNDRR, 2015). This manuscript describes to our best knowledge the only other study to provide a specific multi-hazard risk assessment at country level for Burundi, which has implied overcoming several challenges. Furthermore, this is the first study that also assessed risk related to landslides and strong winds in monetary terms for the sake of comparability with the other hazards. To characterise the current climatology and explore the possible effects of climate change in a near future, both a historical climate (1990-2019) and climate change modelling (considering future period between 2020-2049) were completed. The latter focused on precipitation and winds and included three different climate change simulations performed at 3 km spatial resolution for Burundi considering a business-as-usual RCP8.5 (Representative Concentration Pathways) emission scenario.

This paper presents the methodologies applied in conducting a national, integrated multi-hazard risk assessment in a data scarce environment and aims at supporting Disaster Risk Management (DRM) actors (e.g. national and provincial government, IOM) in prioritising actions and fundings. This implied significant assumptions and simplifications, as discussed later on, but also provided a first baseline for the local authorities to foster disaster management actions, and for the scientific community a preliminary baseline upon which to build better informed models as more technological and DRM capacity becomes available in the country and better disaster impact records are collected. The description of implemented activities and results can support scientists and practitioners in identifying efficient approaches in similarly data-scarce environments and to best meet stakeholder expectations in pragmatic operational frameworks. In the next sections a brief introduction to the case study is provided, followed by the methodological descriptions. Two subsequent sections present and discuss the most relevant results. Before summarising the conclusions and a potential outlook, an additional section describes the activities related to climate change.

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2 Study area

Burundi is one of the smallest and most densely populated countries in central-eastern Africa. Of its 27,834 km2 about 2,000 km2 are occupied by Lake Tanganyika, in the west of the country. It shares borders with Rwanda, Tanzania and the Democratic Republic of Congo. It is divided administratively into 18 provinces and 119 communes which are in turn divided into collines (literally, hills, in French). The economic capital is Bujumbura in the west of the country and political capital Gitega in its centre. The country shows a varied relief with altitudes that range from 774 masl at the northern border of Lake Tanganyika to 2,670 masl of the highest peaks of the Congo-Nile Mountain chain that divides the country north-south. The country is subdivided in five eco-climatic regions (from west to east): the lowlands of the Imbo plain bordering the Tangan which corresponds to an extension basin of the western Rift Valley; the rugged region of Mumirwa; the mountainous range (Congo-Nile Mountain chain); the central plains and the Kumoso; and Bugesera lowlands (Figure 1). Figure 1 also shows the hotspot areas for which more detailed risk assessments for some of the hazards were conducted.

The North Tanganyika-Kivu Rift region, located in the western branch of the East African Rift is characterized by active continental rifting. This rifting process has a rate of ca. 2 mm $year^{-1}$ which though the associated tectonic uplift has formed a rejuvenated landscape enclosing Lake Kivu and Lake Tanganyika. The steep terrain is associated with frequent landslides, mainly caused by rainfall linked to the tropical climate and the orography (Dewitte et al., 2021; Kubwimana et al., 2021). The landslide activity is partly controlled by uplift-driven landscape rejuvenation (Depicker et al., 2021, Depicker et al., 2021a; Kubwimana et al., 2021) and affected by seismic activity. This region plays a critical role in shaping natural hazards in Burundi, as its tectonic activity and varied topography contribute to the prevalence of earthquakes, landslides, and localized flooding across the affected areas.

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The description of the study area remains very basic. One could have expected for example that reference to the rifting context is mentioned. Rifting is associated with the presence of faults and differences in relief, which has implication for earthquake hazard, local climate, and, as said earlier, landslide hazard.

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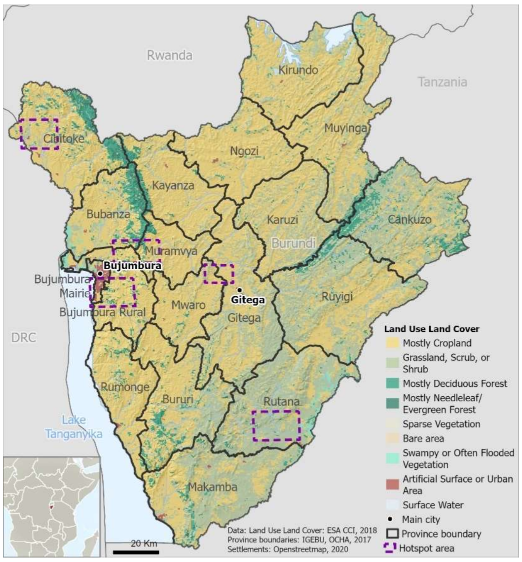

Figure 1 Map showing Burundi its topography, administrative divisions at province level and

The economy of Burundi relies heavily on the agricultural sector, where, despite the scarcity of arable land, farming is practiced by 80% of the population, mostly for subsistence. Burundi's farming system is characterised by small farm sizes, with average lots of 0.5 hectares and a high land use intensity compared to other African countries (Dixon et al., 2019; Schneiderbauer et al., 2020). Nevertheless, agricultural productivity is low and food insecurity is high.

Amongst East African countries Burundi in 2010 had the lowest (13 percent) percentage of urban population, although urbanisation is expected to increase (Dixon et al., 2019), as seen in the trend of urban sprawl in the capital Bujumbura where basic risk mitigation infrastructure such as stormwater drains are lacking (Nsabimana et al. 2023). Poverty is mainly rural and overwhelmingly affects small farmers, who lack technical skills, equipment, and financial capital. Approximately 1.7 million people were in need of humanitarian assistance in 2020 (OCHA, 2020). Investment in public services has not kept pace with rapid demographic growth, which is placing increasing pressure on resources and services such as healthcare and schools (ISTEEBU, 2017). Burundi in 2020 had a projected total population of around 11 million, a density of 442 inhabitants per km2 and a growth rate of 2.23 % in 2019 (ISTEEBU, 2013). Natural hazards and their impacts are the primary driver of human displacement in Burundi, with more than 80% caused by what is described by IOM as 'natural disasters' (IOM, 2020).

2.1 National DRR data context

According to the EM-DAT disaster data platform around 60 disaster events (with at least ten deaths or 100 affected people) occurred between 1997 to 2020, 38 of which corresponded to the five hazards considered in this study (flooding, torrential rains, landslides, earthquakes and violent winds). The remaining events were associated predominantly with epidemic events and droughts. The reported number of deaths was collectively around 300 with approximately 230,000 affected people. Overall, torrential rains and floods contribute most to these figures followed by strong winds. Most of the meteorologically triggered hazards occur along the western provinces of the country, those that drain towards the Tanganyika Lake from north to south, although relevant disasters have been also reported across the eastern provinces of the country. The area is also subject to landslides, usually triggered by intense precipitation, as well as earthquakes.

To complement these data with locally updated records, IOM´s Displacement Tracking Matrix (DTM) platform began the systematic collection of disaster impact data in 2018. According to this database, during the 2018-2021 period around 9,500 houses were totally or partially destroyed and more than 40,000 houses were affected by different disasters. Additionally, around 130 casualties or missing people were reported, as well as around 215,000 affected and nearly 80,000 displaced people. The discrepancies between these two datasets (EM-DAT and DTM) are illustrative of the difficulty encountered by the study team in understanding the overall historic context of natural hazards and disaster impacts in Burundi.

EM-DAT provides a broad, longer-term overview of major disasters in Burundi but lacks detail for smaller or more frequent hazards like localised floods. In contrast, the IOM DTM captures more granular, recent data on displacement caused by hazards but lacks the temporal depth and may omit non-displacement impacts (Table 1).

Table 1 Comparison of disaster impact data characteristics between EM-DAT and the IOM Displacement Tracking Matrix (DTM) in Burundi

	EM-DAT	**IOM DTM**
Scope of Data	National-level disaster events (≥10 fatalities, ≥100 affected, or state of emergency)	Sub-national data focusing on population displacement, infrastructure damage, and localised hazards
Hazards covered	Primarily large-scale events: flood, storm, landslide, drought	Frequent reporting on localised floods, landslides, displacement triggers
Temporal coverage	1978–present (for Burundi), with variable completeness, better from 1980s onward	Data collected since 2018 in Burundi (irregular updates)
Impact metrics	Deaths, injuries, displaced, economic losses (but often incomplete)	Primarily displacement figures, some infrastructure damage, qualitative insights
Spatial resolution	National or provincial	Colline and commune levels
Known gaps	Underreporting of localised or slow-onset events; incomplete economic loss data	Limited to displacement sites; not comprehensive for all disaster-affected areas

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The DRR context remains very general, relying on EM-DAT disaster data, a database that is
known to come with some caveats. No reference is made to the local knowledge about the
hazard (see earlier comments and the non-exhaustive list of references provided at the end of my comments).

Commented [MP25R24]: EM-DAT is certainly limited but has been mentioned as a global source of impact data. As mentioned below, local data and information has been provided by the local IOM office through the DT Matrix. The local IOM office employs local experts and therefore could provide more contextualized information.

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Section 2.1, Line 93: Include the threshold criteria used in EM-DAT to determine what disaster events are recorded.

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Section 2.1, Line 93: To aid the reader's understanding of the challenges posed by hazard data scarcity in the context of Burundi, it would be useful to include a figure or table comparing the impact data documented across EM-DAT and the IOM's Displacement Tracking Matrix (DTM) platform.

Commented [KR31R30]: We have added a comparative table (now Table 2 in the revised manuscript) that contrasts the EM-DAT and IOM Displacement Tracking Matrix (DTM) data characteristics, including their spatial and temporal coverage, granularity, and key limitations.

Strengths	Historical trend insights, international comparability	Granular, recent, and displacement-specific data

3 Methodology

The assessment methodology is presented in Figure 2**Error! Reference source not found.** The graph shows the specific workflow employed for each specific combination of hazard, exposure and vulnerability to achieve AAL-based comparable estimates. The details of the individual steps are described in the hazard-specific sections below. Since most of the considered hazards are highly influenced by climatic conditions, an analysis and modelling of the climatic driver in the historical period 1990-2019 was undertaken. A probabilistic approach was chosen to allow for the estimation of annual average loss figures for all hazards, with different return periods (RPs) selected to better capture the expected frequency/magnitude distribution of underlying processes. Whenever possible the individual risk components, namely hazard, exposure, and vulnerability, were explicitly considered and integrated. In the case of strong winds and intense precipitation a simpler approach based on empirically derived hazard/impact relationships was employed (shown in the figure in the "impact" column). For earthquakes and fluvial flooding in urban environments physical vulnerability models (fragility curves) from literature were used, while for the impact of fluvial flooding on agricultural areas and for landslides a simpler binary fragility model was used, due to a lack of consistent alternatives. National-scale models were employed in most cases, except for fluvial flooding, which was carried out in more detail in several hot-spots and later projected to other flood-prone areas in the country.

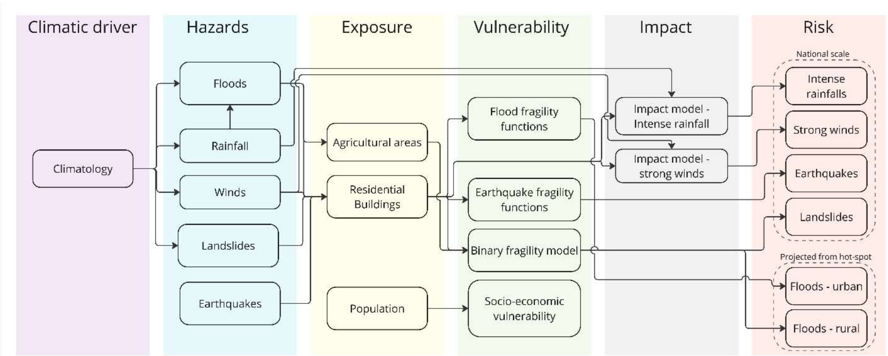

Figure 2 Conceptual diagram of the methodology applied for the multi-hazard risk assessment. The graph shows the specific workflow employed for each specific combination of hazard, exposure and vulnerability in order to achieve AAL-based comparable estimates. The details of the individual steps are described in the hazard-specific sections below.

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In addition to what I mention above about the landslide assessment, a lot of methodological steps and choices are not clearly justified and the descriptions of the methods are overall too superficial, preventing any reproducibility. Reference to the literature is very limited, hence leaving the readers with questions about the relevance and reliability about the methodological Aspects.

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Regarding damage functions for crops, the only mention is in line 115: "for the impact of fluvial flooding on agricultural areas and for landslides, a simpler binary fragility model was used due to a lack of consistent alternatives." This aspect requires more detail. What thresholds were used to determine loss? Was a hazard intensity or distance-based metric assumed for vulnerability to landslides?g

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4 Climatic drivers

The climate of Burundi varies in accordance with the diverse altitude across the country. It can be described as humid tropical and is characterised by the alternation of a rainy period from October to May and a dry season between June and September. Precipitation increases with altitude, with the lowest rates approximately 500 mm along the Rusizi river and Imbo plain, with the maximum rainfall being approximately 2,200 mm in the highest regions. The average rainfall rate across the country is around 1,270 mm. The wettest period of the year usually takes place during April, with the largest number of rainy days (between 16-26). The yearly average temperature decreases with altitude, ranging from around 15.6°C in the high northern Kayanza province to 24.1°C on the Imbo plain. The maximum average monthly temperatures coincide with the end of the dry season (September-October), whereas the lowest average monthly temperatures occur during the dry season (MEEATU, 2012). The study of climate in Burundi was based on a combination of large-area climate predictions and local downscaling techniques. Global Climate Models (GCMs) in the CMIP5 (Coupled Model Intercomparison Project 5), were adjusted to obtain more specific information at Burundi national and subnational scale, climate 'downscaling' was applied using a Regional Climate Model (RCM) called Weather Research and Forecasting (WRF) (Skamarock et al., 2008) in the version 3.9.1.1 (see section 10 for further details and a discussion on the future climate).

5 Exposure

Exposure is a key component of risk, which is at the same time very challenging to assess and often insufficiently considered by practitioners (Pittore et al., 2017). Key exposure information considered in this study includes population, residential buildings, and cultivated areas; additional information on infrastructure was also collected (see Campalani et al., 2023). The datasets used were either sourced from local expert sources or from trusted international projects and databases or derived through specific efforts by combining and processing existing datasets (as in the case of the population distribution and the characterisation of the residential building stock). Where more than one dataset was found, a comparative assessment was carried out and a recommended dataset was selected and shown on maps.

5.1 Population

Population in Burundi has grown from around 8 million people in 2008 (year of the last census: https://www.paris21.org/sites/default/files/BURUNDI-population-2008.PDF) to around 12 million people in 2019 (projection of the National Statistics office ISTEEBU, ISTEEBU, 2020). Thus, the population of Burundi can be considered highly dynamic. In order to provide a realistic representation of the current population distribution, a 100 m resolution building constrained gridded population modelled dataset was chosen over the much coarser population numbers available for the 119 communes. Two modelled population grids were analysed for quality against the available reference datasets. Based on the results of the accuracy assessment a calibration of the 100 m population modelled data was conducted. It is recommended to

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For example, for the climate drivers, no justification is made with respect to the use of the climate models to extract climate information. Why these models? Why not other products?

There is quite a lot of literature on climate product comparison (even for the region – e.g.
Camberlin et al., 2019; Nkunzimana et al., 2020); something of importance especially with
regard to the specific climate variables that are to be used for the hazard assessments.

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5.1 Intense rainfalls and strong winds¶
The analysis of frequency and intensity of torrential rains and strong winds were assessed through the calculation of Intensity-Duration-Frequency (IDF) curves, which relate to the recurrency of a certain type of event (frequency), with a given intensity and duration. ¶
The selection of extreme events intensity was implemented using the Peak-Over-Threshold (POT) method which considers all measurement above a chosen threshold. The 99th percentile

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use the calibrated high resolution population grid sourced from WorldPop[2] (Stevens et al., 2015) as a representation of population exposure. The maps in Figure 3 show the population and building distribution. The spatially explicit population model has been used to better constrain the total count and distribution of residential buildings, as detailed in the following, but could be used to also quantify the potential impacts on health and well-being.

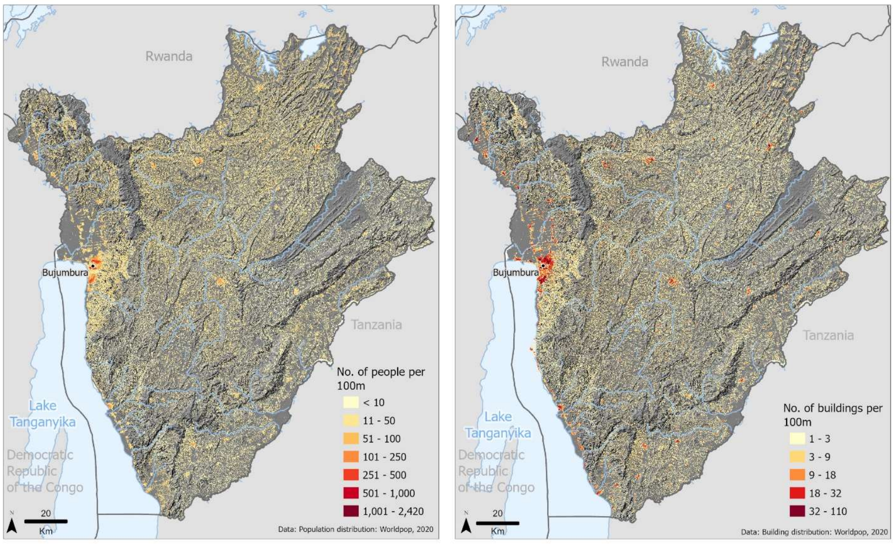

Figure 3 Left: Burundi: distribution of population. Right: Burundi: distribution of residential buildings (number of buildings in a 100m x 100m square cell).

5.2 Residential building stock

Given that no reliable nationwide building type distribution data was available from national institutions, an indirect projection approach was implemented. The process for establishing the number of buildings, their constructive taxonomies and projected distribution at commune scale was implemented based on the following three information sources: 1) IOM's Displacement Tracking Matrix (DTM) colline-scale building screening survey dataset (2020) covering 602 collines and providing approximate construction type distribution estimates and building occupation rates; 2) Global Earthquake Model (GEM) Foundation database (Silva et al. 2018) which provided a province scale validated inventory of building taxonomies (Brzev et al., 2013) and; 3) field visits, during which a general building diversity scheme was set up based on material types and assumed structure.

[2] https://hub.worldpop.org/geodata/summary?id=49676

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Deleted: Left: Burundi: distribution of population. Right: Burundi: distribution of residential buildings (number of buildings in a 100m x 100m square cell).

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The manuscript does not provide the spatial distribution of repair costs for residential buildings and crop values, nor does it include this information in a figure or table, or detail its derivation.
This is crucial considering that a key result is the assessment of the Annual Average Loss
(AAL). One option might be to include another subplot in Fig. 7 showcasing these repair cost values.l

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References style: The footnote 1 (line 288) is not a correct citation. Please note that in that
website, the citation suggested is mentioned.

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The data was processed as follows: first, the GEM taxonomy construction types were aggregated in accordance with the different vulnerability curves available for the different hazards focusing on a limited number of structural types. Secondly the DTM survey data were reviewed and aggregated by wall type. In total four wall type groups were defined: mud, bamboo/wood, adobe and brick/concrete. Lastly the GEM and DTM building types were merged resulting in the 10 baseline taxonomies. The number of buildings per commune was calculated by combining the occupation rates and the total number of buildings scaled by the population distribution. For validation the results were compared with projections for 2019 of the 2008 census-based GEM data resulting in a good match. While a statistical comparison was not feasible due to data constraints, the spatial patterns and distribution proportions showed consistency with the projections and field observations, supporting the plausibility of the estimated building stock distribution. Finally, the commune-scale building type distribution data was represented in pie-distribution charts as shown in for the provinces of Bujumbura Mairie and Cibitoke (see Figure 4). Figure 4 shows illustrative examples of the resulting proportional building taxonomies distribution in the collines of Bujumbura Marie and Cibitoke.

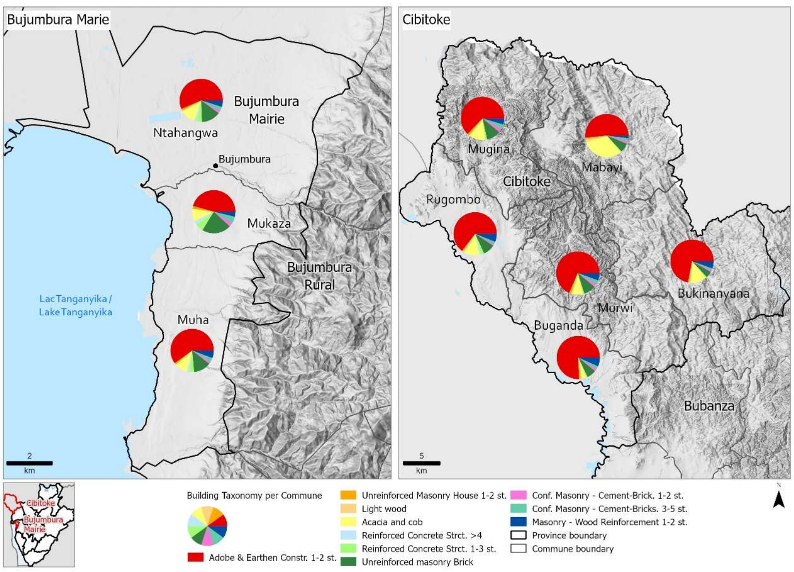

Figure 4 Burundi: Maps of commune-scale building taxonomies distribution maps of Bujumbura Marie (left) and Cibitoke (right) provinces (Data sources: administrative boundaries: ISTEEBU, 2017).

The main structural types of residential buildings are listed in Annex 2. The resulting national-scale exposure model is also provided as additional material.

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Line 292 states that GEM taxonomy Version 2.0 is focused entirely on seismic vulnerability applications, including various attributes. This statement is inaccurate. For Fig. 8, only material and number of stories were included in the ten baseline classes. The authors claim that GEM and DTM building types were merged, but the basis for this is unclear. How was this validation conducted? If a test was performed, why not present it as supplementary information?

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Section 6.2, Line 298: Quantify this "good match" between the results and the projections for 2019.

Commented [KR94R93]: Inserted a sentence here and a response in the Excel.

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n line 299, the phrase "finally..." implies that the presentation of the figure in pie charts is part of the methodology. This is misleading, as it represents merely a selected format of presentation

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5.3 Cultivated areas

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With the largest proportion of Burundian people's livelihoods depending on income from agriculture, land used for farming, i.e. cropland, is an essential asset potentially exposed to natural hazards and particularly to riverine flooding. Again, information on the distribution of agriculturally used land was not available from Burundian institutions. More than 60 % of Burundi is covered by cropland. Several land use classification products derived from very high-resolution satellites were analysed for accuracy. The mostly visual accuracy assessment found the 100m landcover map for 2019 derived from Sentinel 2 satellite imagery best represented land cover in Burundi. In the absence of detailed ground-truth data for Burundi, we performed a visual cross-validation of these products against high-resolution imagery (e.g., Google Earth, Sentinel-2 composites). Pre-processing included the extraction of all the pixels classified as cropland and presenting this information in a cropland distribution per colline map (Figure 5).

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Section 6.3, Lines 308-310: Is there a method of validating this "mostly visual accuracy assessment"?

Commented [KR99R98]: we relied on a visual cross-comparison with available high-resolution imagery (e.g., Google Earth, Sentinel-2 composites)

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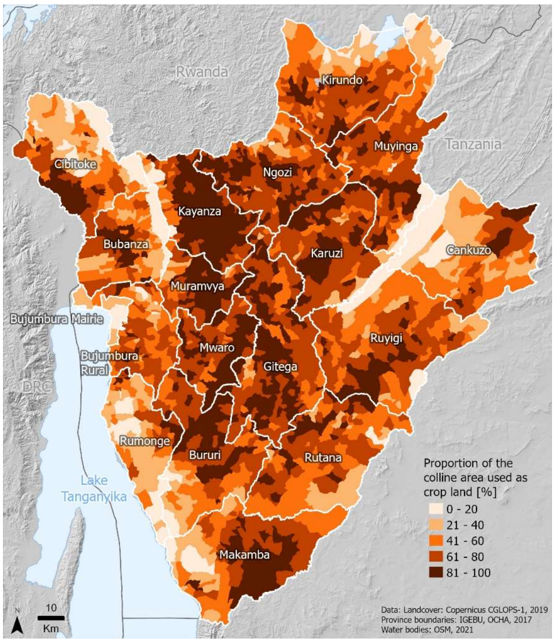

Figure 5 Burundi: Map showing the density of cropland per colline.

Since specific information on how the different types of crops are spatially distributed was lacking, an average crop value of 1'450 USD/Ha was estimated considering the main crops to be found based on information from FAO and other international sources, and their relative intensity and market value, as described in the Annex 2. This modelling approach focuses on lowland regions close to the rivers, which are highly exposed to flood hazard.

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6 Single-Hazard Risk Analysis

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6.1 Intense rainfalls and strong winds

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The analysis of frequency and intensity of torrential rains and strong winds were assessed through the calculation of Intensity-Duration-Frequency (IDF) curves, which relate to the recurrency of a certain type of event (frequency), with a given intensity and duration.

The selection of extreme events intensity was implemented using the Peak-Over-Threshold (POT) method which considers all measurement above a chosen threshold. The 99th percentile of the time series was selected as threshold. The selected exceedances over the selected threshold are fit to a Generalised Pareto Distribution (GPD), which is the most appropriate distribution method for exceedances (Coles, 2001). Using POT increases the number of samples included in the analysis in comparison to other methods (such as Block Maxima) and reduces statistical uncertainties. The POT analysis provided the return levels for three return periods: 2, 10 and 50 years. It should be noted that the results show greater uncertainty the longer the return period. All the results have a spatial resolution of 3 km x 3 km according to the resolution of the models.

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Section 5.1, Line 142: Why was the 99th percentile of the time series chosen as the threshold for the Peak-Over-Threshold (POT) method?

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Torrential rains are intense precipitation events, usually from a convective nature (such as storms), that are associated with high risk of pluvial and river flooding as well as landslides. In the case of Burundi, the rainiest areas are those found at higher elevations. The fallen water flows from the mountains towards the Imbo plain. Historically, lowlands of the Imbo zone received the least rainfall per year. According to Nkunzimana et al. (2019) only 1.1% of daily precipitation from 1960 to 2010 registered in Bujumbura airport was greater than 30 mm, while 88 % of the daily precipitation was less than 5 mm.

Strong winds are classified according to the maximum speed the wind reaches in a specific time interval. They are usually associated with storms and often compounded with strong rains and can damage buildings and infrastructure. For the analysis of strong winds, the maximum wind gust was considered. The data supplied by the modelling includes the average sustained 10-minute wind speed. However, the WRF model does not directly provide information on the maximum wind gust, that is, the maximum wind speed in a time interval of 3 seconds for each time frequency considered. Therefore, to calculate the maximum gust for the country, it was approximated as the product of the average wind by a gust factor, k_{gust} (Eq. 1):

$$v_{gust} = k_{gust} \cdot v_{10-minutal} \quad (1)$$

Where k_{gust} has been set to 1.66 according to the recommendation of the World Meteorological Organization (WMO, see (Harper et al., 2010)).

Vulnerability

In literature there are no physical vulnerability models to describe the impact of strong rains on residential buildings. Therefore, based on the available past disaster records reported by the IOM DTM, nationwide rain and wind intensity-impact relationships have been developed which could be applied proxies for vulnerability (Figure 6). Given the limited amount of observed data, the rain intensity-impact relationship was linearly extrapolated for rain intensities exceeding 60 mm/h, while the one for strong winds has been interpolated for wind gusts exceeding 60km/h.

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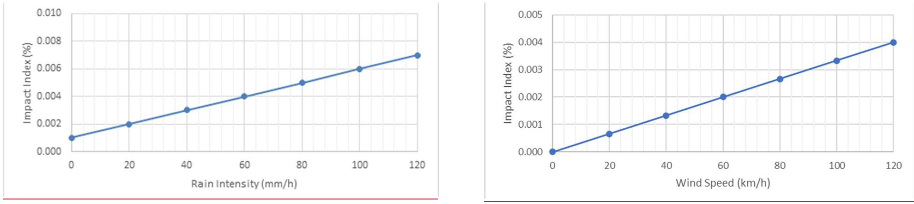

Figure 6 Estimated Intensity-Impact relationship developed for intense rainfall (left) and strong winds (right).

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Risk Analysis

The actual risk estimation process was developed following the steps described hereunder.

1. Recurrent, 2-10-50-100 and 500-year return period, weighted average commune-scale 3h-accumulated rain intensities and 2-10-50 and 100-year return period, weighted average commune-scale 10 minute-aggregated wind speeds were crossed with the commune estimates of adobe, wood and wattle and daub building taxonomies distributions. Each building unit is associate to a fixed value of USD 1,000.

3. For the return periods indicated, the exposed value in each commune was aggregated to the vulnerability index, in accordance with the rain intensity ranges 10-30, 30-50, 50-70, 70-90, 90-110 and 110-130 mm/3hr for intense rainfall and 10-30, 30-50, 50-70, 70-90, 90-110 and 110-130 Km/hr for strong winds. The vulnerability index values that were applied were those associated to the mid-range values of the indicated ranges according to the estimaed intensity-impact relationships.

4. the risk was estimated for each commune and recurrence period. Additionally, the nationwide risk was calculated by the sum of the 119 partial commune risk estimates. The comprehensive nationwide scale risk ratings for each of the five return periods is also defined as the *Probable Maximum Loss* (PML) for the specific return period. Based on the

estimated PML data for the different return periods, the associated *Loss Exceedance Curve* graphs were prepared and the *Average Annual Loss* (AAL) was calculated

6.2 Fluvial flooding

A national scale flood hazard map for Burundi was generated by combining historical and geomorphological approaches. The method consisted of three steps: (1) collection of historical information and data related to flood in the region; (2) preliminary analysis of flood frequency, magnitude and related impact from available information; (3) definition of possibly highly susceptible areas at national scale. Complementarily, (4) geomorphological analyses based on digital terrain model were carried out in those flood-prone areas that were insufficiently covered by the historical flood information. Based on the input provided by local experts, flood plains and other relatively flat areas along river courses were considered as flood prone areas regardless of the lack of flood records in those specific areas.

Information on 64 flood events that occurred between 2000 and 2020 was collected and analysed, collected from international databases from European Commission, Flood List, Darmouth Flood Observatory, International Committee of Red Cross, Global Flood Modelling and Earth Engine. An exploratory data analysis at province level indicated that the highest number of registered flood events were concentrated in the western regions of the country, in the basins that drain to Tanganyika Lake. Almost 40% of the flood events were recorded in the provinces Bujumbura Marie (19%) and Bujumbura Rural (20%) while the provinces of Bubanza (8%) and Cibitoke (10%) also show a relatively high flood proneness. According to available information since the year 2000, flooding damaged around 500,000 homes, directly affected 400,000 people and displaced 600,000 people (displaced people are not included in the affected people group).

Percentile bootstrapping was applied to define high probability flooding areas associated to each flood event included in the database. A preliminary map depicting the estimated flood hazard proneness areas was then developed.

Historic information related to spatially explicit data on rivers classified by their importance (i.e., hierarchy) and proximity to populated areas were used to identify watercourses to be studied in further detail. Topographical stream analyses based on a 10 m digital terrain model allowed the extraction of streams with a hydraulic order higher than 3 for subsequent analyses. In addition to all 3rd order streams within Burundi, smaller streams were also included in cases where the historical data depicted a past flood event.

Finally, the flood proneness map was refined on specific locations that were not adequately covered by the historical assessment due to lack of available information. Main activities entailed updating the land classification for the GIS processing of watercourses and flood-prone areas (valleys and fluvial terraces), the geomorphological assessment of riverbanks to identify erosive forms that may be indicative of historical flood events as well as the assessment of vegetation. This latter feature is

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For the flooding, another example is with this statement "geomorphological analyses based on digital terrain model were carried out in those flood-prone areas that were insufficiently covered by the historical flood information. " that is made without brining extra information. This is much too vague.

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For the pluvial flooding, the collection of the information is not explained. The authors says that they have an inventory of 64 events. How? For exemple, Monsieurs et al '2018) and Nsabimana et al. (2023) did similar work in the region bringing enough information for making sure that the method can be reproduced.

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Section 5.2, Lines 169-175: What is the source/are the sources of this information on the 64 flood events between 2000 and 2020?

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Section 5.2, Line 180: Be cautious with acronyms: here, I presume DTM refers to digital terrain model; however, you previously defined DTM in the context of the IOM's Displacement Tracking Matrix (DTM) platform in Section 2.1, Line 101.

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often related with historically flooded areas in combination with sedimentary areas along the riverbanks. The resulting national-scale fluvial flood proneness map is shown in Figure 7.

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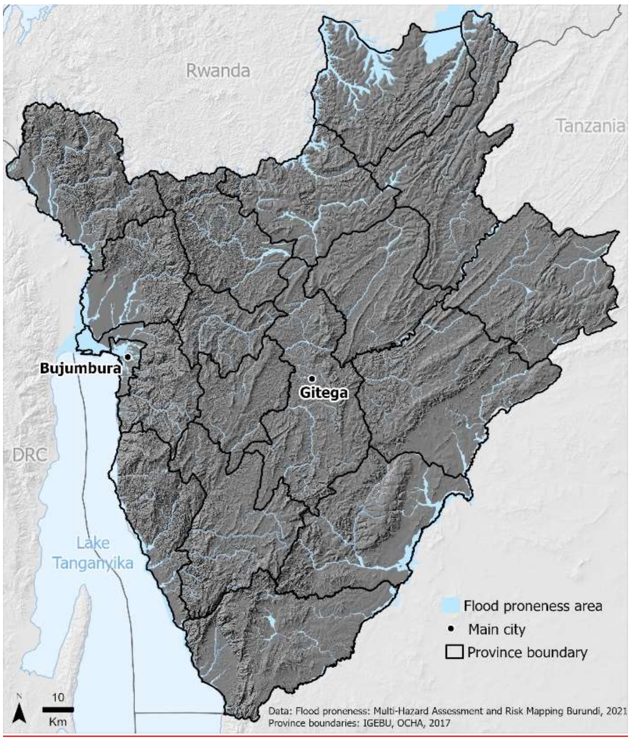

Figure 7 Burundi: National Flood Proneness Map.

The flood proneness map was used to extend the economic risk calculated for five hotspot areas to the national scale. In order to calculate these local-scale risk hotspots a standard probabilistic flood-hazard assessment method was followed. This analysis comprises two processes, first a hydrologic study of the selected catchment area to estimate the recurrent (i.e. associated to the return period) water discharge rates that can be observed at a specific point along the river stream and, second, a hydraulic modelling activity to better characterise how the different recurrent discharge rates might generate flood events within the downstream river sector. The elaboration of the hydrological precipitation-runoff model was carried out using the Hec-HMS software developed at the Hydrologic Engineering Centre (HEC) of the US Army Corps of Engineers.

Vulnerability of residential buildings

Englhardt et al. (2019) propose vulnerability curves adapted to the African context which were used to estimate the relative damage factor associated to the water depth during fluvial flood events across Burundi. This vulnerability model has been employed in an Ethiopian context with building types comparable with those observed in Burundi.

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Vulnerability of crops

As for the impacts of fluvial flooding to agricultural plots a comparable approach was applied as the one implemented for landslide risk. Hence, 100% crop loss was associated to a flood event impacting the area associated to crops in the 2019 high resolution landcover map. This mostly refers to areas in the flood plains that are dedicated to agriculture. The use of a simple binary function is justified, also out of precautionary considerations, by the uncertainty of exposure information (the specific crops are not mapped across the country) and by the consideration that physical vulnerability of crops to floods depends as much on the timing of the event (i.e., in relation to the phenological cycle) as on the specific crop type, as for instance discussed in (Molinari et al., 2019). In the highest vulnerability conditions, most crops will be expectedly destroyed with even a moderate (e.g., larger than 0.4m) flooding.

Risk Analysis

The risk estimation process followed these steps:

1. The hydrological model was employed to estimate the recurrent precipitation for five selected catchment basins, for which IDF curves for each considered return period were developed.
2. In the subsequent hydraulic study, the water levels and flow velocities reached during each rainfall event associated with a given return period were estimated.
3. A set of inundation maps was prepared for each hotspot area both for the current climate and the selected climate change scenarios. Figure 8 shows three of these maps for the 500-year return period (without considering the potential impact of climate change).

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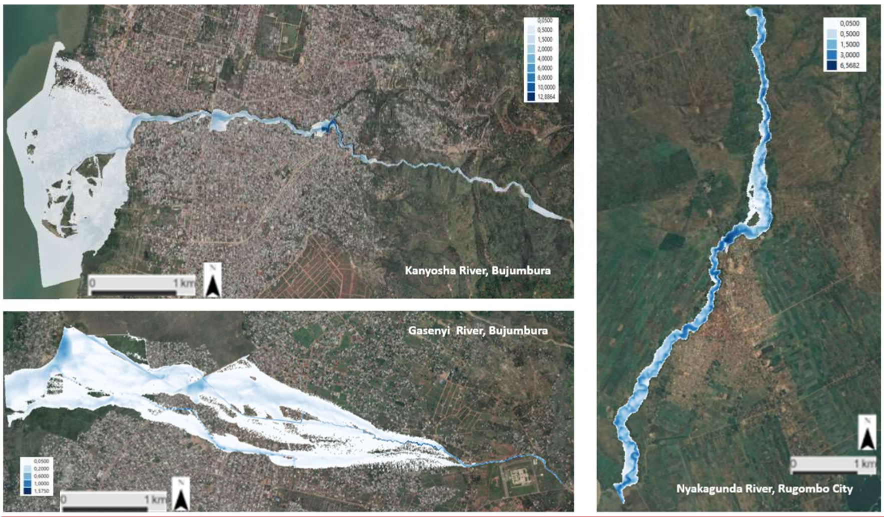

Figure 8 Burundi. Bujumbura and Rugombo: Examples of results of three of the five hotspots Burundi. Bujumbura and Rugombo: Examples of results of three of the five hotspots under study for 500-year return period scenario (© Google Earth)

6.3 Landslides

Landslides are a common process in Burundi, particularly in the area of the North Tanganyika-Kivu Rift, which is also heavily anthropized (Depicker et al., 2021a, 2024). Since a probabilistic risk-oriented landslides hazard model was not available during the project, landslides hazard at national scale was preliminarily assessed in two phases: first generating a national-scale model of landslide susceptibility and then adding a time-recurrence and an intensity-frequency models.

Landslide susceptibility was addressed using a statistical, data-driven approach known as Generalised Additive Model (GAM). A GAM accounts for non-linear relationships between landslides and different environmental factors. The landslide inventory used for building the model consisted of landslide data partly based on studies conducted by Nibigira et al., (2013) including a subset of landslide information published by Broeckx et al. (2018) reaching a total of 770 landslides. After 2020 several other inventories have been published (e.g., Deijns, 2022; Depicker et al., 2021b), which were not available in the time frame of these activities and could be employed in future assessments. The static environmental factors comprised a set of terrain derivatives (i.e. slope angle, topographic wetness index, slope aspect, curvature, relative slope position, geomorphons and terrain ruggedness) derived from the digital terrain model SRTM V4.3 and land cover maps. The resulting model was

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Once again, I am not able to put a critical eye on all the types of hazard assessment. However, when it comes to landslide assessment for which I have more knowledge, I have some concern. The analysis is based on a data-driven approach that is calibrated from an inventory of 770 landslides. The authors say that this information is from Nibigira et al. (2013 – a non peer-reviewed information that cannot be accessed) and from Broeckx et al. (2018). The PhD thesis of Nibigira (2019 - https://orbi.uliege.be/profile?uid=p125344) shows that he has mapped a total of 94 + 338 = 432 landslides over two well-constrained regions of Burundi (see page 66 of the thesis). The data by Broeckx et al. (2018) provide 204 entries for Burundi. We are therefore not having a total of 770 landslides. In addition, Broeckx et al. (2018) and Nibigira (2019) also contain deep-seated landslides. Furthermore, many entries in this dataset include mass movements associated with large gully features and with river bank erosion. These processes, in addition to not being landslides, are also strongly associated with human activities in the region (Dewitte et al., 2021; Kubwimana et al., 2021). Lastly, we shall also keep in mind that the dataset of Broeckx et al. (2018) is spatially biased towards the city of Bujumbura, where image availability and density are higher than in other parts of the country, especially at the time when the inventory was compiled (see Depicker et al., 2021a; Figure 5). The dataset of Nibigira is focused on only two regions of Burundi, which also leads to a spatial bias in the analysis.

Commented [MP114R113]: From the available inventory of Broeckx et al (2018) also events outside Burundi in geomorphologically comparable areas in Africa have been used. Overall the resulting inventory had 770 events. Limitations of this inventory have been addressed in the text according to your comment and suggestion.

Commented [mausdelve115]: Stefan Steger, Mateo quantitatively validated using k-fold cross-validation and showed good performance in correctly identifying areas prone to landslides (median area under the receiver operating curve of 0.89 after 100 model runs).

In order to explicitly consider the dynamic role of precipitation as relevant landslide triggers in the area, the average of the maximum 3-day precipitation for every month was computed and used along with the landslide susceptibility to produce landslide susceptibility maps as a function of the precipitation patterns throughout the year as shown in panels B and C in Figure 9.

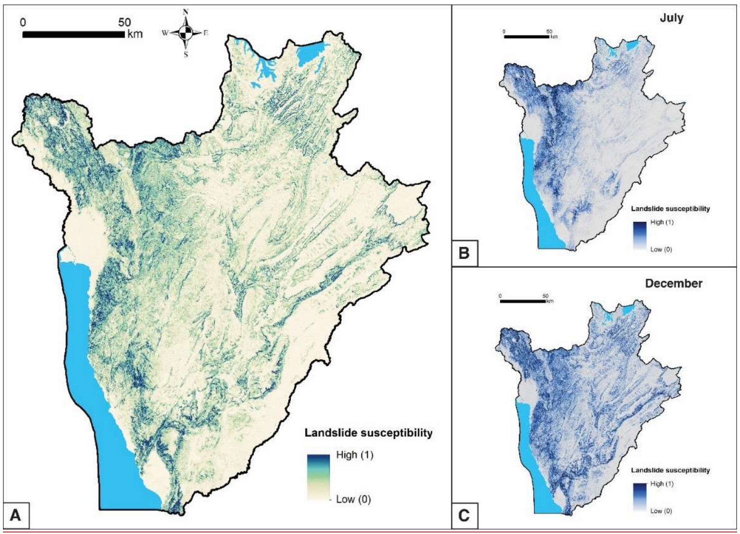

Figure 9 National landslide susceptibility for Burundi (A) and landslide susceptibility for July (B) and December (C), months with respectively low and high precipitations.

A recurrence model was produced to estimate the expected frequency of the landsliding processes at national scale to assess the landslide hazard. Due to the lack of multi-temporal information on landslide observations, a simplified recurrence model was developed using a heterogeneous Poisson Process model where the previously generated monthly landslide susceptibility drives the spatial occurrence of landslides. The model was calibrated by setting the average (expected) annual number of events to 1,000 events.

The choice of a Poisson point process was motivated by the need for a simple and flexible approach to stochastically generate large set of events with a spatially and temporally variable rate. The heterogeneous point process allows for the integration of both the susceptibility map (which indicates propensity and is not a probability) and frequency-magnitude scaling law into a model more suitable for probabilistic landslide risk assessment, albeit very simplified.

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For the temporal analysis associated with landslides, reference to existing assessments with respect to landslide mobilisation rates (Depicker et al., 2021b, 2024) and rainfall thresholds (Monsieurs et al. 2019a, 2019b) would be welcome

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Section 5.3.2, Line 228: Explain why you chose a heterogeneous Poisson Process model to address the lack of multi-temporal information in landslide observations.

Commented [MP119R118]: The use of an heterogeneous Poisson point process is mainly motivated by the need to have a consistent database of stochastic, simulated landslide events to carry out probabilistic landslide risk assessment, in a comparable way as it is done with other natural hazards (e.g., earthquakes, hurricanes). The heterogeneous PPP basically turns the susceptibility map, which is an a-dimensional measure of propensity, into a simplified dynamical model that can integrate susceptibility and frequency-magnitude features. The sentence has been expanded to improve clarity, and a reference has been added.

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Furthermore, it was necessary to characterise the distribution of event intensity, which in the case of shallow landslides can be approximated by their size in terms of spatial extent (Tanyaş et al., 2018). To achieve this, we used a power-law frequency-area distribution to identify the frequency of small landslide events with respect to larger ones. The parameters of this law were estimated by considering the existing inventory of past events, the most likely trigger (precipitation), the literature Corominas and Moya (2008) and expert judgment. were deemed representative for the subsequent risk analysis. The determination of the appropriate scaling law would require a more consistent dataset. However, it was deemed that a fixed power exponent of -2.3 was a plausible estimate. This is for instance the mean value (std dev:0.56) of a set of 27 global inventories including events triggered by rainfall, snowmelt and earthquakes described by (Van Den Eeckhaut et al., 2007) (see also Tebbens, 2020). A minimum event size of 100 m² has been chosen to exclude small events within the roll-over of the distribution.

Vulnerability

Considering the lack of fragility models compatible with the geographical setting and the use of a stochastic approach to estimate the risk, a simplified model for physical vulnerability (fragility) was adopted in the case of landslides. Residential buildings were assigned maximum damage (hence a loss equal to 100% of replacement cost) if their position fell within a given distance (equal to the radius of a circle whose area is proportional to the estimated landslide size) from the location assigned to a landslide event generated stochastically during the simulation, and zero damage (hence, a loss equal to 0) if outside. The vulnerability has been considered the same irrespective from the type of building structure, considering the variety of potential landslide-building interaction modes (Luo et al., 2023) and the significant uncertainty on the characteristics of the landsliding mechanisms (e.g., Hungr et al., 2014). This assumption, at least for the rural areas, is consistent with the findings of (Sekajugo et al., 2024) which observed a very high rate of destroyed buildings (from 71% to 95%) in landslide-affected zones in Uganda.

Risk Analysis

1. The different landslide risk components (hazard, exposure, vulnerability) described in the respective sections were integrated into a Montecarlo numerical simulation procedure framework to derive a probabilistic assessment. A set of 1,000 simulation runs were generated for each month of a year. The output consisted of a set of stochastically generated events, each with a geographical coordinate representing the landslide initiation point, and an intensity described by an area measure (in m²) assigned according to the underlying frequency-magnitude model previously described. The assigned size drives also the impacting mechanism.
2. For each simulated event the related impact and loss is estimated according to the simplified vulnerability model described above and aggregated per year of simulation and per administrative boundary (commune and province).

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Research in the region has shown that landscape rejuvenation due to the presence of migrating knickpoints associated with the rifting faults plays a major role in the distribution of the landslides. This is demonstrated at regional (Depicker et al., 2021a; 2024) and local levels (Kubwimana et al., 2021) for different types of landslides processes, whether form purely natural origin or from conditions associated with human activities (e.g. deforestation). Such influences of the rift is not even mentioned in the manuscript.

Commented [MP122R121]: This has been now mentioned in the discussion, along with the suggested references. Furthermore, need for further improvement of the models and underlying databases has been remarqued in the conclusions and outlook.

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Section 5.3.2, Line 235: What specific aspects of Corominas and Moya (2008) did you apply to determine the parameters of the power-law frequency-size distribution?

Commented [MP125R124]: The Corominas and Moya reference illustrates rater the generic approach. The determination of the appropriate scaling law would require a more consistent dataset. However, it was deemed that an exponent of -2.3 is a plausible estimate. This is for instance the mean value (std dev:0.56) of a set of 27 global inventories including events triggered by rainfall, snowmelt and earthquakes described by Van den Eeckhaut et al. (2007), while for instance inventories of earthquake triggered events shows in average a higher exponent (-2.5 according to Tanyas et al (2019), see also Tebbens (2019). A sentence has been added to the text to motivate this choice.

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Vulnerability of buildings to landslides: In line 354, what exactly does “given distance” from the location assigned to a landslide event refer to?

Commented [MP128R127]: The distance has been estimated as the radius of an hypothetical circle whose area has been assigned by sampling the Frequency-area relationship and centered on the landslide point stochastically generated by the Poisson process. A sentence has been added to clarify this in the text.

Commented [mausdelve129]: Stefan Steger Mateo

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3. The resulting data is analysed to derive, for each administrative area, a so-called loss exceeding probability (LEP) curve, which describes the probabilistic relationship between the amount of loss possibly exceeded and its probability of occurrence. the average annual loss (AAL) was obtained by numerical integration of the LEP curve.

6.4 Earthquakes

The estimation of seismic hazard followed the methodological approach known as Probabilistic Seismic Hazard Assessment (PSHA), as originally introduced by Cornell (1968) and further developed by McGuire (2004) and Kramer (1996). This widely adopted framework integrates the results of seismic source modelling, ground motion propagation, and local soil effects to assess the probability of different levels of seismic ground shaking. The expected accelerations associated with return periods of 100, 250, 475, 975 and 2,500 years (corresponding to exceedance probabilities of 40%, 18%, 10%, 5% and 2% in 50 years, respectively) were computed considering all known seismic sources within a 300 km radius zone of influence around Burundi. Instrumental data were compiled from the National Earthquake Information Center (NEIC) of the United States Geological Survey and the Global Instrumental Earthquake Catalogue of the International Seismological Centre in collaboration with the Global Earthquake Model (ISC-GEM). The Global Centroid Moment Tensor Catalogue has also been revised, which provide data of the moment tensor solutions for events with $M_w \geq 5$. Historical period has been covered with data from the Global Historical Earthquake (GEH) Catalogue with events of $M_w \geq 6$ occurred between year 1000 to 1900.

The initial instrumental catalogue includes 1604 events occurred between 1906 and September 2020 with magnitudes $2.8 \leq M \leq 7.3$ (M represents different magnitude scales given by the agencies: mb, mbLg, ML, MS, Mw).

To characterize the seismic sources of this crustal regime, we selected the model of seismogenic zones defined by (Delvaux et al., 2017) for the Kivu Rift region. Into our study area, the model distinguished seven crustal zones, with depths less than 40 km. The probability of exceeding specific levels of ground motion—both in terms of peak ground acceleration (PGA) and spectral acceleration (SA)—due to all identified seismic sources was then estimated. A logic tree approach was employed to incorporate multiple ground motion attenuation models, enabling the quantification of both the epistemic uncertainty inherent to these models and the aleatory variability associated with different input parameters. The peak ground acceleration (PGA) and the spectral accelerations SA (T) for the previously defined return periods across Burundi were computed under both reference rock site conditions and with local site effects. These seismic hazard maps do not reflect a specific earthquake event but represent the probabilistic levels of ground shaking expected to be exceeded during an exposure period of 50 years.

Figure 10 presents the distribution of PGA, including local site effects, for the 475 year return period, which is widely used in seismic risk and design applications. This return period corresponds to a 10% probability of exceedance in 50 years and is adopted by numerous international and national seismic design codes, such as Eurocode 8 (CEN, 2004), the ASCE/SEI 7-22 Minimum Design Loads for Buildings and Other Structures (ASCE, 2022), and the NEHRP Recommended Seismic Provisions (FEMA P-2082, 2020), as the baseline for the design of ordinary buildings under the Life Safety performance level.

The maximum projected PGA for the 475 years scenario is 0.37g. The hazard maps incorporating site effects reveal significant spatial variability, which reflects the lithological complexity of Burundi. The highest seismic hazard levels are observed in the

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For earthquake hazard, reference the work of Delvaux et al (2017) on seismic hazard assessment for a region that includes the whole Burundi is also missed.

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The entire section "5.4 Earthquakes" lacks bibliographic references. This omission implies that the authors claim all content therein as their own, which is likely not true. Also, in line 254, the authors mention five hotspot localities without further elaboration. If this is not part of the final results, why is it included?

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Commented [MBBO134]: Thank you for your careful review and valuable comments. Following your suggestions, Section 5.4 has been revised.

First, we have incorporated appropriate bibliographic references to support the description of the seismic hazard assessment methodology, including citations to Cornell (1968), McGuire (2004), Kramer (1996), CEN (2004), FEMA (2020), and ASCE (2022). This ensures that all external sources are properly acknowledged.

Second, regarding the mention of the five hotspot localities, after careful consideration, we determined that this information was not directly relevant to the objectives of Section 5.4, which focuses on the national-scale hazard assessment. Therefore, the reference to the hotspot sites has not been maintained in the revised version, in order to prioritize the clarity and focus of the section.

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Commented [MBBO136]: Thank you for your comment. In the revised version of the manuscript, we have added explicit references to international seismic design standards — specifically Eurocode 8 (CEN, 2004), ASCE/SEI 7-22 (ASCE, 2022), and FEMA P-2082 (FEMA, 2020) — which establish a 475-year return period (corresponding to a 10% probability of exceedance in 50 years) as the standard reference for the design of ordinary buildings. This has been clarified in the text.

sedimentary basins and alluvial deposits of the Imbo Plain, in the western part of the country, while the eastern regions, characterized by harder soils and lower seismic activity, show the lowest expected ground motion.

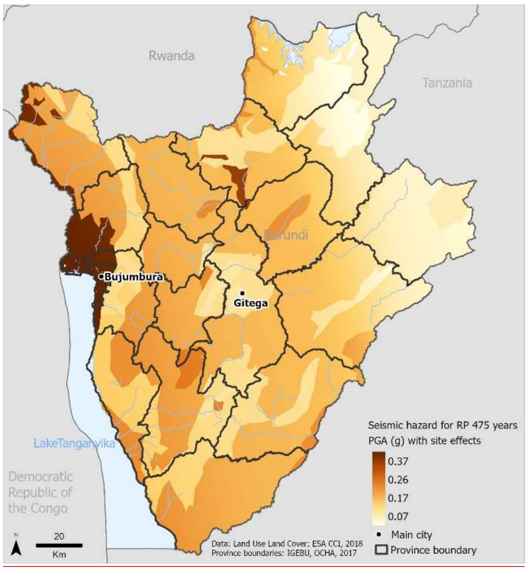

Figure 10. Burundi seismic hazard maps including site effects obtained for RP 475-years.

Vulnerability

The HAZUS scheme from Kircher et al. (2006) was selected as the most appropriate framework for assigning capacity curves because it offers a comprehensive, standardized, and internationally validated set of structural fragility and capacity models. HAZUS provides detailed vulnerability parameters for a wide range of common building typologies, particularly covering low- to mid-rise masonry and reinforced concrete structures, which are the predominant forms observed in Burundi (Brzev et al., 2013).Moreover, HAZUS models have been extensively tested and applied in different seismic risk contexts worldwide, not only in the United States (FEMA, 2012) but also in several international studies addressing developing country settings (e.g., Silva et al., 2018; World Bank, 2014). Given the limited availability of detailed local structural data in Burundi, applying the well-documented HAZUS-based capacity curves constituted a technically sound and practical choice for this study.

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Deleted: Figure 6. Burundi seismic hazard maps including site effects obtained for RP 475-years.

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Risk Analysis

1. For each considered return periods of 100, 250, 475, 975 and 2,500 years the associated accelerations have been used to estimate the expected exceeded damage states of the exposed buildings, according to their physical vulnerability.
2. The distribution of expected damage states was converted to a probable maximum loss (PML) considering an average damage defined as the fraction of reconstruction cost associated to the damage states. Repair costs for extensive (ERC), moderate (MRC) and minor (LRC) damage are calculated as percentages of the reconstruction RISK-EU, W07 (Vacareanu et al, 2004).
3. The PML distribution has been converted into a loss-exceedance curve, whose integral describes the Annual Average Loss (AAL).

7 Socioeconomic Vulnerability

Burundi is characterised by generally high levels of vulnerability relative to other countries (INFORM, 2022) although high resolution vulnerability assessments are difficult to produce due to data and fieldwork constraints (Depicker et al. 2021). We understand vulnerability to be the degree of susceptibility of communities, systems or elements at risk and their capacity to cope under hazardous conditions (Birkmann et al., 2013). The assessment of socioeconomic vulnerability addresses many intangible factors linked to characteristics of communities, such as knowledge and social network qualities. In accordance with the INFORM framework, in this study we also assessed coping capacity, understood as the ability of people, institutions, organizations, and systems, using available skills, values, beliefs, resources, and opportunities, to address, manage, and overcome adverse conditions in the short to medium term (IPCC, 2018). The lack of ability of systems to respond adequately to shocks and to evolve in response to shocks (i.e. to be resilient) is assumed in this assessment to result in a vulnerability to all hazards. Therefore, socioeconomic vulnerability in this assessment is treated as hazard independent.

This socioeconomic vulnerability assessment (SEVA) used an indicator-based assessment framework applying existing data, supported with semi-structured interviews and focus groups with local experts. The latter qualitative methods served to identify context-specific factors of vulnerability and to validate and provide feedback on our assessment framework.

The assessment framework was adapted from the vulnerability and lack of coping capacity dimensions of the INFORM Risk Index developed by the Disaster Risk Management Knowledge Centre (DRMKC) of the European Commission (see Marin Ferrer et al., 2017 for methodology). Adaptations were made in response to data availability and the project client's (IOM) requirements. The INFORM Risk Index is a composite indicator framework in which normalised vulnerability values are aggregated at each level of a hierarchical structure (through indicators, components, categories, dimensions). We additionally included a subcomponent level between indicators and components. The INFORM framework was chosen as it provides an accessible and transparent methodology, offers adaptability to user contexts and utilises existing data.

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Vulnerability and risk to hazards have also been studied, either from a local perspective (e.g. ... [16]

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Moved up [4]: The HAZUS scheme from Kircher et al. (2006) most appropriate framework for assigning capacity curves because it offers a comprehensive, standardized, and internationally validated set of structural fragility and capacity models. HAZUS provides

Moved up [3]: Considering the lack of fragility models compatible geographical setting and the use of a stochastic approach to estimate the risk, a simplified model for physical vulnerability (fragility) was adopted in the case of landslides. Residential buildings

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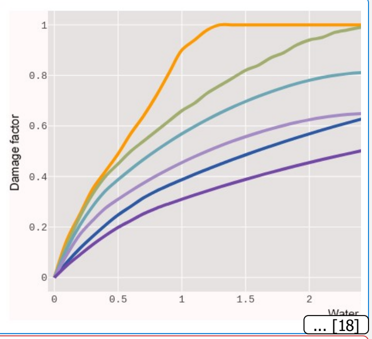
Physical damage was considered only for residential buildings, considering their higher relevancy with respect to other infrastructure in the scope of this risk assessment, and the g ... [17]



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Earthquake vulnerability was based on standard internationally validated fragility curves. To assign the capacity curves that represent the behaviour of the different construction typ ... [19]

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Line 342: notes that coping capacity may be one of the highlights and novelties of the ... [20]

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Commented [mausdelve153]: (Lack of) coping capacity is one of the three Dimensions of the INFORM risk assessment framework, and therefore the methodology for its assessmen ... [21]

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Terms "indicators, components, categories, dimensions" is not well separated, and ... [22]

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Additionally, an INFORM subnational risk assessment in Burundi was published in 2020 (EU-DRMKC, 2020), of which some data were used in the SEVA.

The SEVA was conducted at two resolutions: colline and province. The respective spatial mapping uses (1) data from a survey commissioned by IOM Burundi in September-October 2020 in 532 collines (the DTM-DRR dataset) and (2) data extracted from four national reports and from the INFORM 2020 Risk Assessment for the 18 provinces (EU-DRMKC, 2020). Proxies were used for indicators where data was not available, for example for the indicator 'infant health' three variables were combined (Mortality rate of under 5 year olds; Prevalence of malaria in infants aged 6-59 months; Percentage of infants aged 0-59 months seeking care for diarrhoea) by calculating the unweighted arithmetic mean of their assigned vulnerability classes.

Indicator data were normalised to a scale of 1 to 5 by assigning a vulnerability score to numbers (for metric data) and to statements/categories (for categorical data), with continuous class description from less vulnerable to more vulnerable (Fritzsche et al., 2014). To produce values for components of vulnerability, we used an unweighted arithmetic aggregation (Fritzsche et al., 2014). At each step of aggregation, Min-Max normalisation transformed all values to scores ranging from 0 to 1 (Fritzsche et al., 2014). Values were not aggregated from the component to category and dimension levels to avoid an over-simplification of results and potential misinterpretation by users. If more than 50% of input data for the construction of an indicator, subcomponent or component were missing, this was considered insufficiently complete and therefore not aggregated to the coarser levels. The results of the SEVA are presented as 11 maps showing the 11 vulnerability components with both the colline and provincial assessment presented on each map. Every map is accompanied by a factsheet detailing the data sources, indicator calculation, and completeness of the underlying data. The map in **Error! Reference source not found.** shows the aggregated vulnerabilities.

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Section 7.2, Line 356: Provide a reference for the following statement: "…an INFORM subnational risk assessment in Burundi was published in 2020…".

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Line 361, which proxies?

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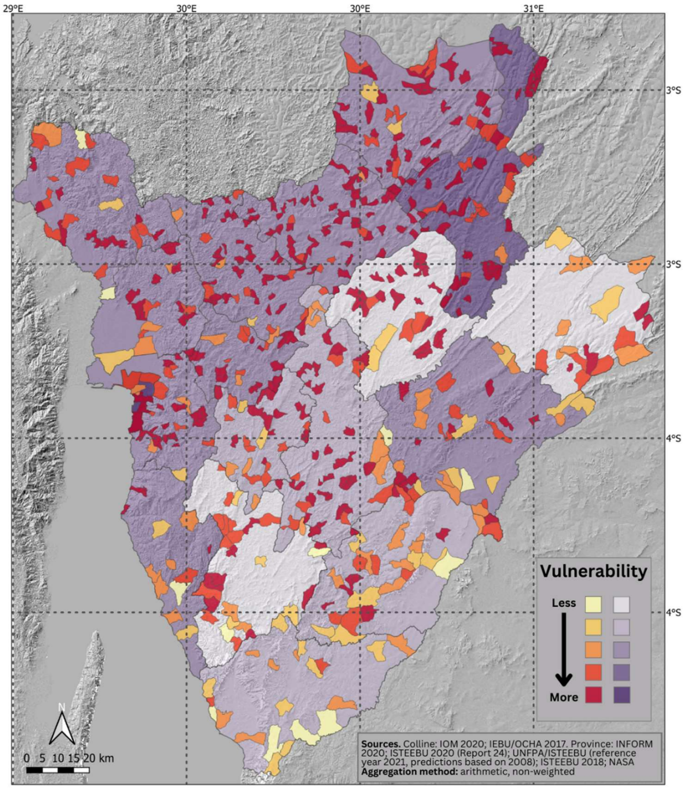

Figure 11. Burundi: Map showing data aggregated under the 'Population Characteristics' component of the SEVA. The underlying subcomponents are, for colline resolution population density and disadvantaged population and for provincial resolution population density

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Deleted: Figure 11. Burundi: Map showing data aggregated under the 'Population Characteristics' component of the SEVA. The underlying subcomponents are, for colline resolution population density and disadvantaged population and for provincial resolution population density increase by 2050 and household composition.

The results of the SEVA show a great heterogeneity in vulnerability both geographically and thematically over the two resolutions assessed, demonstrated by the frequency with which neighbouring collines show significantly different vulnerability levels across one indicator or subcomponent. This could be due to topographical and administrative boundaries which result in genuine differences in vulnerability and coping capacity between collines. The results suggest that differences in vulnerability factors are highly localised, but it must be stressed that these differences should be considered in the context of generally high and widespread vulnerability observed in Burundi. We recommend that users of the SEVA results look into the underlying indicators and subcomponents when seeking to identify particular vulnerabilities or vulnerability hotspots. This is due to the loss of nuanced information caused by the aggregation of data to produce components of vulnerability and the accompanying maps. This loss of information is more apparent the more subcomponents are aggregated.

Due to its limitations (see section 9), the results of the SEVA were not integrated into the monetary physical risk assessment. Consequently, the SEVA is to be considered as complementary to the overall risk assessment.

8 Results

In this section the results of the risk analysis for the individual hazards and their composition in terms of multi-hazard risk are provided and commented.

8.1 Multi-hazard map

In order to provide an intuitive description of the intensity and extent of the considered natural hazards, a series of national-scale, single-hazard maps were produced, each visualising the area exceeding the 85% percentile of the scalar intensity distribution of the specific hazards (Fig. 12) on a 30m resolution grid. The 85% percentile threshold has been chosen arbitrarily to capture the spatial distribution of high-intensity hazardous events without narrowing the description to extreme events. In the case of landslides, the hazard intensity is represented by the normalised susceptibility. These maps were then merged into a multi-hazard representation where each grid element is color-coded according to the number of hazards exceeding the 85% percentile, which ranges from zero to five. The resulting map provides a geographic representation of the potential hotspots for risk arising from multiple natural hazards, and is used to rank the individual communes, as shown in the table in Figure 12 (listing the highest ranking 50 communes). This ranking does not consider the frequency/magnitude relationships of the individual hazards, nor their impacting mechanisms.

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Vulnerability and risk to hazards have also been studied, either from a local perspective (e.g. Nsabimana et al, 2023) or from a regional one (Depicker et al., 2021b).

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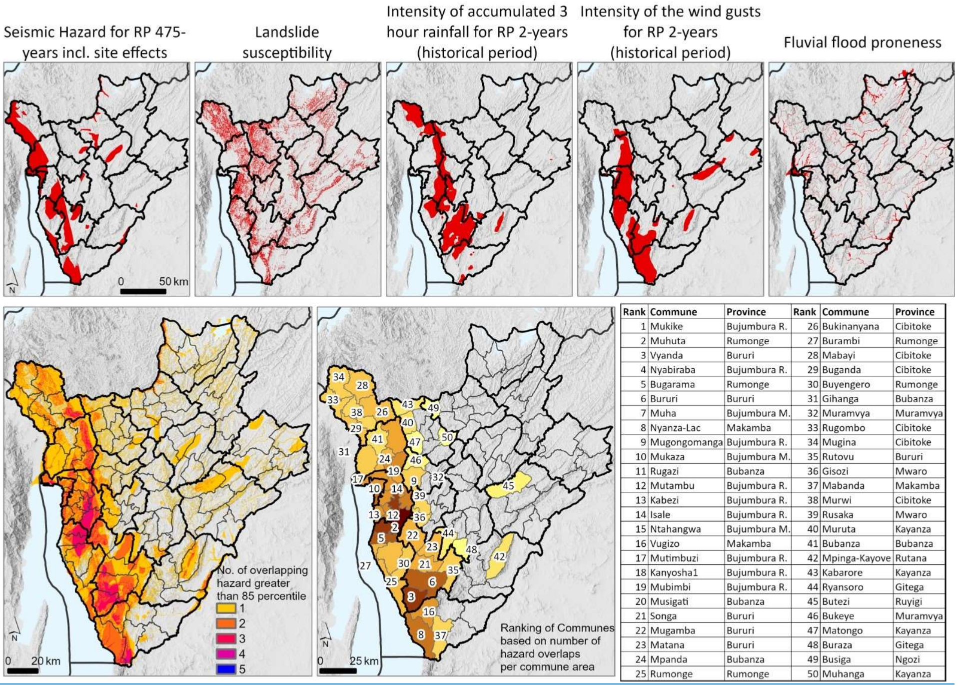

Rank	Commune	Province	Rank	Commune	Province
1	Mukike	Bujumbura R.	26	Bukinanyana	Cibitoke
2	Muhuta	Rumonge	27	Burambi	Rumonge
3	Vyanda	Bururi	28	Mabayi	Cibitoke
4	Nyabiraba	Bujumbura R.	29	Buganda	Cibitoke
5	Bugarama	Rumonge	30	Buyengero	Rumonge
6	Bururi	Bururi	31	Gihanga	Bubanza
7	Muha	Bujumbura M.	32	Muramvya	Muramvya
8	Nyanza-Lac	Makamba	33	Rugombo	Cibitoke
9	Mugongomanga	Bujumbura R.	34	Mugina	Cibitoke
10	Mukaza	Bujumbura M.	35	Rutovu	Bururi
11	Rugazi	Bubanza	36	Gisozi	Mwaro
12	Mutambu	Bujumbura R.	37	Mabanda	Makamba
13	Kabezi	Bujumbura R.	38	Murwi	Cibitoke
14	Isale	Bujumbura R.	39	Rusaka	Mwaro
15	Ntahangwa	Bujumbura M.	40	Muruta	Kayanza
16	Vugizo	Makamba	41	Bubanza	Bubanza
17	Mutimbuzi	Bujumbura R.	42	Mpinga-Kayove	Rutana
18	Kanyosha1	Bujumbura R.	43	Kabarore	Kayanza
19	Mubimbi	Bujumbura R.	44	Ryansoro	Gitega
20	Musigati	Bubanza	45	Butezi	Ruyigi
21	Songa	Bururi	46	Bukeye	Muramvya
22	Mugamba	Bururi	47	Matongo	Kayanza
23	Matana	Bururi	48	Buraza	Gitega
24	Mpanda	Bubanza	49	Busiga	Ngozi
25	Rumonge	Rumonge	50	Muhanga	Kayanza

Figure 12. Burundi: Illustration of national-scale multi-hazard map generation. The top five maps show individual hazard maps exceeding the 85th percentile of the hazard distribution. The map on the bottom left shows the number of overlapping hazards and the map on the bottom right shows those communes potentially most prone to multiple hazards. The table shows a ranking of the 50 potentially most prone communes to multiple hazards (Data sources: administrative boundaries: ISTEEBU, 2017, elevation: NASA SRTM, 2000).

To achieve a more quantitative comparison of the resulting risk, a probabilistic risk estimation was carried out for each of the five hazards at national scale (see Table 1 and Figure 13).

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Figure 12. Burundi: Illustration of national-scale multi-hazard map generation. The top five maps show individual hazard maps exceeding the 85th percentile of the hazard distribution. The map on the bottom left shows the number of overlapping hazards and the map on the bottom right shows those communes potentially most prone to multiple hazards. The table shows a ranking of the 50 potentially most prone communes to multiple hazards (Data sources: administrative boundaries: ISTEEBU, 2017, elevation: NASA SRTM, 2000). ¶

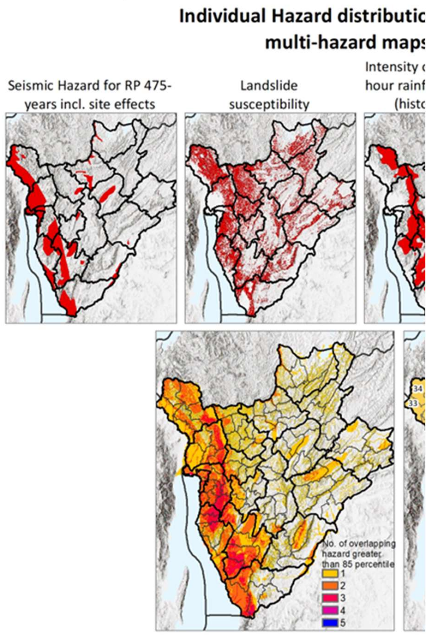

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Table 2 . Overall national and provincial multi-hazard annual average loss (AAL) results.

	Provinces	Annual average loss (AAL) Projections (USD)						Total MH AAL Projection (USD)
		River Flood Urban Areas	River Floods Agricultural Plots (USD)	Torrential Rains	Strong Winds	Earthquakes	Landslides	
1	Bubanza	406,080	529,651	188,237	186,655	1,370,944	107,165	2,788,733
2	Bujumbura Mairie	26,145,119	353,942	165,816	224,736	5,478,708	81,274	32,449,596
3	Bujumbura Rural	6,710,944	1,266,774	267,379	291,446	818,925	174,200	9,529,668
4	Bururi	0	222,139	193,957	146,354	479,563	101,514	1,143,526
5	Cankuzo	0	2,580,732	167,809	108,030	38,857	39,119	2,934,546
6	Cibitoke	73,440	743,557	265,203	204,222	782,860	152,959	2,222,241
7	Gitega	1,920	1,629,039	478,286	330,766	648,812	115,224	3,204,048
8	Karuzi	0	1,397,526	280,611	202,963	489,457	55,883	2,426,441
9	Kayanza	3,360	739,930	441,576	289,662	822,726	159,843	2,457,097
10	Kirundo	0	3,954,746	354,037	327,185	361,785	79,191	5,076,944
11	Makamba	72,960	2,258,549	210,448	206,543	578,559	106,169	3,433,228
12	Muramvya	14,400	333,015	183,732	128,696	440,721	95,867	1,196,431
13	Muyinga	0	2,872,453	373,780	328,027	127,523	117,477	3,819,261
14	Mwaro	0	539,516	187,278	125,984	339,128	63,279	1,255,185
15	Ngozi	26,400	6,752,309	522,261	333,025	500,122	124,148	8,258,265
16	Rumonge	31,200	261,622	205,306	213,485	1,295,037	111,243	2,117,892
17	Rutana	14,400	3,638,219	209,734	146,438	353,177	71,975	4,433,943
18	Ruyigi	111,611	2,984,089	274,786	192,791	380,410	63,084	4,006,770
TOTAL		33,611,834	33,057,807	4,970,237	3,987,009	15,307,315	1,819,614	92,753,816
MH AAL TOTAL (USD)		92,753,816						
Burundi GDP 2022 (USD)		3,340,000,000						
AAL/GDP (%)		2.78%						

To explicitly consider the contribution of exposure and vulnerability and obtain a consistent geographical representation of expected multi-hazard risk, an aggregated spatial risk density index (in USD/km²) was computed for each commune by dividing the aggregated AAL value by the geographic extension (km²), the results of which are shown in Figure 13.

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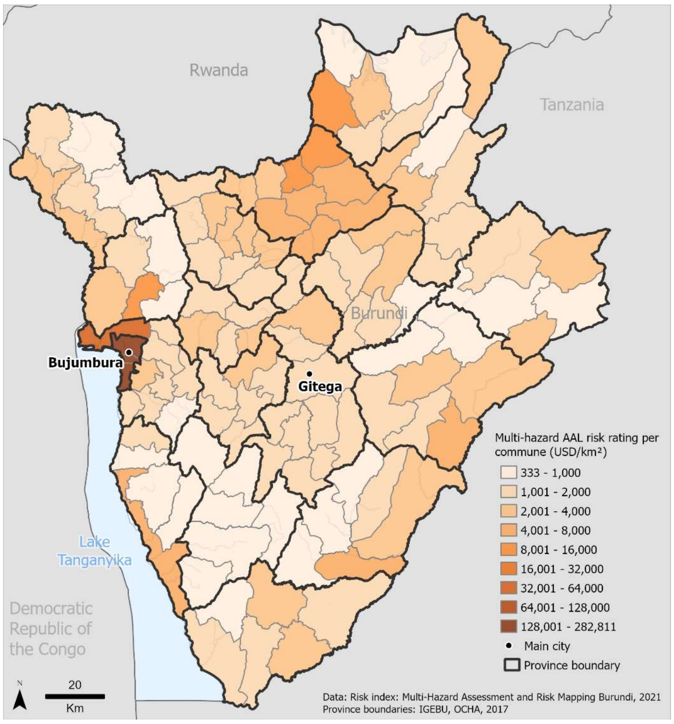

Figure 13. Burundi: Nationwide commune level multi-hazard AAL risk ratings with all hazards included. The AAL is associated with loss to residential buildings except in the case of river floods where also loss of agricultural crops has been addressed.

9 Discussion

The multi-hazard map (Fig. 12) highlights the communes with the larger number (in terms of their uppermost percentile) of overlapping natural hazards. This representation indicates several potential risk hotspots in the western part of the country, along the Congo-Nile Mountain range, the North Tanganyika-Kivu Rift and bordering the Tanganika Lake, where earthquakes, intense precipitations and strong wind gusts are possible. When a more comprehensive multi-hazard risk assessment is carried out, in terms of economic impact and considering exposure and vulnerability, a different picture emerges (Figure 13). The annual average loss (AAL) is more evenly distributed across the country, with a pronounced hotspot in Bujumbura, as expected giving the concentration of assets, with other risk hotspots in the Ngozi and Kirundo provinces in the north, as well as in the

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This part should be a key aspect of the research. However a proper discussion is missed and there is nothing that is said with respect to the existing assessments. What is the added value of this research? What is its use? Where are the caveats?

The authors put an emphasis on climate change, which is of course a valid point. However, the main concerns about the natural hazards in this region are the exposure of the population and the weakness of the management (see for example Raju et al., 2022 that discuss such aspects in general). In addition, the impacts of human activities in the incidence of natural hazards such as landslides and floods (for example Depicker et al., 2021a, 2024) and the implication it has for the risk (Depicker et al., 2021b) are clear. These are points that for such as work would need to also be discussed, especially for a research that it aimed at targeting stakeholders. Overall, in that sense, the contextualized aspect of this research is weak I believe.

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eastern areas. The single-hazard AAL estimates are driven mostly by floods, impacting either urban areas or cultivated areas, and by earthquakes. Economic loss to crops has been addressed only in the case of river floods, so that risk to crops due to torrential rains, winds, landslides, or earthquakes were not assessed. This is based on the assumption that river floods affect crops disproportionally with respect to the other hazards, both because of the physical impact of water, the spatial extension of the flooded area and its duration. The expected AAL related to the impact of riverine floods in urban areas amounts to more than 33Mi USD, nearly ten times bigger that the GAR15 estimate (UNDRR, 2015). The flood risk estimates have not yet been validated through comparison with other sources, but a clear confirmation of the high level of risk was provided by the recent (2024) floods. From September 2023 to April 2024, in fact, the El Niño has wreaked havoc across Burundi, with floods (and landslides) affecting more than 200'000 people, forcing more than 37'400 to flee their homes and damaging 40'000 hectares of agricultural fields, resulting in the loss of 10% of 2024 crops (UNICEF, 2024). The contributions of the Bujumbura provinces can be explained due to the concentration of population and associated infrastructure in these provinces. The highest single contribution (0.78% of GDP) is indeed associated with fluvial floods in Bujumbura Mairie. The potential high exposure of this area was clearly shown by the Copernicus rapid assessment report triggered on the eve of the April 2024 floods, where more than 130km² of flooded area were predicted (Copernicus, 2024) also due the continuously increasing level of the Tanganika lake (Gbetkom et al., 2024). With regards to Ngozi province, the significant AAL of 6.5 million USD is mainly due to potential losses to agricultural crops. Earthquakes, although relatively infrequent, still represent a concrete threat over longer time frames: the estimated 15.3Mi USD, while much higher than the GAR15 estimate of 3.87Mi USD (UNDRR, 2015) is very consistent with the recent estimate of 17Mi provided by (Paul and Silva, 2025). In this study a preliminary probabilistic landslides risk assessment has been carried out, which is still uncommon in the context of landslides hazard and risk assessment but allows for landslide risk to be quantified and compared with other natural hazards. This probabilistic model is based on a database of landslides compiled with data available in 2020, which is expected to be affected by the spatial heterogeneity of the data and by the potential biases associated with the potential presence of deep-seated landslides and mass movements associated with large gully features and with riverbank erosion. However the statistical characterization was quite robust, which indicates a relatively high level of consistency in the underlying data. After 2020 several other landslides inventories have been published (e.g., Deijns, 2022; Depicker et al., 2021b), which could be employed to further improve the model in future assessments. Other necessary simplifications and assumptions are related to the need to extend susceptibility estimates to probabilistic hazard models. According to these preliminary estimations, landslides contribute to multi-hazard risk comparatively less than other hazards, with an estimated 0.005% of GDP, but it is still significant and could further increase following the modification of precipitation patterns in the area due to Climate Change and the perduring physical and socioeconomic vulnerability conditions, particularly in the rural regions.

It should be noted that these assessments assume independence among the hazards, refer only to direct physical impacts on residential buildings and agricultural plots, and do not explicitly account for climate change. However, a preliminary evaluation of the potential impact of climate change has been carried out based on a combination of large-area climate predictions and local downscaling techniques and is provided in Annex 1. The mean daily precipitation projections show a robust increase in

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the mean daily precipitation, ranging from 0.2 to 3 mm, compared to the historical period (1990-2019). The highest relative changes are found in the Imbo Plane, ranging from 25 to 40%. This trend is projected mainly for the rainy season. The eastern part of the country where the dry eastern plateaus are located also show high relative changes in the mean daily precipitation values. Regarding the total contribution from wet, very wet, and extremely wet days to the total precipitation, for several areas, such as Bujumbura Mairie, the north of Bujumbura Rural and the south and central areas of Bubanza, as well as some areas of Kirundo and the north part of Ruyigi, the models show a positive trend in the expected changes with increases between 6-14% in the percentage of precipitation accumulated during the wet and very wet days. The contribution of the extremely wet days varies from 4 to 10%. Results from daily wind speed during gusty days (days with wind speed values above 90th percentile) show a slightly decreasing trend, but in general, the wind speed values of the gusty days are expected to be comparable with the historical period, with moderate winds reached during the windiest days.

To support the multi-hazard risk assessment, exposure models describing the distribution of population and residential buildings have been developed. This has required extensive efforts due to the lack of coherent and up-to-date information, and the inconsistencies across official data (even on the naming and administrative boundaries) required for regional and global models to be used. The databases developed and maintained by IOM proved very useful to integrate important local information.

Since natural hazards are expected to strongly affect people and communities, a separate socio-economic vulnerability assessment (see 7.2 and Fig. 11) was also carried out based on the available data ranging from 2015-2020 and on consultations with local authorities and experts. Overall, it´s clear that the natural hazards play a strong role in the resulting risk, but the distribution of multi-hazard AAL shows that the contribution of exposure and vulnerability are equally significant. Furthermore, there is a complex interplay between the population and its activity and the climatic drivers which is not explicitly accounted for in the models but is expected to further increase the risk. For instance, deforestation, sprawling urbanization, road construction and irrigation increase landslide mobilization rates and favour erosion mechanisms across the hilly regions and in the periphery of urban centres (Depicker et al., 2024). Diffuse socioeconomic vulnerability as well as systematic lack of resources and capacities by local civil protection and decision makers is also heavily intensifying the materialization of risks (Raju et al., 2022).

10 Conclusions and outlook

To explore the impact of natural hazards in Burundi and their distribution at different geographical scales, two approaches were followed. Following a single-hazard assessment, a multi-hazard map highlighted the communes with higher numbers (in terms of their uppermost percentile of overlapping natural hazards. This representation indicates several potential risk hotspots in the western part of the country, along the Congo-Nile Mountain range and bordering the Tanganika Lake, where earthquakes, intense precipitations and strong wind gusts are possible. A more comprehensive multi-hazard risk assessment was carried out, in terms of economic impact and considering exposure and vulnerability, a different picture emerged. An aggregated AAL of

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To summarize, the authors propose a research that aims to tackle a lot of issues on different hazards, their vulnerability, and climate change related aspects. This is a very ambitious work. However, lack of (i) methodological justification, (ii) use of local knowledge, (iii) discussion with respect to previous work, and (iv) absence of state of the art literature are factors that weakens the quality of this work. In addition, the research shows a lack a connection with its assume target audience. Per say, that is an point that one could understand, especially with respect to the constraint of going in the field (COVID restriction) and connecting with the local experts and institutions. Nevertheless, one would then have assumed a more elaborate discussion on those aspects.

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A separate socioeconomic vulnerability assessment was carried out based on the available data and on consultations with local authorities and experts and provides complementary information on the ways natural hazards are expected to affect exposed people and communities. Since socioeconomic vulnerability is a dynamic process that evolves over time in response to changing local conditions, the monitoring of these dynamic processes is better able to represent the true vulnerability of a community. It is therefore suggested that the SEVA be updated as new data becomes available and new indicators added.

In general, data scarcity was a significant hurdle to overcome in the multi-hazard assessment of risk; several desired datasets were not accessible, did not exist or were incomplete, and were therefore not included. Data collection and field visits were not possible due to travel restrictions related to the COVID-19 pandemic as well as COVID-19 diagnoses within the team delaying (or leading to the cancellation of) fieldwork. To mitigate this, it was attempted to validate the conceptual approach and data sources with local experts, but this was limited due to the difficulty in engaging relevant informants from abroad using mainly online meetings. The use of large-area and global datasets, most from authoritative sources, proved anyway useful to set the stage for more in-depth assessments where possible, or to achieve a baseline result otherwise. The use of AAL-oriented risk analysis implies a different and pragmatic perspective on the use of data. While AAL provides an actionable metrics which is well understood by decision makers and large-scale organizations, the monetization of risk often implies strong simplification and assumptions, which are ill-received by several scientific communities. A systematic understanding of such uncertainties is therefore crucial, while at the same time improved probabilistic approaches should be developed to tackle them efficiently. This outlines a further difficulty interacting with local experts and stakeholder, since the methodological approach required to obtain probabilistic estimates at national scale requires significant data, knowledge and information beyond the sheer consideration of hazards. The need for the analytical integration of exposure, physical and socio-economic vulnerabilities (Michellier et al., 2020) entail a significant multi-disciplinary effort which often strains local practitioners and research institutes lacking financial resources and personnel (Dike et al., 2018). Future work should include a more extended consultation process with local experts and a more in-depth consideration of the institutional and operational framework of local stakeholder is also advisable to ensure a more efficient uptake of the collected data and findings.

Notwithstanding the limitations implicit in the narrower scope of the economic perspective on risk, the approach based on AAL allows for a consistent aggregation of risk arising from natural hazards with very different characteristics (e.g., intensity and frequency/magnitude distributions). This approach, being probabilistic in nature, also allows for the broad consideration of the aleatoric uncertainty underlying the considered processes, although a systematic analysis of the uncertainty was not carried out and should be addressed in future works. On the other hand, epistemic uncertainty is significant due to the limited

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Section 11, Lines 513-514: Expand on this sentence detailing the stakeholder engagement: "To mitigate this, it was attempted to validate the conceptual approach and data sources with local experts, but this was limited due to the difficulty in engaging relevant informants.". This could be mitigated by expanding the discussion to include future work.

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capacity in the modelling of some of the hazards and to the lack of context-specific data. In particular the potential effects of climate on future risk conditions should be directly accounted for in the AAL estimates. Several of the models described in this manuscript had to rely on simplifications and assumptions that should be revised in the future as new data and knowledge is increasingly made available. In particular, the risk from river floods (both on residential buildings and crops) given its significancy, should be further addressed by and with local experts and stakeholders. The estimation of landslide risk from probabilistic assessment was also relatively innovative and as such can be further refined and validated. More in general, the assumption of independence of hazards should be subject to further studies to better account for cascading and compounding mechanisms in the impacts, e.g. the triggering of landslides due to intense precipitation and earthquakes, and the high probability of compounding across the impacts related to hydrometeorological hazards.

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Following the conclusion of the activities described in this manuscript, a public shared data repository[3] has been implemented by national and local authorities in Burundi, who engaged in extensive restructuring and update of the risk management processes. As a first result, 90 communes and 17 provinces have developed or updated contingency plans and simulation exercises have been implemented for stress-test and validation purposes[4]. These findings clearly indicate that more intense and concerted efforts are needed in Burundi to develop and maintain those data, information and knowledge that are paramount for understanding, treating and monitoring the different risks increasingly threatening socio-ecological systems and communities. This also includes consistent exposure and vulnerability data, as well as a systematic collection of impacts, damage and loss. Integrated risk assessment should be understood as a continuous process, calling for substantial resources to be mobilized by local and national authorities, and for the scientific community to further engage in pragmatic joint activities with decision- and policy-makers. In this context, non-governmental organizations operating on the territory, such as IOM in the case of Burundi, can also play an important role in collecting and sharing important information and bridging gaps with local institutions.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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Contributions:

M.P. and E.P. designed the study.

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[3] http://23.239.19.79/

[4] https://reliefweb.int/report/burundi/first-kind-nationwide-project-reinforces-burundis-resilience-climate-induced-disasters

E.P. Contributed to the development of the flood hazard map and the related analyses and developed the compilation of the risk assessment estimates (AAL) of the five hazards consulted directing the generation of the commune, province and country wide scale risk maps.

M.M. developed the landslide models and carried out the related analyses.

M. B. B.O. conducted the Probabilistic Seismic Hazard Assessment.

M.P., K.R., E.P. and P.C. developed the exposure models and carried out the related analyses

S.S. and J.L.D. developed and conducted the Socioeconomic Vulnerability Assessment.

J.P. and M.P. conducted the climate change analysis.

K.R. designed the figures with input from all other authors.

J.L.D. coordinated the manuscript production.

All authors proofread and commented on the manuscript.

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E.P. developed the flood hazard map and carried out the related analyses. ¶
out the related analyses. ¶
M. B. B.O. conducted the Probabilistic Seismic Hazard Assessment. ¶
M.P., K.R. and P.C. developed the exposure models and carried out the related analyses. ¶
S.S. and J.L.D. developed and conducted the Socioeconomic Vulnerability Assessment.¶
J.P. and M.P. conducted the climate change analysis. ¶
K.R. designed the figures with input from all other authors.¶
J.L.D. coordinated the manuscript production.¶
All authors proofread and commented on the manuscript.¶

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Official citations for datasets and other relevant sources are missing (e.g., Worldpop, IPCC).

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Annex 1: Climate Change Analysis

In order to understand the potential trends of risk in the future due to the evolution of climatic drivers, a study of climate change in Burundi was carried out based on a combination of large-area climate predictions and local downscaling techniques. Global Climate Models (GCMs) in the CMIP5 (Coupled Model Intercomparison Project 5) were used to obtain information about how the climate could change at continental scale. In order to adjust such large-area climate prediction to obtain more specific information at Burundi national and subnational scale, climate 'downscaling' was applied using a Regional Climate Model (RCM) called Weather Research and Forecasting (WRF), version 3.9.1.1 (Skamarock et al., 2008).

By combining the broader predictions from CMIP5 with the precise details that the WRF model's downscaling method provides, a more comprehensive picture of how climate change could impact the specific area of Burundi can be obtained. The methodology is described in Fig. 14, and assumes as baseline the historical period 1990-2019, and a short-term future period from 2020-2049.

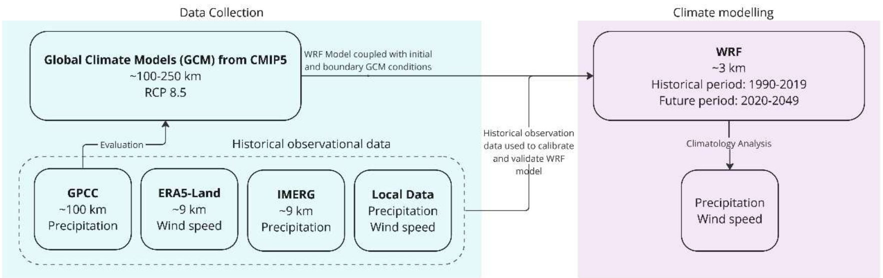

Figure 14. Climate change dynamical downscaling methodology.

The study of climate change and therefore the future changes in extreme events cannot be deterministic, given the large existing uncertainties related to the climate system itself, the uncertain evolution of emissions, and the limited capabilities of current climate models. That is why, three distinct global models were downscaled using the WRF model, namely MPI-ESM-MR, CNRM_CM5, and CanESM2. These three models were selected amongst the available global climate models to reproduce the essential characteristics of the current climatic conditions in Burundi's historical period, and to capture the range of climate change signals present in the entire ensemble of GCMs.

As for the regional WRF model for Burundi, the model displayed a strong correlation in replicating the annual precipitation cycle, albeit with a tendency to overestimate this atmospheric variable during the rainy season. Similarly, the model exhibited good correlation with monthly averages of daily precipitation and the count of rainy days per month. Concerning wind speed, the model is consistent with scientific recommendations for mean daily wind speed and the 90th percentile of mean daily wind speed.

Commented [mausdelve185]: Reviewer 1 (Dewitte)

The climate change analysis was carried out with a rather straightforward analysis. I am surprised that such analysis is not carried out with reference to the state of the art (for example Souverijns et al., 2016) and the fact that conclusions on the issues of climate change are difficult to draw in the region due to the absence of relevant data; which often leads to conflicting perspectives (IPCC, 2021).

Commented [mausdelve186]: Jesica Max

Commented [mausdelve187]: Reviewer 2 (Anon)

Given the difficulty in assessing impacts, open sources, such as the Climate Impact Explorer (https://climate-impact-explorer.climateanalytics.org/impacts/) and the ISIMIP repository (https://data.isimip.org/), could have offered valuable initial insights. Additionally, as pointed out by Reviewer 1, several existing datasets have been completely neglected.

Commented [mausdelve188]: Jesica

10.1 Impact of climate change on precipitation

Bujumbura Mairie is the province where the greatest increase in precipitation is expected with a projected relative increase in the 3-hourly precipitation of up to 58.1% for the return period of 50 years.

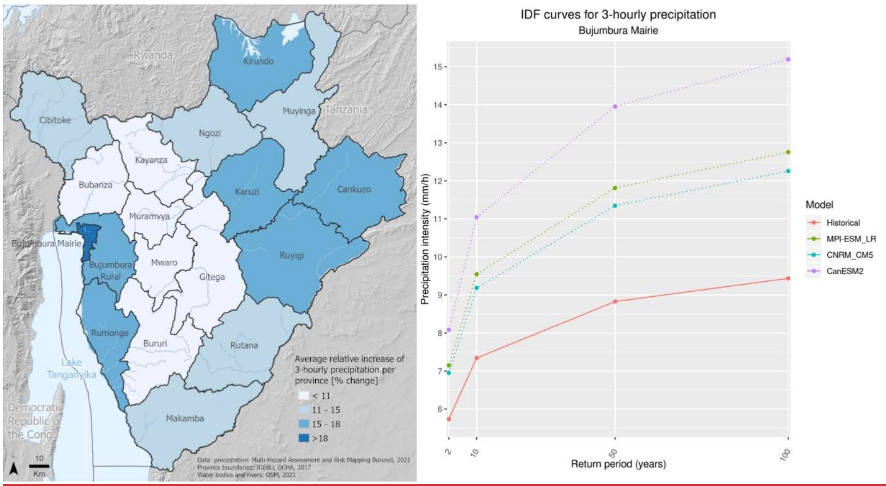

Figure 15. Left: Burundi provinces according to the projected increase of intensity and frequency of the 3-hourly precipitation. Right: Precipitation intensity for a duration of 3 hours predicted for the Bujumbura Mairie province by the forced WRF model. This includes simulations for the historical period and projections using three global climate models, analysed across different return periods (2, 10, 50, and 100 years). In Fig. 15, left, a summary of the results by province is shown, considering the average of the three future projections and the three return periods considered (2, 10 and 50 years). Darker blue colours indicate greater relative increases in the 3-hourly rains expected in the future compared with the historical value. The analyses indicate (e.g. Fig. 15 right) that for the same return period and duration, torrential rains in Burundi will be more intense (or alternatively, that precipitation of a given high intensity will be more frequent). The smallest increases in the intensity are projected in the central part of the country (Kayanza, Mwaro, Muramvya, Bubanza, Gitega and Bururi).

10.2 Impact of climate change on wind

Figure 16 shows a summary of the results obtained by province, considering the average of the three future projections and the three return periods considered. Red indicates the relative increases in strong winds expected in the future when compared with the historical value. Blue indicates the relative decrease in the intensity and frequency of strong winds in the future. Darker colours indicate greater decrease or increase. In the case of no conclusions, the provinces appear in white. In all the central provinces (Bururi, Cibitoke, Gitega, Karuzi, Kayaza, Makamba, Muramvya, Mwaro, Ngozi, Rutana and Ruyigi) the

Commented [mausdelve189]: Reviewer 2 (Anon)

Although I previously suggested moving the impact of climate change to an Appendix, I am concerned about lines 470-472, where the authors mention that Fig. 15 is derived from averaging three "future projections" (global climatic models) and "three return periods." Is this map an average of three return periods and three climatic models? The authors should provide a justification or methodology for this assumption. How should these results be interpreted, and are they genuinely useful for practical applications?

Commented [mausdelve190]: Max

Commented [MP191R190]: Thank you for the suggestions. The section has been turned into an annex to improve readability of the manuscript. As for your specific comment, the map is only supposed to provide an intuitive visualization of where in Burundi climate change could have a bigger relative impact. Since the models agree in shape in any province, taking the average is expected to provide a semi qualitative spatial estimate. The resulting representation would be biased in favor of longer return times, but this is consistent with a cautionary principle.

intensity of the wind gust is expected to increase when considering the same return period. The greatest increases in intensity are projected for Kayaza, Karuzi and Rutana provinces. For Bubanza and Bujumbura-Mairie provinces, small decreases in the strong winds are expected. There is no agreement of the models for the northeast part of the country (Cankuzo, Muyinga and Kirundo) and the west provinces of Bujumbura-Rural and Rumonge for strong winds.

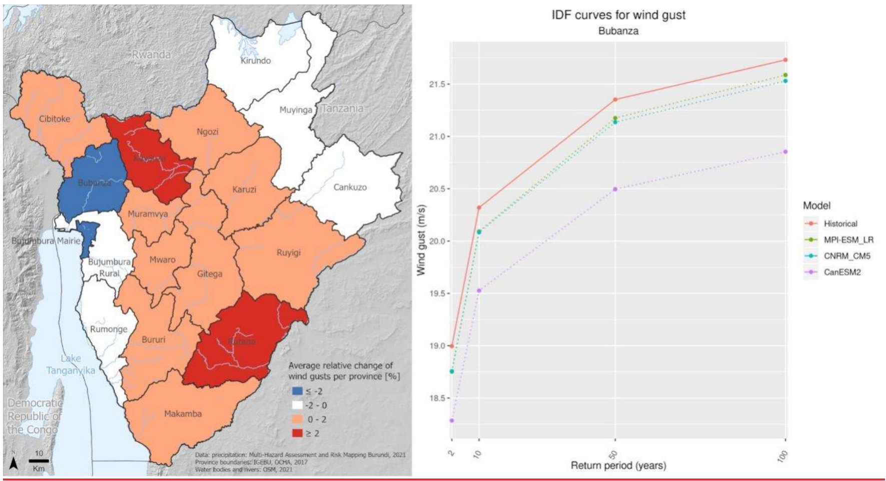

Figure 16. Left: Burundi provinces according to the projected increase (red) or decrease (blue) of intensity and frequency of the wind gust. Right: Wind gust predicted by the forced WRF model with different models for the Bubanza province and return periods.

Annex 2: Exposure models

Residential Buildings

The structural features and typical geometries of residential buildings commonly found in Burundi has been estimated as described in Table 3 below. Please refer to (Brzev et al., 2013) for further information on the taxonomical descriptions. The estimated composition of the exposure model in terms of these typologies at *colline* level (referring to 2021 population and housing situation) is available as additional material to this manuscript.

Table 3 Structural types and geometry of residential buildings in Burundi. The description in terms of the GEM taxonomy has been included as well as the replacement value (in USD) estimated by local experts.

Building description	GEM Taxonomy	Average number of floors	Average floor area (m2)	Average Building Taxonomy Surface (m2/building)	Replacement Values (USD/m2)
reinforced concrete with Infilled frames	CR/LFINF/H:1-3	1.5	250	375	648
	CR/LFINF/H:4-7	5.5	250	1375	730
	CR/LFINF/H:8+	8	250	2000	490
Confined masonry	MCF/H:1-2	1.5	120	180	390
	MCF/H:3-5	4	120	480	190
Reinforced masonry with wood reinforcement	MR+RW/H:1-2	1.5	120	180	70
Unreinforced masonry with adobe / earth	MUR/ADO/H:1	1	32	32	110
Unreinforced masonry with earth	EU/H:1	1	32	32	110
Unreinforced masonry with rubble stones	MUR/STRUB/H:1-2	1.1	32	35	115
Unreinforced masonry with bricks	MUR+CRBS/H:1	1.1	32	35	70
	MUR+CBS+MOC/H:1-2	1.1	32	35	70
Light wood	W/WLI/H:1,2	1	16	16	72

Heavy wood	W/WHE/H:1,2	1	16	16	72
Wattle and daub	W/WWD/H:1	1	20	20	72

Agricultural crops

The extension of the agricultural crops was derived by a land-cover map. Their replacement value was established in terms of the average value and expected productivity of the plots for the average type of crops, considering the lowland agriculture in the flood plains (based on expert judgment and local sources). In order to establish a plausible replacement value, the average productivity and monetary value of crops throughout the country was compiled from FAO[5] and other international sources. As is illustrated in Table 4, the weighted average value for the assumed typical river floodplain crops has been estimated as USD 1,450/ha (rounded) based on the production data of year 2018 (last available at the time of risk assessment).

Table 4 Main expected crop types and related cultivation intensity and value. Cotton is included in the table as common crop on flood plains but was not considered for calculating the weighted average value as no national yield data for 2018 was available.

Crops	Prod Unit	Unit Crop Value (USD/tonne)	Yield 2018 (tonne/ha)	Prod Value Ha (USD/Ha)	Prod 2018 (tonne)	Productive Surface 2018 (Ha)	Crop Value 2018 (USD)	Average Crop Production (USD/Ha)	Weighted Average Crop Value (USD/Ha)
Cotton	USD/tonne	325.1	0.68	221	No data	-	-	-	-
Wheat	USD/tonne	522	1.41	736	22,751	16,135	11,876,022	736	**1,467**
Cassava	USD/tonne	221.1	8.07	1,784	2,390,000	296,159	528,429,000	1,784	
Maize	USD/tonne	438.9	1.53	672	290,498	189,868	127,499,572	672	
Potatoes	USD/tonne	351.1	11.17	3,922	302,665	27,096	106,265,682	3,922	
Rice, paddy	USD/tonne	371.1	1.19	442	55,671	46,782	20,659,508	442	
Beans	USD/tonne	575.4	0.66	380	393,233	595,808	226,266,268	380	
Sugar cane	USD/tonne	37.9	58.37	2,212	178,439	3,057	6,762,838	2,212	
Sweet potatoes	USD/tonne	142	11.17	1,586	583,019	52,195	82,788,698	1,586	

[5] https://www.fao.org/faostat/en/#data/QI

Page 2: [1] Commented [mausdelve6]	mausdelves	04.04.2025 10:47:00

Reviewer 2 (Anon)

The SEVA and Climate Change analyses were not integrated into the final results and therefore feel distracting. I suggest either completely removing them or presenting them as an Appendix, treating them as auxiliary analyses rather than part of the main text. The same applies to the details for the flood model for the five catchments (Fig. 4), as this is also distracting.

Page 2: [2] Commented [mausdelve7]	mausdelves	04.04.2025 11:29:00

Reviewer 2 (Anon)

Access to geodata products is not only pertinent to reviewers; potential future readers may seek access to replicate the methodology using the developed tools in other study areas. This is crucial for adhering to and upholding the FAIR principles (Findable, Accessible, Interoperable, and Reusable) (Wilkinson et al., 2016)

Page 2: [3] Commented [mausdelve8]	mausdelves	04.04.2025 11:35:00

Reviewer 2 (Anon)

A more thorough review of the English writing is recommended, focusing not only on grammar but also on the presentation of ideas. I am particularly surprised that this was not noted by the senior co-authors of the manuscript, who should have provided careful supervision and strict approval before resubmission.

Page 2: [4] Commented [mausdelve9]	mausdelves	04.04.2025 11:36:00

Reviewer 2 (Anon)

Please ensure uniform font style throughout the document. The text currently displays mixed font styles that do not comply with the NHESS template (e.g., line 212)

Page 2: [5] Commented [mausdelve10]	mausdelves	04.04.2025 11:38:00

Reviewer 2 (Anon)

There are several disconnected sentences that appear as if different texts were mixed together without harmonization by a careful reade

Page 2: [6] Commented [mausdelve11]	mausdelves	04.04.2025 11:39:00

Reviewer 2 (Anon)

Similarly to Reviewer 1, I am surprised that no local authors were invited to contribute to this study. I recommend that the authors consult the EGU statement on Scientific Neocolonialism

Page 2: [7] Commented [MP12R11]	Pittore Massimiliano	15.07.2025 10:10:00

As stated in the conclusions, due to the short timeframe of the project and its extensive requirements and the difficulties related to COVID-19, the contribution from local authors has been unfortunately much smaller than expected. The authors therefore prefer to bear full responsibility for the approaches followed and the choices made. All technical reports, collected and produced data have been shared with the local authorities and potentially interested scientific partners for further studies.

Page 2: [8] Commented [mausdelve13]	mausdelves	15.04.2025 07:12:00

Max - respond to comments
Jess - check English and formatting
Kathrin - prepare/check final manuscript for submission

Page 2: [9] Commented [mausdelve14]	mausdelves	03.04.2025 10:44:00

Reviewer 1 (Dewitte)

However, what I want to point is that in its current version, this research misses the point of being framed around the state of the art knowledge in the region. Besides the implication it has for the science it itself, it is also problematic for the confusing message it could bring to the stakeholders.

Why should new assessments be made if they are not discussed/compared with respect to current ones?

Why should the local knowledge and expertise from researchers based in local institutions, even when available online, not be used?

Page 2: [10] Commented [mausdelve16]	**mausdelves**	**03.04.2025 11:04:00**

Reviewer 1 (Dewitte)

The state of the art is missed, especially on multi-hazard risk assessment. It is thereover difficult to position the research beyond a simple case study in the literature. Furthermore, the introduction brings quite a substantial amount of methodological information. Overall, the introduction reads more like a technical report that an research paper.

Note that the introduction points to cascading and compounding hazards, issues that are barely addressed in the subsequent analysis.

Page 9: [11] Deleted	**Pittore Massimiliano**	**13.07.2025 21:47:00**

Page 9: [12] Deleted	**Pittore Massimiliano**	**13.07.2025 21:47:00**

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Page 9: [14] Commented [mausdelve78]	**mausdelves**	**04.04.2025 10:50:00**

Reviewer 2 (Anon)

My understanding is that population (from Worldpop) was used solely to derive building counts, with no risk-related metrics developed (e.g., casualties, human displacement); only monetary risk metrics were assessed. This should be clearly stated from the outset.

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Page 23: [16] Commented [mausdelve137]	**mausdelves**	**03.04.2025 10:42:00**

Reviewer 1 (Dewitte)

Vulnerability and risk to hazards have also been studied, either from a local perspective (e.g. Nsabimana et al, 2023) or from a regional one (Depicker et al., 2021b).

Page 23: [17] Deleted	**Pittore Massimiliano**	**13.07.2025 22:51:00**

Page 23: [18] Deleted	**mausdelves**	**12.07.2025 19:07:00**

Page 23: [19] Deleted	**Pittore Massimiliano**	**13.07.2025 21:52:00**

Page 23: [20] Commented [mausdelve151]	**mausdelves**	**04.04.2025 11:15:00**

Reviewer 2 (Anon)

Line 342: notes that coping capacity may be one of the highlights and novelties of the manuscript. However, little detail on the methodology and its impact on final results is provided. This should be commented on in the conclusions.

Page 23: [21] Commented [mausdelve153]	mausdelves	16.04.2025 10:30:00

(Lack of) coping capacity is one of the three Dimensions of the INFORM risk assessment framework, and therefore the methodology for its asssessment is the same as for the other dimensions. The text has been edited to better reflect this "In accordance with the INFORM framework,..."

Page 23: [22] Commented [mausdelve154]	mausdelves	04.04.2025 11:17:00

Reviewer 2 (Anon)

Terms “indicators, components, categories, dimensions” is not well separated, and sometimes used interchangeably.