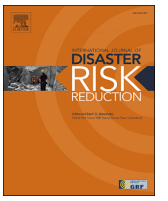
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Exposure and physical vulnerability to geo-hydrological hazards in rural environments: A field-based assessment in East Africa

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ABSTRACT

Geo-hydrological hazards (landslides and floods) are often associated with large impact on physical infrastructures, affecting strongly the exposed population. Understanding in detail the nature of exposure and what determines the extent of impact is a prerequisite for building resilient structures and reducing vulnerability. However, such information is rarely available, especially in rural communities where people are often the most vulnerable. In this study we document the impact of landslide and flood hazards in 17 sub-counties in the mid- and south-western parts of Uganda between May 2019 and March 2021 through extensive fieldwork involving local stakeholders. We quantify the economic value of the physical damage of landslide and flood hazards on exposed buildings, roads and bridges. We then determine statistically the factors that influence the physical vulnerability of the elements at risk based on damage ratios, i.e. monetary value of each individual building damage divided by its initial construction value. A total of 91 and 212 buildings were documented from the landslide and flood hazard affected zones, respectively. Out of the 91 landslide affected buildings, 71 % were completely destroyed and 4 % severely damaged, while 19 % had minor-to-no damage at all. For floods, 37 % of the buildings were completely destroyed and 6 % were severely damaged, while 53 % had minor-to-no damage. The impact of landslides and floods is unevenly distributed across the study sub-counties and the extent of loss they cause also vary with exposed elements. Based on parameters that could be documented through our field-based approach, we conclude that while the physical vulnerability of buildings to landslides is equally associated with both landslide size and building structural characteristics, the physical vulnerability due to floods is largely linked to the flood depth. This quantitative study therefore shows the need for plans, policies and strategies geared towards improving the building resistance to landslides and controlling settlements in flood prone places.

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1. Introduction

Population increase is a worldwide issue, particularly in the Global South where demographic growth is often above average [1]. This growth is commonly associated with uncontrolled and informal settlements; leading already more vulnerable people to settle in areas more prone to geo-hydrological hazards such as floods and landslides [2–5]. Landslides and floods are often associated with large impact on physical infrastructure like buildings, roads and bridges rendering many people homeless or limiting access to critical health care, education, and business centres [6–8]. The impact is expected to increase especially in countries of the Global South due to population increase and the associated land use and land cover change [9,10]. To reduce the risk associated with these hazard processes, there is need to understand not only the hazard components, but also the nature of the elements exposed to the hazards, the impacts induced and what controls the level of impact (vulnerability) [11–13]. This is clearly stressed by the Sendai framework for disaster risk reduction (DRR) which specifies that countries should not stop at hazard identification but rather seek to understand disaster risk in all its dimensions including detailed exposure and vulnerability assessments for comprehensive risk analysis and development of reduction strategies [14]. Although the United Nations International Strategy for Disaster Risk Reduction (UNISDR) has supported many countries to develop national databases of different hazards as a step to risk assessment and management, in most countries, and especially in Africa, it is still a challenge. Previous studies on landslides [15–21] and floods [21,22] have commonly concentrated on hazard assessment and still lack information on exposure and vulnerabilities to explicitly understand the risk and come up with viable reduction strategies [23]. The limited understanding of exposure and vulnerability should be dealt with if more is to be done on reducing risk other than just treating symptoms [24].

Exposure refers to people, property, systems or other natural or artificial assets present in a hazard environment [25]. Vulnerability refers to the degree to which a community, a system, property or element is susceptible to damage by hazard [25]. In the framework of disaster risk analysis, vulnerability assessment can be done following two approaches i.e. the social and physical approach [26]. From the social approach, it encompasses all the socio-cultural, economic, and environmental factors that influence the capacity of an element or society to withstand or cope with the impacts of a hazard [27,28]. The physical vulnerability approach on the other hand looks at the degree of loss or damage (ratio of repair/reconstruction costs to the initial value of the affected building) on an element exposed to a hazard of a certain magnitude or intensity expressed on a scale of 0–1 [29–33].

To evaluate physical vulnerability, the exposed elements must be identified first and quantified [34,35]. Exposure assessment begins with the identifications of elements that might be directly affected by a hazard in case it happens. For each identified element category, different methods are chosen to characterize them in terms of number, spatial distribution, and structural features to ascertain their economic worth [31,36–38]. Identification of exposed elements such as buildings requires a database with geo-referenced housing units and their characteristics such as construction materials and designs, number of floors and rooms, existing protection and maintenance, or economic value [39–41]. Databases related to georeferenced building exposure and vulnerability characteristics are becoming more available, but are still lacking in many countries [42]. As such, previous studies have employed varying techniques to obtain the required data for exposure and vulnerability evaluation. These include the use of orthorectified aerial images [43], integration of digital topographic maps with landcover maps [44], automatic interpretation of high resolution satellite imagery [45] as well as field-based documentation of exposed and impacted buildings to be able to assess their physical vulnerability [46–48]. Although it has become easier to obtain building and road data with the advent of Open Street Map (OSM), there are still uncertainties related to completeness of OSM-based building dataset for some countries [49]. Moreover the OSM building footprints lack information on building structural characteristics, yet such information is crucial for assessing physical vulnerability [50].

Physical vulnerability does not only depend on the characteristics of a hazard (e.g. intensity) but also the pre-existing features (such as building material, size, design and maintenance) of the building [51]. Therefore, constraining a physical vulnerability model usually requires systematic records of historical occurrences (including location, time, size and damages) of damaging events on the physical elements exposed. Such information is difficult to explicitly obtain as the built environment is dynamic. Several approaches to assess physical vulnerabilities to geo-hydrological hazards have been proposed [35]. Majority of them relate physical vulnerability to a function of the intensity of the process (e.g. landslide or flood) and the structural characteristics of the affected element [41,52]. Some studies have evaluated physical vulnerabilities of building and transport infrastructure based on vulnerability indicators, such as structural parameters (type of construction material, number of floors and nature of foundation) that define the resistance of the element and those that relate to the location of the element [26,53–55]. Others propose the use of vulnerability curves (also called loss function or fragility curves) developed from empirical relations between landslide/flood intensities and the impacts caused [35,41,46,56]. From an economic perspective, physical vulnerability of elements at risk can be expressed as a damage ratio (financial amount of damage in relation to the original element value) [57]. Direct physical damage costs can be derived using information from existing insurance figures, real estate prices or interviews conducted with the affected persons and construction engineers [58]. Using systematically collected hazard impact data and quantifying in monetary terms the needed reconstruction costs at regional and local scale can help local authorities and policy makers to come up with appropriate response strategies [59].

However, such kind of data are missing for many parts of the world, leading to most studies to concentrate in specific contexts where lots of insurance data are available. The consideration of building characteristics as indicators of vulnerability has mostly been used for purposes of deriving vulnerability without investigating how each of the indicators influences the extent of damage and yet important for enhancing building resistance to geo-hydrological hazards [60]. Also, such studies are rare in the Global South specifically in rural environments. According to Ref. [61], it is important to investigate how building properties based on local architectural designs and materials influence the impact of geo-hydrological hazards on buildings.

In this study, we focus on the rural mountainous environment of western Uganda (Africa), a region which, like many tropical mountainous highlands, is known to be impacted by landslides and floods and where population vulnerability is high [62–64]. We

document the economic impact of landslide and flood hazards on buildings, roads and bridges in selected sub-counties. Recognizing the potential role of local stakeholders in co-creating knowledge relevant for risk reduction and the need to contextualize the value of physical damage [11], we surveyed local mansion builders and road engineers to derive the damage costs (repair or reconstruction costs) of each affected building, road section and bridge. The physical vulnerability is expressed as a degree of loss of documented buildings in landslide and flood affected zones. Using different physical vulnerability and hazard intensity indicators, the factors that influence the degree of loss are statistically evaluated. However, when a building is affected by a landslide or flood, the impact is not only on the building but also the people inside the building whose vulnerability is partly associated with the physical strength of the building [65]. We therefore present additional field data related to the people who were inside the building at the time of landslide or flood occurrence and an operational approach to monetize the losses associated with persons displaced due to landslide and flood hazards is proposed.

2. Materials and methods

2.1. Study area

The study was conducted in 17 sub-counties of the densely populated zones of the Rwenzori (Kasese and Bundibugyo districts) and Ankole (Buhweju and Bushenyi districts) subregions in western Uganda (Fig. 1). The regions form part of the western branch of the East African Rift that is known to be prone to landslide and flood hazards [17,20,21,66,67]. Kasese and Bundibugyo are districts along the border of Uganda and the Democratic Republic of the Congo: in the last decade, it has experienced frequent geo-hydrological hazards particularly landslides and floods [68–70]. While floods in these two districts are mainly flash floods [71], the nature of landslides differs due to differences in lithological and topographic characteristics [15]: Kasese experiences mostly shallow landslides while Bundibugyo experiences mostly large deep seated landslides; in both districts the landslides recorded in the past decades have been triggered by rainfall [15]. Although most of the previous studies in Uganda have focused in the Rwenzori [66,71–73], Kigezi [21,74,75] and Mt. Elgon [17,20,76] highlands, Buhweju and Bushenyi districts are also susceptible to floods and landslides [77]. The study districts in both subregions (Rwenzori and Ankole) have a high average population density of 250 and 219 inhabkm^{-2}, respectively, compared to the national average of 173 inhabkm^{-2} [78]. The housing conditions in the study districts are also largely semipermanent, that is, building walls are made of mud and pole (on average 71 % and 69 % for Rwenzori and Ankole study areas, respectively), making them vulnerable to geo-hydrological hazard impacts. The study region is characterized by a bi-model rainfall pattern (March to May and August to November) with the mean annual rainfall ranging from 800 mm to 2000 mm although it can be higher than 2500 mm in the very high altitude zones of the Rwenzori mountains [79].

2.2. Field-based landslide- and flood impact assessment

Between September 2020 and March 2021, the impact of landslide and flood hazards on buildings, people in the buildings and road infrastructure were systematically documented through fieldwork in the 17 selected sub-counties (Fig. 2). The selection of the sub-counties was informed by the existing records made by citizen scientists [80] and previous studies [15,69,81]. For flood impact assessment, sub-counties adjacent to the major rivers in the subregions were selected since most flood occurrences are localized along major rivers. Landslide impact documentation on the other hand was done across the geographical space covered by the selected sub-counties since landslide occurrences are spatially spread. For flood and landslide impact documentation, all the buildings located in the flooded area or zone affected by slope failures (including zone from which the mass movement initiated as well as the deposition area), respectively, were observed in the field and documented using a standard digital questionnaire irrespective of extent of damage. For each of the parishes in the selected sub counties, a local guide was selected in consultation with the sub-county community development office to guide the identification of buildings affected by landslides with the help of local leaders and local residents. With these local guides, all landslide/flood occurrences with recorded damage were visited.

To ensure all the relevant information was captured, a structured digital questionnaire (full details in Supplementary file A.docx) was used regarding the affected building and the people who were in the building at the time of the hazard occurrence (see Table 1). Information that was recorded for each building included hazard related data (location, size of landslide/flooded area, flood depth, time of occurrence and estimated distance to river channel); damage related information (extent of damage on buildings: see Table 2 for detailed description; damage on roads and bridges); damaged infrastructure characteristics (location of the affected building or road, the size of the building, structural characteristics of the building: wall, floor and roof materials, building foundation platform, number of rooms, type of use, age of the building, number and characteristics of the occupants in the case of a homestead building). The building typologies were pre-categorized as listed in Table 2, based on the building categories given by Uganda Bureau of Statistics (UBOS) and the already built experience in the study area ([78]; Table 2). However, after fieldwork, due to limited or no records for some building typologies, the nine categories were regrouped into five categories (Table 2, column 3) used thereafter for analysis. The schematic diagram illustrating the stepwise process followed throughout the research is given in Fig. 3.

2.2.1. Damage cost estimation and physical vulnerability

2.2.1.1. Damage on buildings. The costs of damage on building by landslides or floods are generally expressed as costs of repair (for partial damages) or reconstruction costs [33,52,58]. Reconstruction costs here include value of materials and labour but do not include value of land. In situations where uniform building typologies and costs exist, reconstruction costs are derived from local authority or insurance companies [35,56]. In western Uganda rural communities, people largely depend on local construction engineers and mason builders to estimate the costs associated with the reconstruction or repair of damaged buildings. The values usually depend on the sizes of the buildings (defined in terms of number of rooms) and type of construction materials.

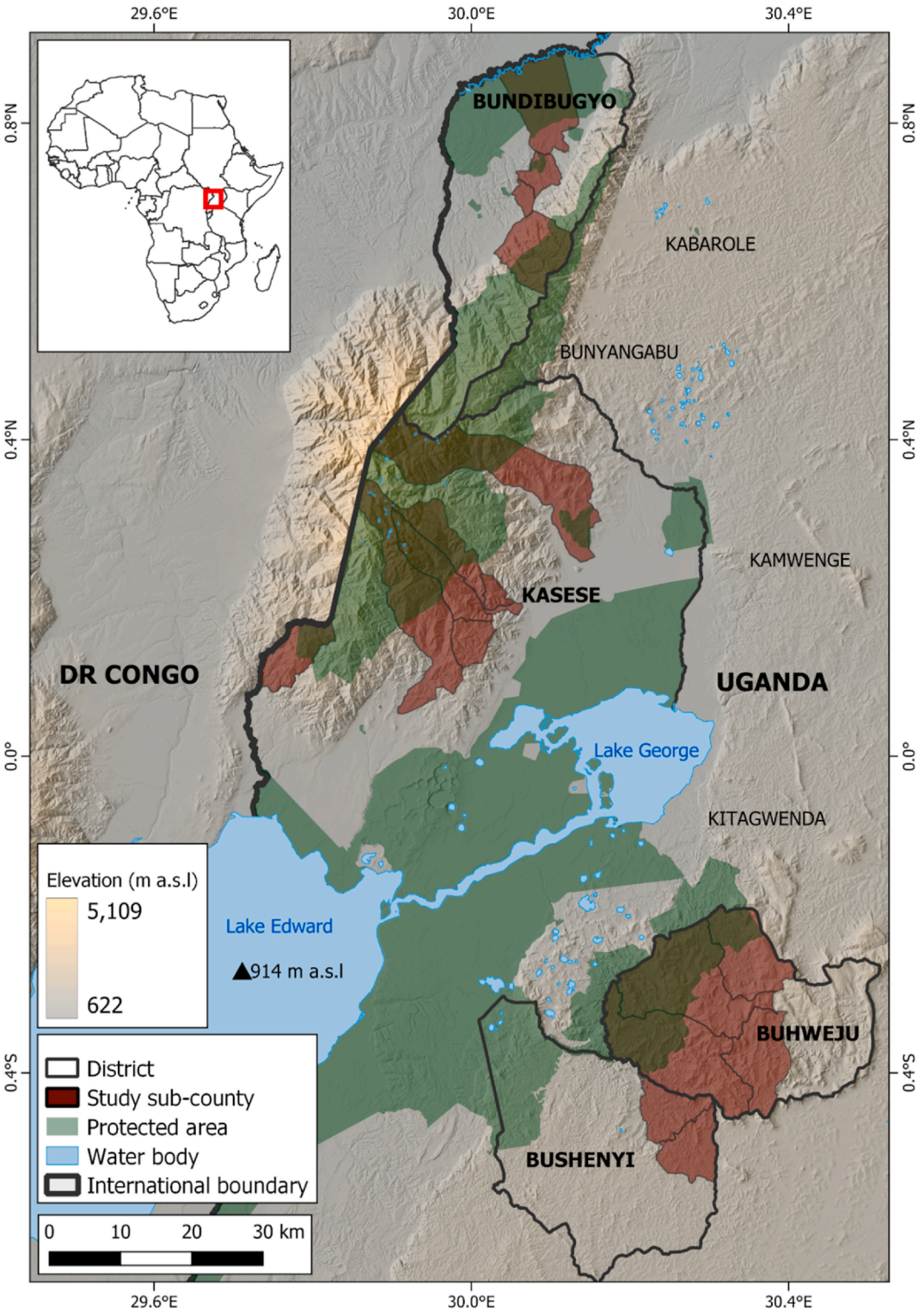


Fig. 1. Location of the 17 studied sub-counties (coffee brown) in each of the districts. Protected areas are natural areas with no settlements.

Within the 17 sub-counties considered during impact documentation, six sub-counties were selected for damage cost/reconstruction cost estimation with the help of local authorities. Forty eight experienced local engineers/mason builders (eight from each of the six sub-counties (2 in Kasese; 2 in Bundibugyo; 1 in Buhweju and 1 in Bushenyi) were identified and engaged both individually and in groups to estimate the costs of building construction/reconstruction and repairs based on predefined building typologies and extent

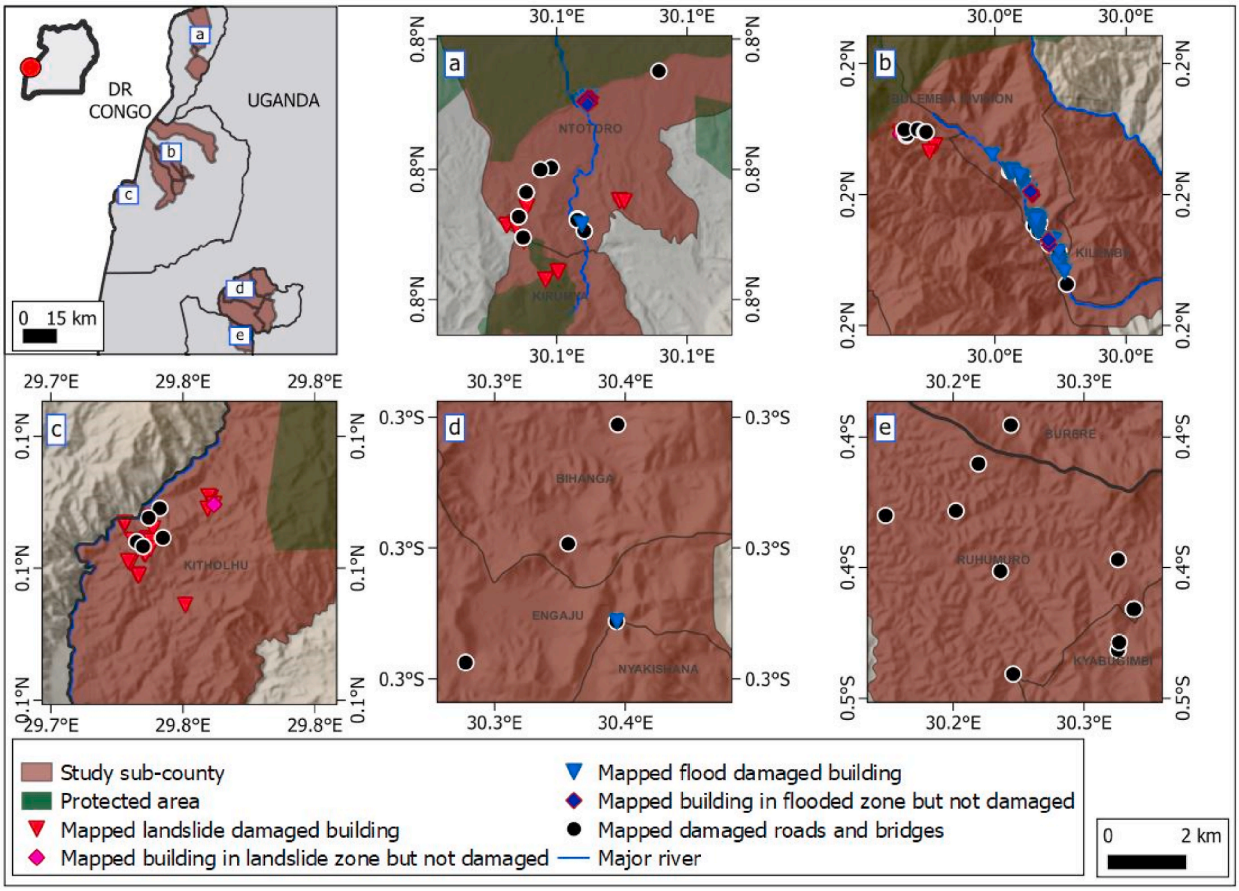


Fig. 2. Example of spatial distribution of documented damage associated with floods and landslides in Bundibugyo (a), Kasese (b and c), Buhweju (d) and Bushenyi (e) districts.

Table 1
Characterization extent of building damage in the field.

Extent of building damage	Description
No damage at all	Building in landslide/flood zone but not affected and normally occupied
Slightly/minorly damaged	Buildings with small cracks that only required replastering without the occupants vacating or dampness of the floor
Moderately damaged	Buildings with major crack in the wall (a big crack in the building wall that necessitated the occupants to vacate the particular room until its well repaired), minor wall collapse that can be repaired and some rooms cannot be used without repair
Severely damaged	Building with bigger part of the wall or roof completely destroyed
Completely destroyed	Building totally destroyed by the landslide/flood and require reconstruction

of damages. Average costs per type and size of building for each sub-county were calculated and used to derive median costs for the different types and sizes of buildings and types of repairs documented for all studied sub-counties of each district. The common building types that were considered are as indicated in Table 2 although no iron sheet or timber buildings were observed in the affected zones that were visited. For each building type, the cost estimation was done for different sizes ranging from a single roomed building (considered as the smallest) to six rooms (considered as the most common large houses). First, each of the eight mason builders selected from a specific sub-county was given one week to value the different building types before bringing them together in a group. Average cost estimates from respective sub-counties were used to value district specific building damages because the cost estimates differ across districts depending on the source of raw materials and distance of the building site from the nearest business hub where key material like cement, iron sheets, etc are bought, and the terrain. In addition, the construction labour costs charged by a given mason builder partly depends on what is commonly charged by other builders in the same locality. Beyond a district or region, this kind of influence stops to exist. The physical vulnerability (in this paper also referred to as the degree of loss) due to landslide and flood hazards for each building was then determined.

Table 2
Building material categorization in the field (column 1 and 2) and regrouping for the analysis (column 3 and 4).

Building typology	Description	Regrouped building typologies	Category in terms of durability (UBOS, 2016)
Cement blocks	Compressed sand and cement blocks	**Cement blocks**	Permanent
Bricks with cement and plaster	Stabilized mud brick wall constructed with sand and cement mixture and plastered	**Brick and cement**	Permanent
Bricks with cement but no plaster	Stabilized mud brick wall constructed with sand and cement mixture but not plastered	**Brick and cement**	Permanent
Bricks with murram and plaster	Stabilized mud brick wall constructed with mud but plastered with sand and cement mixture	**Brick and murram**	Permanent
Bricks with murram but no plaster	Stabilized mud brick wall constructed with mud and not plastered	**Brick and murram**	Permanent
Mud and pole with plaster	Wall made of wood poles, mud and reeds but plastered with sand and cement mixture	**Mud and pole with no plaster**	Semipermanent
Mud and pole with no plaster	Wall made of wood poles, mud and reeds and not plastered	**Mud and pole with plaster**	Semipermanent
Wood	Wall made of timber alone	No impact recorded on this type of building	
Iron sheets	Wall made of iron sheets alone	No impact recorded on this type of building	

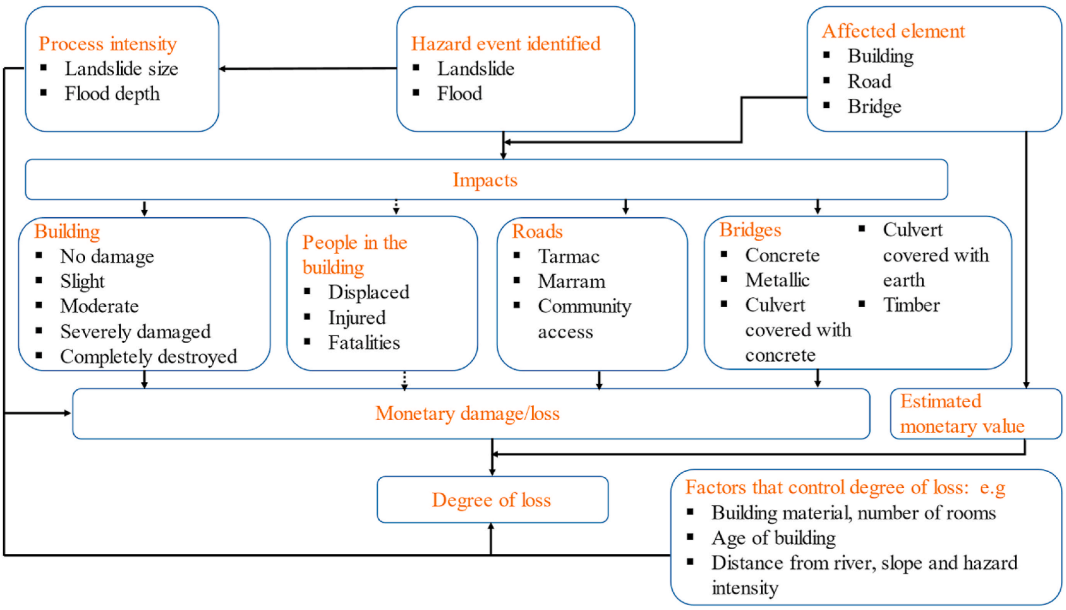


Fig. 3. Flowchart of the applied approach for the assessment of the factors that control physical vulnerability.

2.2.1.2. Impact on people in the buildings. For the damage on people in the buildings, although a number of flood events caused injuries and claimed lives, there were no sufficient data records to be analysed. Therefore we focused on the displaced people; more specifically on the costs associated with the displacements. The data were obtained through fieldwork. When a landslide or flood damages a homestead building, the occupants usually have three options. They either move to designated rescue camps, they are given refuge by relatives or rent houses in safer places [82] as they look for resources to reconstruct or repair the damaged houses. Because of the complexity in documenting and validating the costs associated with accessing the gardens, the inconveniences to those sheltered by relatives, replacing homestead utensils and beddings, the period spent away from the homestead (in weeks) was recorded and the standard average rent fees per bedroom per month in the affected sub-counties were used as proxies for the costs related to displacements. For homesteads that had not yet returned to their homes at the time of data collection, only the period up to the time of data collection was considered. As such, the longest period of displacement recorded was up to 16 months (for the homesteads that were displaced by major flood/landslide of October–December 2019). Where a homestead constituted more than five members displaced, a double roomed house was considered while a homestead that consisted of less or equal to five members displaced, a single room was considered.

2.2.1.3. Damage on roads and bridges. In the same way, the average cost per meter length of a damaged or destroyed section of the road network and bridges were estimated in consultation with the district road engineers based on the predefined types of roads and bridges. A section of the road/bridge found in the affected zone was recorded as either damaged or not damaged, there was no characterization of the extent of damage. The types of roads considered in this study include tarmac, main murram (dirt road that

connects villages to trading centres and town councils) and community access roads. To highlight extent of damage on the entire road network (km) per type of road affected, an OpenStreetMap (OSM) road data was accessed via the Humanitarian OpenStreetMap website and used to determine the total road length per road type in QGIS [83]. In OSM, the roads are classified as paved, asphalt, unpaved, compacted and unclassified. Here paved and asphalt roads are considered as tarmac, unpaved and compacted are considered as main murram while the unclassified are considered as community access roads. OSM road data has in some studies been found more complete than existing national road data [84,85]. For the bridges, the types included concrete (reinforced) bridge, metallic bridge, culvert covered with concrete, culvert covered with earth and timber bridge. The impacts associated with temporary road closure were not documented because such temporary road blockages are usually quickly unblocked by community members using their local tools. This made it difficult to document and monetize such impact.

2.3. Factors that control the physical vulnerability

Physical vulnerability in this study is defined as a relative estimate of the extent of loss to a given element or elements located within a hazard affected area [86]. The physical vulnerability for each building identified in the flood or landslide affected zone (Fig. 4) was expressed as a ratio of the repair/reconstruction costs and initial monetary value of the affected building [87,88]. To be able to determine the factors that control the degree of loss due to landslide or flood damage, descriptive statistical analysis was first carried out to understand the nature of the data generated (Appendix A). As the degree of loss data is bounded between 0 and 1 and most values were clustered either near 0 or towards 1, a fractional logistic regression modelling approach (calibrated using all the field data collected) was used following a backward elimination method [89] to arrive at the final model results containing the significant factors that control the degree of loss [90–94]. Fractional logistic regression is a modelling approach based on quasi-likelihood method recommended to estimate continuous variables bounded between zero and one where some values are either clustered near zero or one [93,95]. For both landslides and floods, the regression analysis was done at three levels.

- First it was conducted with the degree of loss against hazard related factors: size of landslide or flood affected area, flood depth and distance to river channel for the case of floods;, slope, and landslide susceptibility for the case of landslides. The susceptibility was extracted for each location of the recorded building from the regional western branch of the East African rift landslide susceptibility map produced using a logistic regression model [96].
- The analysis was then repeated using building related factors: type of building material, number of rooms, size of the building, building foundation platform and age of the building.
- Lastly, an analysis combining both physical vulnerability factor categories was done. However, to take care of the potential influence of district specific characteristics, a district dummy variable was tested in the model.

At each stage multicollinearity (i.e. situation where independent variables in a model are correlated [97]) tests were performed by calculating the variance inflation factor. To get insights on the contribution of each significant factor, a univariate fractional logistic regression for each factor was performed using the degree of loss as a dependent variable. The McFadden R^2 - one of the common pseudo-R^2 statistics for evaluating predictive powers for logistic regression models [98] was then used as an indicator of the percentage controlled by each of the factors [18]).

3. Results

3.1. Landslide and flood impact documentation

A total of 91 and 212 buildings (including homestead, commercial, public office, health centre, worshiping centre and school directly located in 72 landslide and 39 flood affected zones, respectively, were documented for the period between May 2019 and March 2021. Occurrences that had no known history of reaching buildings, roads or bridges were not visited during fieldwork. Out of the 91 buildings found in the landslide-affected zones, 71 % were completely destroyed and 4 % severely damaged (Table 3). The fraction of completely destroyed buildings was even higher for the Bundibugyo district (95 %). Only 19 % had minor-to-no damage at all. On the other hand, only 37 % of the 212 buildings documented in the flooded zones were completely destroyed while 6 % were severely damaged. 53 % had minor-to-no damage. The analysis showed that, over our short period of observation, landslide and flood damage on buildings are almost absent in the Ankole subregion (Bushenyi-Buhweju) compared to the Rwenzori subregion (Table 3). This however neither implies that Ankole subregion is not affected by landslide and flood hazards nor does it mean the building types in the subregion are resilient to the hazards. The impact on roads is evidence that landslides and floods do occur (Table 4).

The houses affected by landslides are largely (64 %) semi-permanent buildings (mud and pole plastered + not plastered). To the contrary, permanent buildings (54 %; brick and cement + cement block) are slightly more affected by floods (Fig. 5). This contrast can be attributed to the fact that landslide hazard is more spatially spread in remote villages where semi-permanent dwellings dominate while flood impacts are more localized along rivers flowing through urbanized and growing centres.

A total of 699 m of damaged road (0.1 % of total road network in the study sub-counties) was recorded from 38 landslides comprising mainly of community access roads (88 %). On the other hand, a length of 1621 m of damaged road (0.3 % of total road network in the study sub-counties) comprising mainly of tarmac roads (58 %), with lower fraction of main murram and community access roads, was recorded from the 39 flood affected zones (Table 4). Up to nine concrete bridges and 10 culverts covered with earth damaged by floods were recorded in the study area.



Fig. 4. Examples of physical damage by landslides on buildings (a and b) and roads (e) and physical damage by floods on buildings (c and d), roads (f) and bridges (g and h) documented during fieldwork.

3.2. Landslide and flood monetary loss

Although there were more buildings affected by floods than landslides (Table 5), the median monetary loss per building is five times higher for landslides ($1097) than for floods ($190). This is mainly because a higher proportion (71 %) of the buildings affected by landslides (Table 3) was completely destroyed while those affected by floods were almost equally distributed between the minorly damaged (46 %) and the completely destroyed (37 %). When considering the total damage costs of buildings, floods are responsible for slightly higher costs (343 k$) than landslides (265k$). Kasese district is mostly affected by high costs from floods, whereas Bundibugyo bears much larger costs from landslides.

The estimated average cost per 100 m of tarmac, main murram and community access roads in the study sub-counties is approximately $41,740, $1042 and $762 respectively. A unit cost per concrete bridge depends on the span length while that of a culvert depends on the diameter, span length and whether the culverts are covered with concrete or earth. The span length of the concrete bridge and culverts that were damaged by the flood hazard ranged between 6-20 m and 2.5–8 m respectively. The average estimated

Table 3
Statistics of the level of damage of buildings documented in landslide and flood-affected areas per district.

Geo-hydrological hazard	Extent of damage	Bundibugyo	Kasese	Buhweju	Bushenyi	Total
Landslide	No damage all	0	2	0	0	2 (2 %)
	Minor damage	2	13	0	0	15 (17 %)
	Moderately damaged	0	5	0	0	5 (6 %)
	Severely damaged	0	4	0	0	4 (4 %)
	Completely destroyed	43	22	0	0	65 (71 %)
	Total	**45 (49 %)**	**46 (51 %)**	**0**	**0**	**91**
Flood	No damage at all	10	6	0	0	16 (7 %)
	Minor damage	42	54	1	0	97 (46 %)
	Moderately damaged	3	5	0	0	8 (4 %)
	Severely damaged	2	10	0	0	12 (6 %)
	Completely destroyed	43	36	0	0	79 (37 %)
	Total	**100 (47 %)**	**111 (52 %)**	**1 (1 %)**	**0**	**212**

Table 4
Length of damaged roads due to landslide and flood, per road type and district (in meters) as documented in the field.

Geo-hydrological hazard	Type of road	Bundibugyo	Kasese	Buhweju	Bushenyi	Total
Landslide	Tarmac	0	0	0	0	0 (0 %)
	Main murram	0	56	27	0	83 (12 %)
	Community access	364	113	75	64	616 (88 %)
	Total	**364**	**169**	**102**	**64**	**699**
Flood	Tarmac	30	915	0	0	945 (58 %)
	Main murram	80	125	40	20	265 (17 %)
	Community access	55	187	114	55	411 (25 %)
	Total	**165**	**1227**	**154**	**75**	**1621**
	Bridges					
	Concrete	3	3	0	3	9
	Culvert covered with earth	3	2	4	1	10
	Total	**6**	**5**	**4**	**4**	**19**

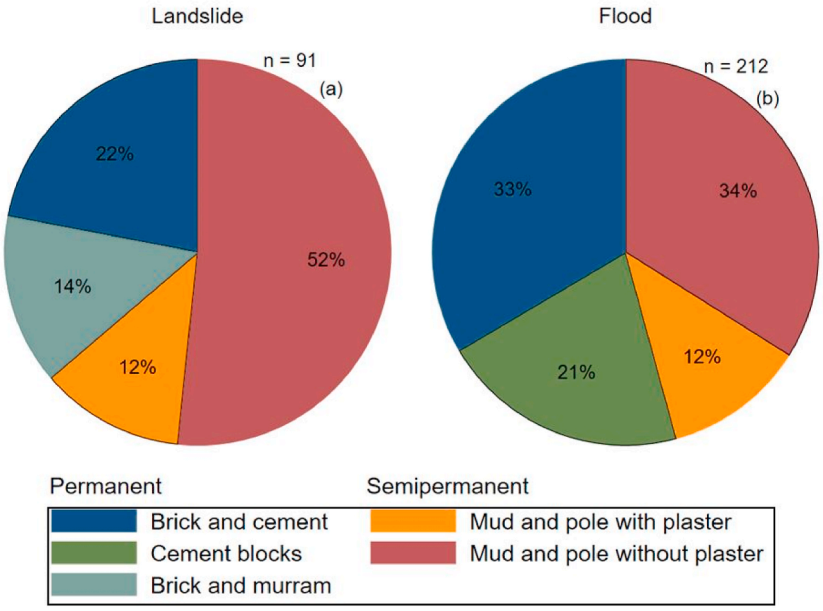


Fig. 5. Percentage of different building types in landslide (a) and flood-affected (b) areas across the 17 sub-counties.

costs per concrete bridge of span lengths 5–10 m and 10–20 m are $187,500 and $375,000 respectively. On the other hand, the average estimated costs per culvert covered with earth of span lengths 2–5 m and 6–9 m was estimated at $700 and $1200 respectively. The absolute total monetary loss per road type and bridge are summarized in Table 6. While landslides affect mainly the community access roads (84 % of the total road network damage costs), floods affect dominantly the main transport (tarmac) roads (98 % of the total road network cost damage by floods). In addition, looking at Tables 5 and 6, landslides impact more on buildings than road in-

Table 5
Median monetary loss per building for different level of damage for buildings affected by landslides and floods (1 USD = 3600 Uganda shillings (Ug.Shs)).

Extent of damage	Landslides			Floods		
	Number	(Ug.Shs * 10^3)	USD	Number	(Ug.Shs * 10^3)	USD
No damage at all	2	0	0	16	0	0
Minor damage	15	570	158	97	230	69
Moderately damaged	5	680	189	8	290	83
Severely damaged	4	2100	583	12	1000	278
Completely destroyed	65	5000	1390	79	6600	1830
Median	**91**	**3950**	**1097**	**212**	**687**	**190**
Total loss						
Kasese	46	153,000	42,500	100	906,000	251,700
Bundibugyo	45	802,000	222,800	111	330,000	91,700

Table 6
Estimated economical costs of damage to the road network and bridges for landslides and floods.

Geo-hydrological hazard	Type of road	Length (m)	Damage cost (Ug.Shs * 10^3)	Amount in USD (I USD = 3600 Ug.Shs)
Landslide	Tarmac	–	–	–
	Main murram	83	3113	865
	Community access	616	16,900	4694
	Total	**699**	**20,013**	**5559**
Flood	Tarmac	945	1,420,000	394,444
	Main murram	265	9938	2760
	Community access	411	11,300	3139
	Total	**1621**	**1,441,238**	**400,343**
	Bridge			
	Concrete	9	8,100,000	2,250,000
	Culvert covered with earth	10	32,000	8890
	Total	**19**	**8,125,000**	**2,258,890**

frastructure while flood hazard impact is equally high for building and road infrastructure. Overall, the destruction of bridges is by far the main economic impact of flood hazards.

3.3. Landslide and flood monetary loss due to people displacement

On average, every homestead displaced by a landslide in the study sub-counties takes six months (ranging from 0 to 16) to re-establish and return to the original homestead while those displaced by a flood takes on average 3.5 months (ranging from 0 to 15). The average monthly price of rent/homestead displaced in the study area is $33 ranging between $14 (single roomed) to $58 (double roomed house). A total of 61 and 143 homesteads were displaced for varying periods by landslides and floods respectively (Table 7). Although there is no big difference between the number of homesteads displaced by landslides across districts, the period of displacement and consequently the total loss associated with displacements due to landslides in Bundibugyo is more than double that of Kasese – which can be accounted for by more severe damage to building in that district. On the other hand, the total loss associated with people displacements due to floods is much higher in Kasese compared to Bundibugyo (Table 7). Overall, the total costs of displacement due to flood hazard almost double that of landslides, despite the number of months being not so different. A pairwise spearman's rank correlation analysis (Appendix B) revealed that the duration of the period during which people were displaced before returning to their original homes is significantly positively associated with the degree of loss, size of the homestead, and the intensity of hazard (landslide size/flood affected area) and negatively associated with the size of the building.

3.4. Landslide and flood physical vulnerability

The average degree of loss is systematically larger for landslides than floods for all building types (Table 8); with higher degree of loss for mud and pole buildings for landslides, and mud and pole buildings without plaster for floods.

Table 7
Monetary losses associated with homestead displacements due to landslides and floods.

Geo-hydrological hazard	Cost due to displacement	Bundibugyo	Kasese	Total
Landslide	Number of homesteads	33	28	61
	Total number of months	400	116	516
	Amount (Ug.Shs * 10^3)	34,700	14,700	49,400
	Amount (USD)	**9640**	**4080**	**13,720**
Flood	Number of homesteads	65	78	143
	Total number of months	403	332	735
	Amount (Ug.Shs * 10^3)	33,500	56,500	90,000
	Amount (USD)	**9305**	**15,695**	**25,000**

Table 8
Average physical vulnerability of different building types to landslide and flood hazards with interquartile range in parentheses.

Geo-hydrological hazard	Building type	Number of buildings	Average degree of loss
Landslide	Brick and cement	19	0.62 (0.93)
	Brick and murram	14	0.39 (0.94)
	Mud and pole with plaster	11	0.83 (0)
	Mud and pole without plaster	47	0.86 (0)
Flood	Brick and cement	71	0.34 (0.97)
	Cement blocks	44	0.39 (0.97)
	Mud and pole with plaster	25	0.29 (0.98)
	Mud and pole without plaster	72	0.59 (0.96)

The vulnerability curves of buildings for landslide and flood hazards were respectively constructed by plotting the degree of loss against landslide size and flood depth as proxies for landslide and flood intensities respectively (Fig. 6). For each of the hazards, a logistic curve was fitted. Although a large scatter exists, Landslides exceeding 100 m^2 in size (Fig. 6a) and flood depth greater than 1 m (Fig. 6b) are very likely to cause complete destruction of the exposed building. Degree of loss for lower level of damage typically does not exceed 0.2 (or 20 % of the original value of the building).

For landslides, while the majority of buildings documented in Bundibugyo were completely destroyed, the degree of loss in Kasese is more distributed across the scale (Fig. 7a). The degree of loss is high for the <10 m^2, as these correspond mainly to retaining wall collapse on building whose impact can be very large although small in size.). The loss is however generally higher among larger landslides and buildings made of mud and pole materials (Fig. 7(b and c)). The scatter plots illustrate a contrasting distribution of the degree of loss across the slope in the two districts of Kasese and Bundibugyo. While more building damage was recorded in the steep slopes of Kasese, the damages in Bundibugyo were found more in the lowlands with lower slope (Fig. 7d). This contrast however is partially accounted for in the landslide susceptibility (Fig. 7e) that includes the different lithologies. Fig. 7 (f) shows that most of the buildings affected by landslides are recent.

Generally there are more old buildings affected by floods in Kasese than in Bundibugyo (Fig. 8a). The degree of loss due to floods is higher among the schools although the numbers of schools recorded are low compared to other types of buildings (Fig. 8e). High degrees of loss are also associated with buildings built out mud and pole without plaster (Fig. 8f) and with buildings with total earth floor material (Fig. 8g). Higher degree of loss are also recorded for flood of larger area and deeper water, whereas the slope and the age of the building do not seem to influence the degree of loss.

Considering landslide hazard and building structure related factors separately, the regression analysis revealed that landslide hazard related factors (landslide size, distance to river channel and landslide susceptibility) control about 24 % of the variations in the degree of loss of landslide on buildings (pseudo $R^2 = 0.242$; Prob > chi2 = 0.000). On the other hand, building structure related factors (age of the building, building wall material and building foundation platform) control about 30 % of the variations in the degree of loss on buildings (pseudo $R^2 = 0.301$; Prob > chi2 = 0.000).

When both landslide hazard and building structure related factors are considered in the same model (Table 9), the degree of loss is significantly influenced by the age of the building, type of building wall material, landslide size and other area specific factors - here bundled together and included as a district dummy variable in the model (pseudo $R^2 = 0.375$; Prob > chi2 = 0.000). The dy/dx column represents the marginal increase or decrease in chances of the degree of loss increasing due to a unit increase in the explanatory variable. A one year increase in the age of the building increases the chances of the degree of loss tending to one (complete destruction) by 1 %. When the building wall material change from brick and cement to mud and pole with or without plaster, the chances of the degree of loss of the building being 1 increases by 13 % and 19 % respectively although the change is only significant with the

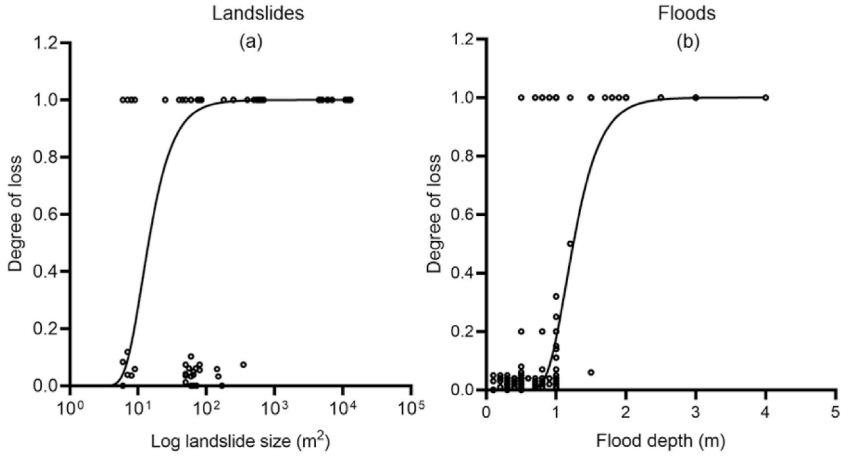


Fig. 6. Vulnerability curves of buildings for landslides (a) and floods (b).

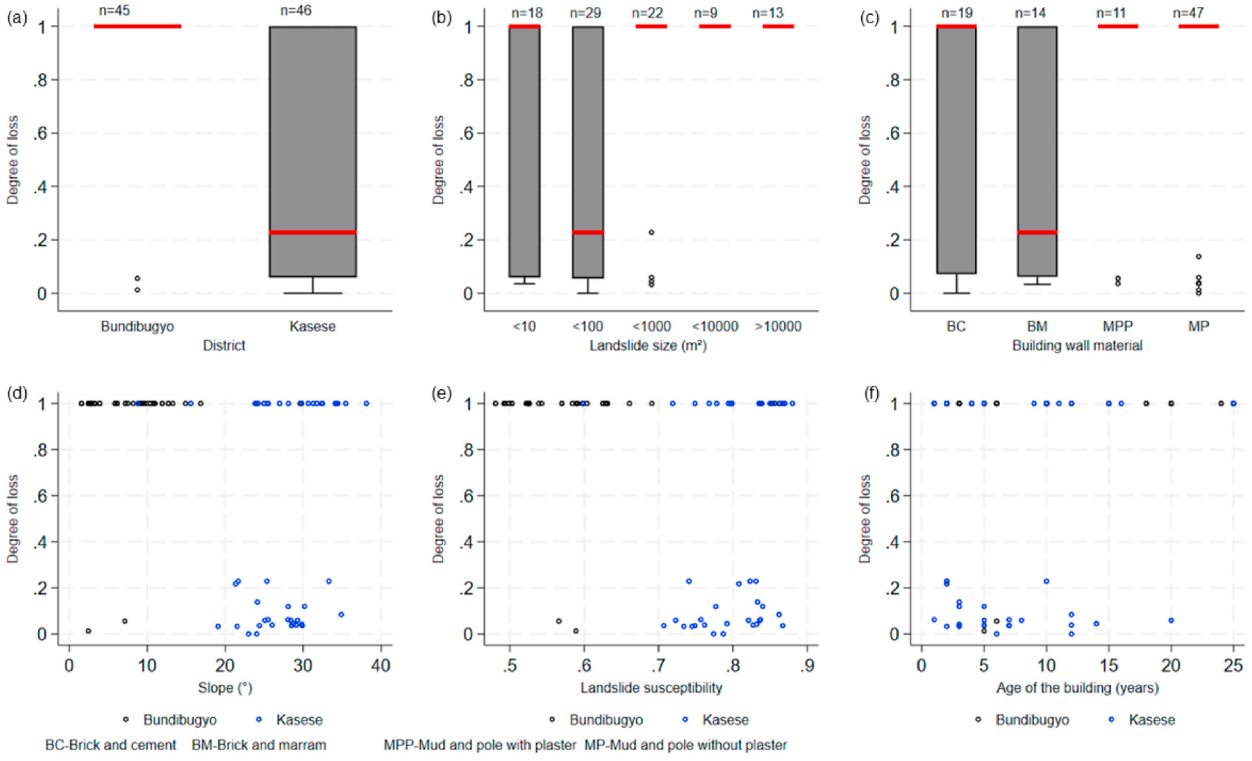


Fig. 7. Box and scatter plots showing the distribution of degree of loss due to landslide damage on buildings across geographical space (a), landslide size (b), building wall and materials (c), slope (d), landslide susceptibility (e) and age of the building (f). The red line on the boxes represents the median. Where only one red line exists without a box, it implies that all the degree of loss values are either zero or one. The small black hollow circles (in a, b and c) represent outliers.

mud and pole without plaster buildings. Also if the landslide size increases from below 10 m^2 to above 1000 m^2, the chances of the building being destroyed increases by 22 %, other factors kept constant. The odds ratios for the building affected by landslides between 1000 m^2 and 1 ha and those exceeding 1 ha are very high because all the buildings recorded within these landslide size categories were completely destroyed. The results also show the buildings in Bundibugyo have higher chances of being destroyed by landslides than those in Kasese. Slope and landslide susceptibility were tested in the model but due to multicollinearity issues and their strong association with district specific characteristics, they were dropped.

For degree of loss due to floods, the regression results show that hazard related factors (flooded area, slope, distance to river channel and flood depth) control about 61 % of the variations in the degree of loss (pseudo $R^2 = 0.610$; Prob > chi2 = 0.000). On the other hand, the building structure related factors (age of the building, size of the build, building wall material and floor material) control only 11 % (pseudo $R^2 = 0.110$; Prob > chi2 = 0.000). When both flood hazard and building structure related factors are combined in the same model (Table 10), the degree of loss is significantly influenced by the type of building wall material, flooded area, slope and flood depth (Pseudo $R^2 = 0.687$; Prob > chi2 = 0.000). A district dummy and building age variables were tested in the model but excluded due to multicollinearity. The results show that the chances of the degree of loss being one significantly reduces when a mud and pole building is plastered and significantly increases when a mud and pole building is not plastered (Table 10). A 1 m increase in flood depth, increases the chances of the building being destroyed by 37 %. On the other hand, a unit increase in slope angle (measure of the steepness of slope determined by the tangential angle at a given point on the land surface) increases the chances of the building being destroyed by 1 %. Increase in flooded area from between 10 and 100 m^2 to flooded area between 100 and 1000 m^2 significantly increases the building degree of loss.

4. Discussion

4.1. Absolute versus relative monetary loss

While different buildings with varying structural characteristics can have the same degree of damages (e.g. one if buildings are completely destroyed), the average monetary loss varies depending on the type of materials and size of the building. Depending on the type of building and the number that is completely destroyed in a particular area, the total monetary loss can vary across different geographical space irrespective of the type of hazard (Table 5). According to Ref. [70], the average total annual loss of buildings due to landslides in Kasese and Bundibugyo districts is $50,000 and $10,000 respectively [70]. Kasese and Bundibugyo districts are constituted by 30 and 19 sub counties respectively. Comparing the World Bank estimates with the estimates from this study for landslides occurring over two years ($42,500 for Kasese; seven sub counties and $222,800 for Bundibugyo; 4 sub counties (Table 5)), the World Bank study appears to be of the same order of magnitude as our results for Kasese while it underestimates the landslide cost of damage

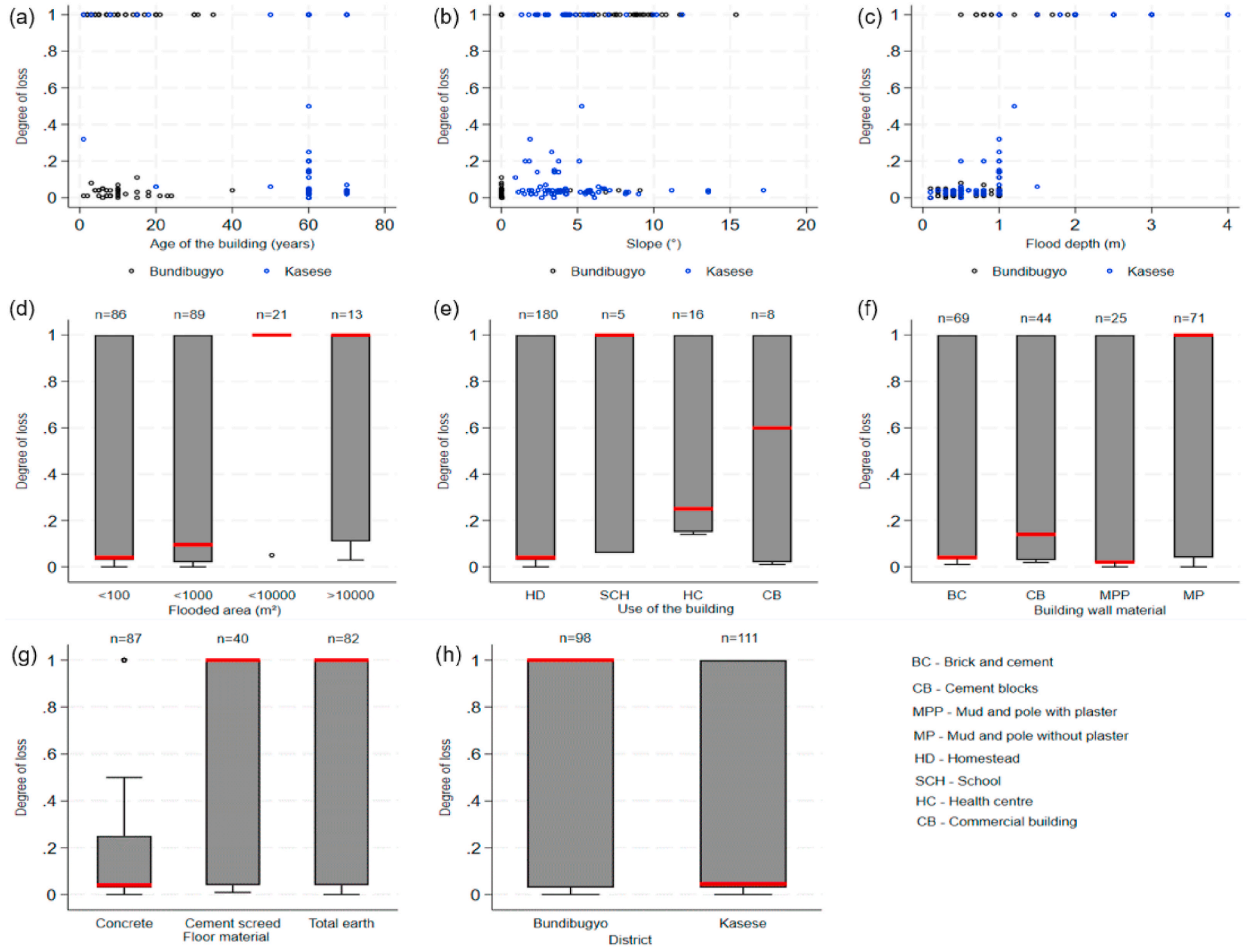


Fig. 8. Box and scatter plots showing the distribution of degree of loss due to flood damage on building across age of the buildings (a), slope (b), flood depth (c) flooded area (d), use of the building (e), building wall (f) floor materials (g) and districts (h). The red line on the boxes represents the median. Where only one red line exists without a box, it implies that all the degree of loss values are either zero or one.

Table 9
Fractional logistic regression results of the building degree of loss due to landslides and univariate analysis of the significant variables. *p < 0.05

Variable	Odds ratio	dy/dx	Univariate McFadden's R^2
Age of the building	1.089*	0.010	
Building wall material			
Bricks and cement	Reference category		0.118
Bricks and murram	2.667	0.131	
Mud and pole with plaster	4.269	0.128	
Mud and pole no plaster	7.139*	0.188	
Landslide size			
Less than 10m^2	Reference category		0.204
Between 10 and 100m^2	0.249	−.204	
Between 100 and 1000m^2	1.555	0.052	
Between 1000 and 1ha	7.731E+6*	0.218	
More than 1ha	3.967E+6*	0.218	
District ID			
Kasese	Reference category		
Bundibugyo	7.628*	0.237	0.241
Constant	0.302		
Pseudo R^2	**0.375**		

Table 10
Fractional logistic regression results of the building degree of loss due to flood hazards and univariate analysis of the significant variables. *p < 0.05

Variable	Odds ratio	dy/dx	Univariate McFadden R^2
Building wall material			
Brick and cement	Reference		.050
Cement blocks	.619	−.030	
Mud and pole with plaster	.190*	−.086	
Mud and pole no plaster	18.700*	.264	
Flooded area			
Between 10 and 100m^2	Reference		.145
Between 100 and 1000m^2	2.113	.050	
Between 1000 and 1ha	14.630*	.217	
More than 1ha	.354	−.058	
Flood depth	328.486*	.372	.542
Slope	1.250*	.014	.048
Constant	.000		
Pseudo R^2	**.687**		

on buildings in Bundibugyo. Although we did not survey all sub-counties in Kasese, we focused on the most affected ones. The differences in Bundibugyo can be attributed to the difference in spatial scales and methods between the two studies. While estimates in this study are based on field-based inventories and area specific costing by local engineers for events happening over two years in selected sub-counties, the World Bank assessment was based on publicly available exposure and hazard information in global and national databases that might miss some details [70].

Our estimated total loss of buildings due to floods was higher in Kasese ($251,700) than Bundibugyo ($91,700). This agrees with the [77] assessment that estimated the range of the maximum yearly flood damage on buildings in Kasese and Bundibugyo districts to range respectively between $257,670 – $3,415,000 and $257,670- $653,300 given that the OPM results are at a district scale (four times bigger than the scale of this study). Results of our study cannot be directly extrapolated to long term yearly average costs at district level, but provide detailed data against which a more regional approach should be calibrated.

The total monetary loss on roads is different for landslides and floods and depends mainly on the type of road affected. According to Ref. [59], the variations in the costs of damaged road due to landslides depend on the types of roads and the density of landslides in that particular area [59]. Although more buildings and road length can be damaged due to landslides and floods, this study shows that the damage to bridges due to floods is the most important type of damage in terms of absolute total costs ($2,258,890 compared with $788,022 value of building, roads and people displaced all combined). This is also illustrated in Fig. 9. Because of one concrete bridge documented in Bushenyi district, its share on the total absolute monetary loss goes up to 23 %. A team of consultants constituted by the Uganda Ministry of Water and Environment (MWE) estimated the cost of repairing nine bridges and major roads due to the May 2013 Kasese floods at $2million [99]. This estimate is not far from the estimates from this study since the documented road and bridge impact in Kasese represents over 75 % of the total impact document on roads and bridges. Overall, the total monetary loss is significant but not equally distributed (Fig. 9). For landslides, the monetary loss on buildings account for 95 % and 89 % of the total

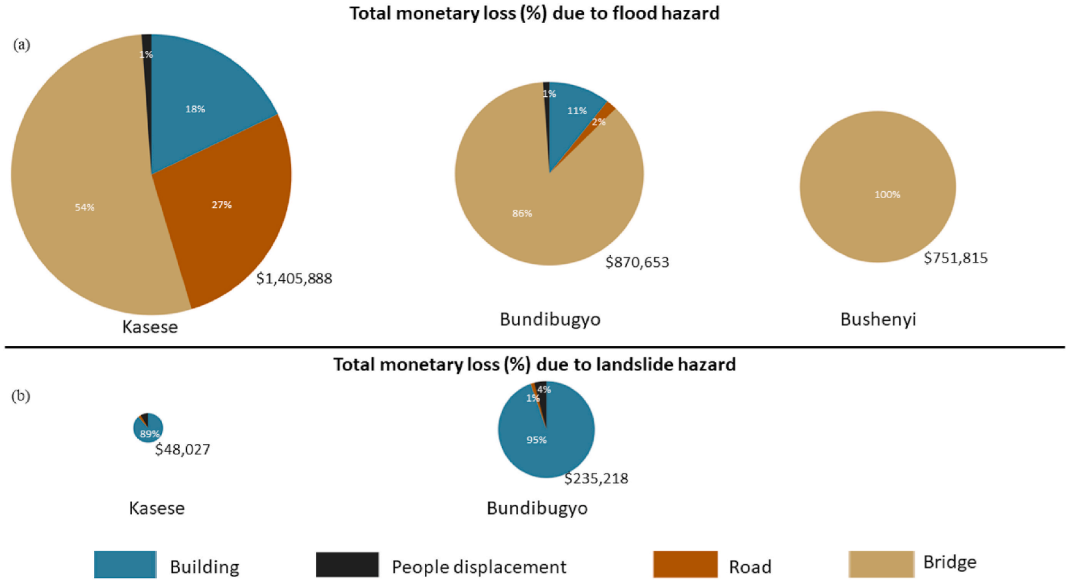


Fig. 9. Distribution of total monetary damage due to floods (a) and landslides (b) in US dollars across districts.

cost in Bundibugyo and Kasese respectively. On the side of floods, the loss related to bridge damage is highest in all the districts (Fig. 9), followed by impact on roads in Kasese and impact on buildings in Bundibugyo.

4.2. Landslide versus flood hazard impacts

Although the number of buildings affected by floods is more than twice those affected by landslides, the total monetary loss does not differ significantly. This is due to the higher average degree of loss of buildings affected by landslides - 71 % of the documented buildings in the landslide zones were completely destroyed - compared to 37 % of floods. This contrast can be explained by the fact that the degree of loss of buildings due to landslides is influenced by both hazard and building characteristics (Table 9). The findings in this study do not differ from previous studies that highlighted that vulnerability significantly modulates the risk outcome relative to hazard exposure [100]. The physical vulnerability of buildings to landslides not only depends on landslide intensity but also on building resistance that depend on the construction materials [37,41,56,101]. Also landslides tend to be spatially scattered on more marginal rural land [80] where mud and pole buildings dominate. Although fewer buildings are affected per landslide event, relative to floods, exposed buildings have a higher chance of destruction, especially for large landslides and for more vulnerable buildings. The dominance of mud and pole buildings in the study sub-counties implies poor and vulnerable rural communities that find it hard to quickly reconstruct their lost shelters after being destroyed by natural hazards – as confirmed by the longer duration of temporary re-settlement induced by landslide relative to flood. Therefore, efforts aimed at reducing the physical impact of landslides in the region need to combine both measures that reduce settlements in very high landslide susceptible zones and enhance the structural strength of the buildings.

Spatial analysis of the flood-impact buildings in the study area demonstrates that 65 % of them were located within 200 m from the main river channels. These locations along rivers typically concentrate in village centres and along road infrastructure, especially in the steepest sub-counties where the presence of flat land is more limited. Although enhancing the building wall strength by plastering with cement damp-proofs the building from flood water and significantly reduce the extent of damage [102], this study shows flood intensity (flood depth) is the major influencing factor (Table 10). For a flood depth exceeding 1 m, the building material in the context of our study area might not matter. These results highlight the greater importance of hazard intensity and exposure relative to physical vulnerability in the case of flood; which does not differ from other studies [36,46,103] although the geographical context and physical strength of the elements analysed might vary. Although flood resilient building structures need to be promoted in flood prone areas in the region, efforts should focus more on reducing exposure to floods.

4.3. Distribution of impact across geographical space

Our study was conducted over a period of two years. This implies that over such a timeframe, a temporal bias on the spatiotemporal patterns of hazard occurrence associated with rainfall cannot be discarded from the analysis [75]. Nevertheless, our observations are based on numerous accurate field records and we believe that our data are robust enough to highlight some key aspects on the geographical distribution of the impact. The distribution of impact varies across the different districts from which data was collected. Although the number of buildings affected by both landslide and flood hazards is almost the same in both Bundibugyo and Kasese districts (Table 3), the extent of damage differs as the percentage of those completely destroyed by landslides in Bundibugyo is twice those destroyed in Kasese. This is because Kasese district is affected by relatively small shallow planar landsides in the steepest slopes while Bundibugyo district experiences majorly deep-seated rotational landslides of larger size affecting less steep slopes at lower elevation [15]. These lower elevation areas are more densely inhabited and hence the larger the impact. According to Ref. [77], 20–40 % and 60–80 % of the buildings in Kasese and Bundibugyo districts are respectively exposed to landslide hazard. On the other hand, 20–40 % and less than 20 % of the buildings in Kasese and Bundibugyo are respectively exposed to flood hazard [77], confirming the opposite importance of the two hazards in the two districts. The [77] report shows larger parts of the districts are exposed to landslides than floods, but impact is not generally larger than for floods. This implies that exposure is much higher in flood prone areas.

The little to no impact documented on buildings in the sub-counties of the Ankole subregion can be attributed to generally lower population density [78] and lower landslide susceptibility [96] compared to the Rwenzori. From Tables 4 and it can be deduced that the damage on the roads by landslide and flood hazards is generally higher in the Rwenzori subregion although impacts are also recorded in the Ankole subregion. The damages on the roads in Bundibugyo district were more from landslides while the damages in Kasese district were more from flood hazards. Landslides impact more on the community access roads while floods cause more damages on the tarmac roads. These findings are not different from what has been found out elsewhere. According to Ref. [17], most of the road networks affected by landslides in Mt. Elgon region are rural main murram and community access roads under the management of the district local governments [17]. Although the costs on these community roads are lower, the fact that they are damaged could have significant consequence since they connect communities to major roads that lead to central business districts.

From our field-based operational approach, we observe that hazard characteristics also strongly influence the extent of physical impact on the exposed buildings. Table 3 shows that 96 % of the landslide-affected buildings in Bundibugyo were completely destroyed while 48 % was completely destroyed in Kasese district. These difference can partly be attributed to the difference in the size and type of landslide that dominate the respective districts. The size of the landslides whose impact was documented in Kasese ranged between less than 10 m^2 and less than 1000 m^2 while those documented in Bundibugyo were between less than 10 m^2 to above 1ha. This contrast in size is attributed to different in landslide types and material affected also vary across districts [15]: large deep-seated rotational landslides observed in Bundibugyo from thick clay-dominated sediments, whereas shallow regolith limit the depth and size of landslides on steepest slopes of the Kasese district. This points to the fact that other landslides' characteristics next to sizes are im-

portant in controlling the level of damage, such as deformation speed and mechanics, but these are difficult to document in post-mortem damage estimate in the field.

Although the vulnerability curves in Fig. 6 are comparable to some developed in other studies [37], they show that some buildings can be completely destroyed even at landslide sizes below 10 m^2 and flood depth close to zero. The degree of loss due to flood hazard also rapidly increase as the flood depth exceed 1 m; which differs from other studies that indicate the degree of loss gradually increases with the intensity [36,46]. These differences can be attributed to the heterogeneity of the building typologies whose degree of loss was used to draw the curves. A single room mud and pole building in study sub-counties for example is on average 9 m^2. For such a building, even a landslide slightly less than its size (like those related to collapse of retaining walls) can cause total destruction. Depending on the slope angle, shallow but rapid flood water would cause complete destruction of mud and pole buildings without plaster.

4.4. Implications for policy and future research

In this research, we have provided the first case study on quantitative physical vulnerability assessment in a rural data scarce environment and demonstrated how, with the involvement of local stakeholders, the degree of loss can be elevated even for low intensity geo-hydrological hazards in communities where standardised building guidelines are absent. It provides a local context specific understanding of what influences the physical damage extents on buildings and an accurate estimate of the order of magnitude of the damage costs which local governments and policy makers can use to develop landslide and flood risk reduction programs. However, the study tackles only some components of risk. To comprehensively understand the risk associated with a geo-hydrological hazard, all the dimensions of vulnerability (physical, social and environmental) for the exposed elements need to be accounted for [12]. This study mainly focuses on the direct costs of physical damage and only attempted to quantify the monetary loss due to people displacements for which adequate data was obtained. It did not include indirect costs associated with road disruptions, loss in businesses, household items, livestock or farmland for example. It did not consider the social vulnerability and capacity of individual household controlling their capacity to cope with the impact of the hazard. Understanding the strengths and weaknesses of affected populations in managing risk is very important [104]. According to Ref. [81], landslides cause up to 20 % loss in income from agriculture in the Rwenzori region. Studies have also shown landslide [105] and flood [106] hazard intensities are also influenced by the speed of the landslide movement and the speed as well as the sediment content of the flood water respectively. These aspects were not looked at in this study as they could not be directly observed during our fieldwork. There is therefore need for continuous systematic data collection, including at the time of the hazard event itself, to facilitate additional studies that better account for the intensity of the hazards and also characterize the indirect costs including psychosocial and environmental costs of landslides and flood hazards. Our results, while they provide more details on the type of impacts and physical vulnerability variables, are based on an inventory of a limited number of landslide and flood events occurring over two years in a limited number of sub-counties, so care should be taken when extrapolating these results at a broader spatial and temporal scale.

5. Conclusion

This study aimed at quantifying the economic impact on key infrastructure and identifying the factors that are associated with the physical vulnerability of buildings and road infrastructure to geo-hydrological hazards (landslides and floods) in a bid to build resilient human and societal systems. By quantifying the monetary loss due to physical damage by landslide and flood hazards informed by local stakeholders, we provide a practical operational approach for quantifying vulnerabilities associated with landslides and floods on physical infrastructure in a rural setting where standardized building designs and costing approaches are missing. The study also demonstrates how landslides and floods impact different types of critical infrastructure and how the impact severity is distributed, based not only on variation in hazard intensity, but also on contrast in exposure and physical vulnerability of the build-up infrastructure. An additional contribution of this study is the approach to monetize the costs associated with people displacements. The absolute total costs are mainly associated with completely destroyed buildings although the cost related to damage of bridges is also significantly much higher than those on roads and people displaced. The findings show the urgent need for plans, policies and strategies geared towards reducing landslide and flood risk on building and critical infrastructure in the region. For landslides, the physical strength of a building seems to play a dominant role. For floods however, beyond 1 m flood depth, the building strength in the current context is of limited importance showing the need to limit settlements in flood prone areas.

Our study in Uganda provides unique quantitative data on exposure, impact and physical vulnerability of infrastructure in tropical Africa rural environment, for which such information is critically lacking. The generated vulnerabilities and values of exposed buildings and roads, and estimated economical damage induced by landslide and flood hazards in the selected study region, provide a starting point for future spatially explicit estimation of potential economic risk associated with these hazards at regional or country scale, in order to identify district and sub-counties requiring specific attention for risk reduction initiatives. The improved knowledge on the determinants of physical vulnerability and risk impacts provide key information to select appropriate risk reduction actions.

CRediT authorship contribution statement

John Sekajugo: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Grace Kagoro-Rugunda:** Funding acquisition, Project administration, Supervision, Writing – review & editing. **Rodgers Mutyebere:** Writing – review & editing. **Clovis Kabaseke:** Funding acquisition, Project administration, Writing – review & editing. **David Mubiru:** Data curation, Project administration. **Violet Kanyiginya:** Data curation, Writing – review & editing. **Liesbet Vranken:** Writing – review & editing. **Liesbet Jacobs:** Writing – review & editing. **Olivier Dewitte:** Conceptualization,

Methodology, Supervision, Writing – review & editing. **Matthieu Kervyn:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix CSupplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2024.104282.

Appendix A. Descriptive statistics and correlation coefficients

	Variables	Mean	SD	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	(1) Degree of loss	0.74	0.42	–									
	(2) Age of the building	9.18	7.01	0.24*	–								
	(3) Number of rooms	3.71	1.302	−0.04	0.19	–							
	(4) Size of the house	41.28	27.41	0.01	0.06	0.10	–						
	(5) Building wall material (dummy)	–	–	0.21*	0.06	−0.03	−0.58*	–					
	(6) Building floor material (dummy)	–	–	0.11	0.04	0.07	−0.47*	0.71*	–				
Landslide	(7) Building foundation platform (dummy)	–	–	0.40*	0.00	−0.10	0.27*	0.04	−0.01	–			
	(8) Distance to river channel (m)	395.2	186.99	−0.10	0.09	−0.09	0.33*	−0.06	−0.24*	0.04	–		
	(9) Landslide size (dummy)	–	–	0.39*	0.25*	0.29*	0.07	0.12	0.05	0.45*	−0.17	–	
	(10) Slope	17.63	11.29	−0.41*	−0.24*	−0.05	−0.19	−0.05	0.06	−0.67*	−0.01	−0.63*	–
	(11) Landslide susceptibility	0.69	.13	−0.43*	−0.24*	−0.02	−0.19	−0.08	0.03	−0.63*	0.03	−0.58*	0.95*
	(1) Degree of loss	0.43	.47	–									
	(2) Age of the building	34.63	27.18	−0.15*	–								
	(3) Number of rooms	3.79	1.41	−0.10	−0.31*	–							
	(4) Size of the house	89.97	80.32	−0.15*	0.29*	0.01	–						
	(5) Building wall material (dummy)	–	–	0.18*	−0.28*	0.21*	−0.25*	–					
	(6) Building floor material (dummy)	–	–	0.27*	−0.79*	0.27*	−0.37*	0.47*	–				
Floods	(7) Use of the building	–	–	0.04	0.03	−0.44*	0.48*	−0.18*	−0.11	–			
	(8) Flood depth (m)	1.13	.89	0.54*	0.20*	−0.23*	0.08	−0.09	−0.15*	0.19*	–		
	(9) Flooded area (dummy)	–	–	0.39*	−0.19*	0.11	0.15*	0.06	0.19*	0.13	0.26*	–	
	(10) Distance to river channel	178.17	132.41	0.23*	−0.21*	0.13	−0.02	−0.06	0.12	−0.04	−0.01	0.22*	–
	(11) Slope	3.77	3.56	0.28*	0.29*	−0.24*	−0.02	−0.19*	−0.23*	−0.05	0.25*	0.23*	0.28*

*For landslide, N = 91; for flood, N = 212; * shows significance at p < 0.05; SD - Standard Deviation.*

Appendix B. Landslide and flood combined correlation matrix of people displacementcosts and selected variables

Variables	(1)	(2)	(3)	(4)	(5)	(6)
(1) People displacement costs	–					
(2) Degree of damage	0.40*	–				

(*continued on next page*)

(*continued*)

Variables	(1)	(2)	(3)	(4)	(5)	(6)
(3) Cost of repair	0.03	0.38*	–			
(4) Building wall material	0.03	0.24*	−0.27*	–		
(5) Size of the building	−0.24*	−0.20*	0.26*	−0.34*	–	
(6) Household size	0.13*	−0.11	0.10	−0.21*	0.21*	–
(7) Hazard intensity (size of landslide/flooded area)	0.20*	0.33*	0.15*	0.07	0.12*	0.07

* *shows significance at* $p < 0.05$.

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