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INSYDE-BI: A Flood Damage Model for Residential Buildings in Burundi

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Abstract **-** In recent years, the frequency and intensity of floods have increased globally, posing a significant threat to communities and their infrastructure. This paper introduces the adaptation of an existing flood damage model, INSYDE, originally developed for the context of Italy, to the unique conditions of the Republic of Burundi, Africa. The proposed model, named INSYDE-BI, aims to enhance understanding of flood-induced damages to residential buildings in Burundi, considering the hazard and building factors specific to the region. The adaptation process involves the examination of local building practices and vulnerability factors as well as the modeling of specific damage mechanisms to certain building's components. By integrating these region-specific elements, INSYDE-BI seeks to provide a more accurate and contextually relevant assessment of flood-related risks and damages for residential structures in Burundi.

Keywords**:** floods; damage; buildings; Burundi.

1. Introduction

Floods, natural phenomena occurring along watercourses and occasionally inundating floodplains, pose significant challenges to both rural and urban areas. Triggered by adverse weather conditions leading to prolonged torrential rains, floods can escalate into catastrophic events, causing profound devastation to lives and human structures. The force of floodwaters often carries substantial amounts of soil and debris, exacerbating damages and complicating rescue efforts.

In Burundi flooding stands as a significant threat to both structures and population, inflicting substantial economic losses, human casualties and displacements. Despite recurrent flooding, many households choose to remain in their ancestral lands, emphasizing the complex relationship between communities and the ever-present risk of floods. Human efforts to mitigate floods, ranging from embankments to canalizations, often coexist with activities that exacerbate their devastating effects, such as inadequate land protection, deforestation and unplanned construction in areas prone to flood risks.

In this context, establishing a flood damage model becomes imperative for effective risk management and mitigation strategies. In the literature, available flood damage models fall into two main categories [1]: empirical models, which leverage historical damage data to relate hazard and vulnerability variables (data-driven approaches), and synthetic models, employing an expert-based conceptual approach grounded in hypotheses and assumptions about damage mechanisms (what-if analysis). The present study focuses on the development of a synthetic flood damage model for residential buildings in Burundi, namely INSYDE-BI. Building upon the original INSYDE framework, developed in Europe in previous years [2-3], INSYDE-BI adopts the same expert-based approach to derive flood damage curves specific to residential structures in Burundi. In the subsequent sections, we describe the methodology employed for model development, present key considerations for the Burundian context and discuss the significance of INSYDE-BI in enhancing flood risk assessment and management practices in the region.

2. Data and methods

2.1. INSYDE

INSYDE [2] is a synthetic flood damage model designed to estimate economic damage for residential buildings. Leveraging expert-based mathematical functions, INSYDE provides a comprehensive framework for assessing the total damage (D) per building.

The calculation of total damage involves a summation of repair (or removal and replacement) costs for various affected building components (C_i), further delineated into subcomponents (C_{ij}). The damage cost to each subcomponent is determined by a mathematical function incorporating the physical extent of damage (ext_{ij}). This extent, expressed in physical terms (e.g., square meters of damaged walls), is multiplied by the unitary price (up_{ij}) associated with a specific activity related to the damaged building component. An additional factor (r_{ds}) is introduced, which varies based on the modeled damage mechanism, be it deterministic or probabilistic; in the latter case, this factor represents the probability of damage occurrence to the considered component relative to a specific hazard characteristic intensity.

The variable ext_{ij} is a function of several damage explicative variables, encompassing aspects related to both the hazard (e.g., external and internal water depth, flow velocity, inundation duration, sediment load, presence of contaminants) and the characteristics of the affected building (e.g., geometric features, such as footprint area, internal and external perimeters, as well as qualitative features, like building type, quality and maintenance level). In instances where input data may be lacking or extensive data collection is impractical, the model provides default values for each parameter.

The adaptation of the INSYDE model to other contexts, as Burundi, demands understanding of the country's geographical, hydrological, and socio-economic features to ensure the model accurately reflects the local reality. In the next section, we outline the adopted methodology and the rationale behind the systematic collection of data from various sources for model development to the case of Burundi.

2.2. Study area: the Republic of Burundi

The Republic of Burundi (Figure 1), a small landlocked country in East-Central Africa, lies south of the equator in the Great Lakes region, characterized by an elevated plateau with an average altitude of 1700 m. Spanning 27,830 km^2, the country comprises five distinct topographic units: Imbo Plains in the west, mountainous areas of Mirwa, the Congo Nile Divide, the Central Plateaus and depressions in the east and northeast. Burundi's hydrography is defined by two major basins, the Congo and the Nile. The central-northern plateau is part of the Nile basin, with the Ruvubu River as the main contributor. The rest of the country drains into Lake Tanganyika, which, via its outlet Lgukua, feeds the Lualaba River, the initial stretch of the Congo River.

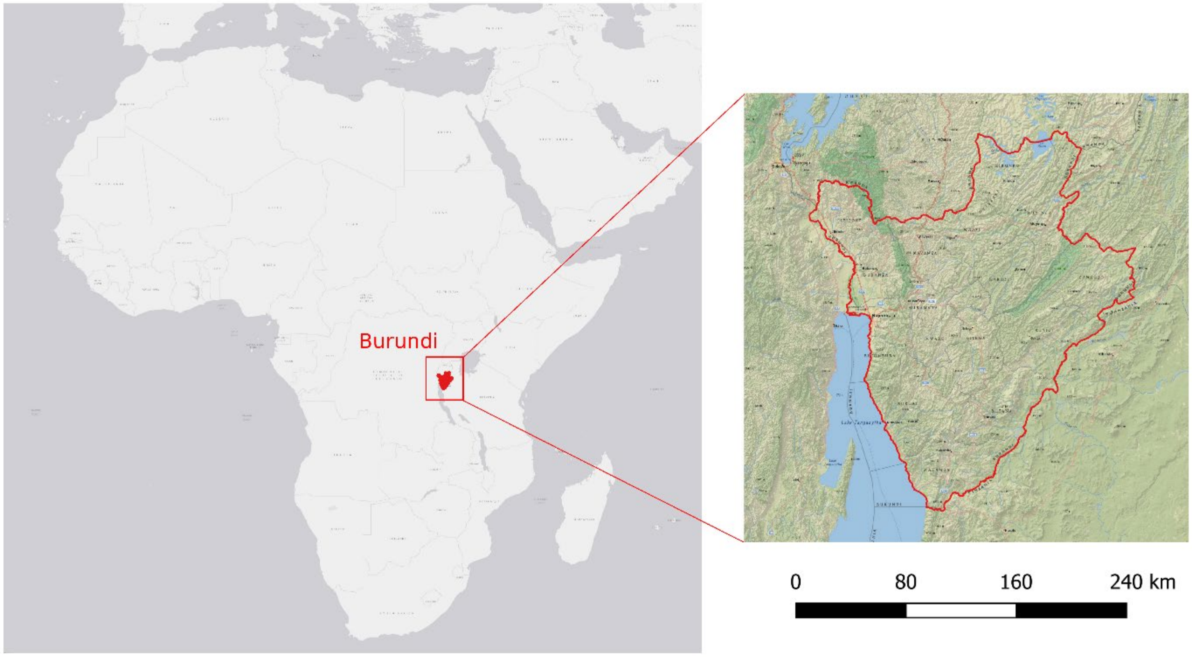

Fig. 1: Study area: the Republic of Burundi.

The tropical climate, influenced by altitude and Lake Tanganyika, varies with more substantial precipitation (over 1400 mm/year) on the eastern plateau, gradually decreasing towards the lake region and Ruzizi Valley, resulting in a drier season from October to March.

Owing to the country's morphological characteristics, different hydraulic hazard zones are identifiable. Analysis of past damaging events indicates fewer significant damages in the central part, where settlements are generally not close to watercourses, in contrast to the densely populated western plains.

For instance, in 2021, the coastal region along Lake Tanganyika, housing nearly 850,000 people, experienced extensive flooding in April and May. Particularly severe damages occurred in Kanyenkoko, Rumonge Province, where 216 houses and warehouses storing food supplies and fisheries were inundated. Subsequent rainfall in May further elevated water levels of the lake, causing additional damages in Mushasha and Kinyinya areas. The Office for the Coordination of Humanitarian Affairs reported concerning impacts, with approximately 40,000 individuals displaced due to floods from January to May 2021. The consequences extended beyond immediate injuries, causing long-term damages to economic, healthcare and educational infrastructures. Adequate housing, food supplies and livelihood support became critical needs for affected population, with compromised water access, sanitation services and education, which also exacerbated other risks, including an increase in gender-based violence.

2.2. Adaptation of the INSYDE framework to the case of Burundi

The physical environment of Burundi is complex and diverse, with various elements influencing flood dynamics. From terrain morphology to hydrographic conditions, climatic features to settlement patterns, each aspect plays a crucial role in influencing possible flood damage. For this reason, the fundamental phase for model development or adaptation involves a detailed examination of typical flood events and residential buildings in Burundi, aiming at defining INSYDE-BI's inputs, default values and assumptions on damage mechanisms.

This step includes a thorough analysis of hydrological and hydraulic records, historical flood events, existing flood hazard and risk maps and a review of past and ongoing projects related to flood damage estimation in the country. The objective is to ensure the relevance of considered hazard features in the specific regional context. Similarly, the characterization of the housing stock involves a literature review of papers and statistical reports on the building spatial structure within Burundi. Additionally, virtual and/or field surveys are conducted to gather specific information not readily available through standard desk-based data retrieval. Finally, unit prices for repair/replacement works on different building components are adjusted to align with the unique implementation context of Burundi.

3. Results and discussion

3.1. Hazard and building features in INSYDE-BI

The key input features identified for INSYDE-BI, following data collection and analysis, are presented in Table 1, which illustrates characteristic values for both hazard and building variables implemented in the model, along with their typical range of values determined for Burundi.

Regarding hazard features, an essential differentiation between riverine (occurring in plains) and torrential, flash flooding (occurring in steep areas) has been introduced due to varying inundation characteristics within the country, in terms of water velocities and sediment loads, influencing damage mechanisms.

In terms of exposure and vulnerability features, the analysis of building data in Burundi indicated that isolated houses are the predominant housing type, covering each, on average, approximately 50 m^2. This pattern holds true in both rural and urban settings, with urban regions featuring more multi-dwelling buildings, followed by independent houses and houses with a perimeter fence, known as *rugo*. Overall, nearly half of the population resides in houses with one to three rooms (49.2%). Houses are generally more spacious in rural regions, where more four-room houses (34.1%) are present with respect to urban areas. Notably, the latter show a higher percentage (16.3%) of single-room dwellings compared to rural areas (6.9%). Across the country, the most frequent construction material is represented by raw earth bricks (59.5%), followed by wood with non-cemented earth (24.0%) and masonry (8.2%). Urban areas exhibit a slightly better quality of housing, with a higher prevalence of masonry houses (27.2%). Nationwide, thatch is the most common roofing material (35.8%), followed by corrugated metal sheets (33.1%) and local tiles (25.6%). While thatch is more traditional, metal sheets offer better quality but come at a higher cost. Urban areas show a significant preference for metal sheet roofing (77%), indicating a higher quality of materials compared to rural areas (28%). Overall, 85% of house flooring is earthen, with cement representing only 8.1%. Urban areas have a higher percentage (47.6%) of cement-covered floors compared to rural areas (4.1%), reflecting better economic conditions in urban settings [4].

Table 1: Hazard and building features in INSYDE-BI .

Hazard features	**Typical range of values**
External water depth, *he* [m]	[0-3], with incremental step 0.1 m
Internal water depth, *h* [m]	h=he-GL
Inundation duration	Riverine flooding in plains: >24 h Flash flooding in steep areas: < 6 h
Water velocity, *v* [m/s]	Riverine flooding in plains: 0.5 m/s Flash flooding in steep areas: > 1.5 m/s
Sediment load, *s* [% of water volume]	Riverine flooding in plains: 2.5% Flash flooding in steep areas: 5%
Water quality, *q* [binary variable, 0: No, 1: Yes]	1

Building features	**Typical range of values**
Footprint area, *FA* [m^2]	50
Internal area, *IA* [m^2]	0.9·FA
External perimeter, *EP* [m]	$4\cdot\sqrt{FA}$
Internal perimeter, *IP* [m]	2.5·EP
Number of floors, *NF* [-]	1
Interfloor height, *IH* [m]	3
Ground floor level, *GL* [m]	0.1
Building type, *BT* [-]	1: Multi-family building 2: Single-family building [default]
Building structure, *BS* [-]	1: raw earth bricks [default] 2: masonry 3: wood
Finishing level, *FL* [-]	0.8: low 1.0: medium 1.2: high
Level of maintenance, *LM* [-]	0.8: low 1.0: medium 1.2: high

3.2. Damage mechanisms implemented in INSYDE-BI

The second step for adaptation involves the formulation of damage functions to accurately represent potential flood damage mechanisms that may arise in Burundi, given its specificities in terms of both hazard and building features. Table 2 provides an overview of the various damage components included in INSYDE-BI, outlining the variables that influence the considered damage mechanisms.

Specifically, significant differences in flood vulnerability, leading to either complete structural collapse or the partial activation of specific building components, are expected for different building materials (*BS*) and finishing levels (*FL*). For example, masonry buildings are typically associated with a higher *FL*, indicating the presence of more damageable components, such as interior and exterior plaster, concrete pavement and building systems. Moreover, the resistance of such buildings to flood actions is greater due to the material used, resulting in higher hazard thresholds for the activation of respective damage components compared to less resistant buildings.

Differently, traditional wood and mud buildings, characterized by a lower FL and featuring natural plaster, earthen floors floors and thatched roofs, exhibit minimal resistance to floods, making them susceptible to severe damage even under shallow shallow water depth and low flow velocity. Given their non-resistant structure, INSYDE-BI assumes structural collapse (100% total damage) if water depth he exceeds 1 m or flow velocity v is greater than 1 $\mathrm{m/s}$; alternatively, partial damage is is assumed, with possible damage to certain building components under low values of the hazard variables. A similar approach applies to raw earth brick buildings, which have lower resistance compared to masonry but higher than wooden structures. They are assumed prone to collapse if either of two conditions is met: when he exceeds 2 m or v is greater than 1.5m/s, irrespective of inundation duration d, or in case of long duration flooding (d > 12 hours), for any value of he or v. Otherwise, partial damage is supposed to occur, activating a number of damage components which depends on FL: for this BS, in the model, a higher FL implies the presence of internal and external plaster and an electrical system, which are instead supposed to be absent in lower quality structures.

Table 2: Damage components and subcomponents considered in INSYDE-BI in case of partial damage (x), with indication of the variables involved in the modeled damage mechanisms (□ implicitly modeled component: the threshold for activation of the damage mechanism to the specific component is beyond the threshold for building collapse).

	BS			
	Masonry	Raw earth bricks	Wood	Variables involved in the damage mechanism
Clean-up				
C1: Waste disposal	x	x	x	*h, s, q, IA*
C2: Cleaning	x	x	x	*h, q, IA*
Removal				
R1: Partition walls	x	□	x	*h, d, IP, IH*
R2: Plasterboard	x	□		*h, IA*
R3: External plaster	x	x	x	*he, d, v, q, LM, EP*
R4: Internal plaster	x	x	x	*h, d , q, LM, IP*
R5: Doors	x	x	x	*h, d, v, IA*
R6: Windows	x	□	□	*h, d, v, IA*
Replacement of non-structural elements				
N1: Partitions replacement	x	□	x	*h, d, IP, IH*
N2: Plasterboard replacement	x	□		*h, IA*
Structural components				
S1: Soil consolidation	x			*he, v, IA, NF, IH*
S2: Local repair	x			*he, v, s, EP*
Replacement of finishing elements				
F1: External plaster replacement	x	x	x	*he, d, v, q, LM, EP*
F2: Internal plaster replacement	x	x	x	*h, d , q, LM, IP*
Replacement of doors and windows				
W1: Door replacement	x	x	x	*h, d, v, IA*
W2: Windows replacement	x	□	□	*h, d, v, IA*
Building systems				
P1: Electrical system replacement	x	x		*h, IA*
P2: Plumbing system replacement	x			*h, IA*

In the specific context of Burundi, the *rugo* (fence around the house) plays a crucial role in the building's vulnerability to flooding. More specifically, its impact on flooding varies depending on the materials used, typically either masonry or wood. In the latter case, the *rugo* has no effect, as almost the entire flow passes through it without reducing the water velocity and depth. Conversely, when masonry is used, there is a reduction in the hydraulic characteristics of the flood before it reaches the building, which is modeled in INSYDE-BI by assuming a water depth h equal to one third of that outside the fence and a flow velocity of 0.05 m/s at the building location. This means that the house cannot be damaged (or damaged with a reduced impact) without first damaging the fence itself; clearly, the effectiveness of the *rugo* is contingent upon its own structural integrity, which is assumed to be a function of water velocity and depth according to the model of Clausen and Clark [5].

3.3. Examples of resulting flood damage functions in INSYDE-BI

Figure 2 and 3 report illustrative examples of relative damage curves derived from INSYDE-BI, for different building materials under representative flood scenarios occurring in Burundi: riverine flooding in plains (characterized by low flow velocity and prolonged inundation durations) and flash flooding in steep areas (featuring high flow velocities and short inundation durations). In the former case, for representation, a constant velocity value of 0.5 m/s is set, with inundation duration ranging from 24 to 72 hours; conversely, in the latter, the duration is fixed at 4 hours, with velocities varying between 0.5 and 3 m/s. Relative damage in Figure 2 and 3 is expressed as the ratio of total economic damage to the various building components to the total reconstruction value of a hypothetical 50 m² building.

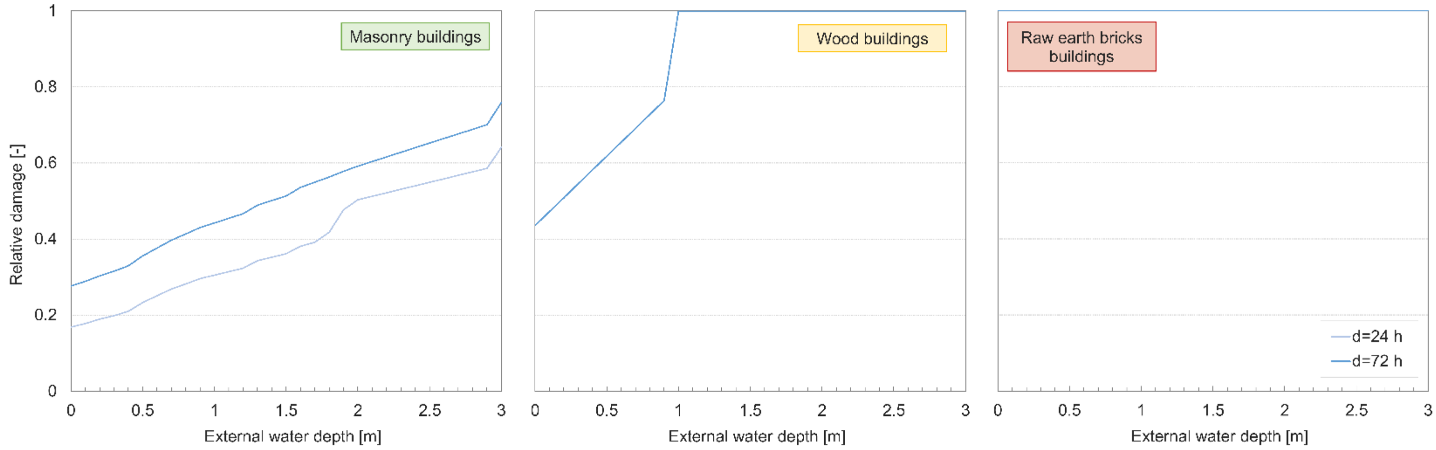

Fig. 2: Examples of INSYDE-BI damage functions for different building materials: case of riverine flooding in plains.

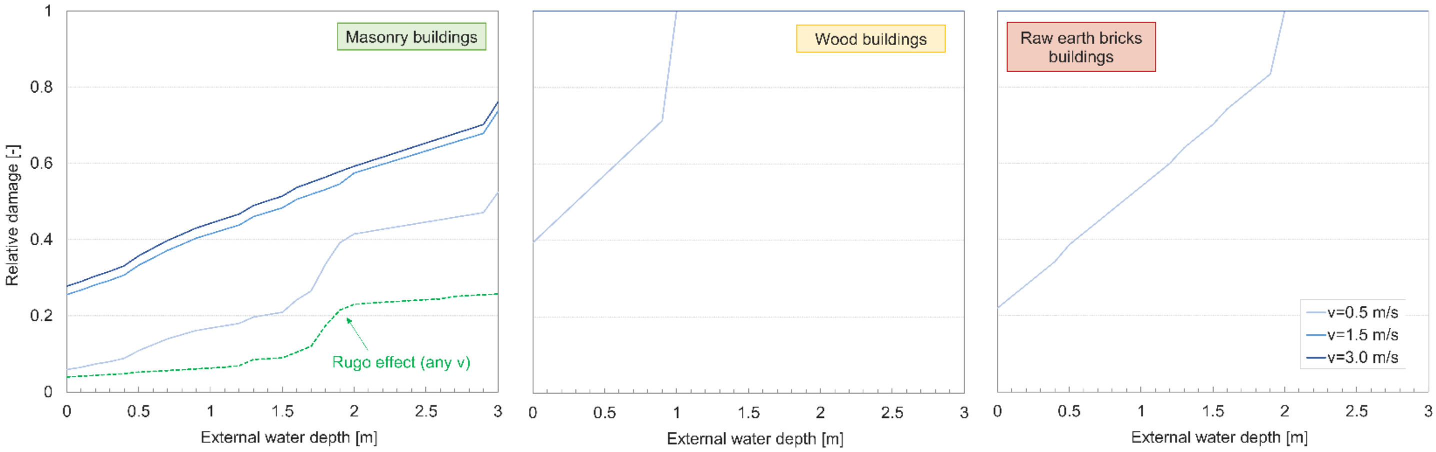

Fig. 3: Examples of INSYDE-BI damage functions for different building materials: case of flash flooding in steep areas.

Based on the modeled damage mechanisms in INSYDE-BI, Figure 2 shows that damage for masonry buildings in riverine flooding in plains increases with water depth and duration, with a dependence from the latter until reaching a critical threshold of 32 hours; beyond this point, damage functions converge with those represented for a 72-hour inundation. Wooden buildings display depth-dependent damage, with duration only influencing events lasting less than 5 hours, a scenario not representative of floods in Burundian plains. Conversely, raw earth brick structures consistently experience total damage, due to their minimal resistance to water contact, resulting in structural collapse beyond 12 hours.

For flash floods, relative damages in masonry buildings are influenced by both water depth and velocity, exhibiting a distinct increase in damage for velocities exceeding 3 m/s, in line with the approach proposed by [5]. Furthermore, Figure 3 shows (in green line) the positive impact of the *rugo* in reducing flow velocity and water depth. Indeed, this mechanism proves effective in scenarios featuring high flow velocities and short durations, while its efficacy diminishes in plains, where, due to longer inundation duration, water can permeate from the *rugo* entrance to the building. Wooden structures also manifest velocity and depth-dependent damages, with collapse occurring even under modest events (he=1 m, v=1 m/s) due to the low resistance of this construction material. Similarly, raw earth brick buildings exhibit a comparable pattern, albeit with higher collapse thresholds ($he > 2$ m and $v \geq 1.5$ m/s).

4. Conclusions

Through the development of the INSYDE-BI model, this study explored flood vulnerability and building damage mechanisms in the unique context of Burundi, highlighting the diverse impacts of building materials and hazard factors on structural resilience. The analysis of riverine and flash flooding in Burundi's plains and mountains revealed distinct damage patterns. Masonry buildings exhibit varying responses to water depth and inundation duration, whereas wooden and raw earth brick structures tend to experience total damage due to their minimal resistance to water contact. The study also highlighted the positive impact of traditional fences around buildings (*rugo*) in reducing flow velocity and water depth in specific flood scenarios.

The developed model and related findings emphasize the importance of tailoring flood damage models and building resilience strategies to the local context, recognizing regional variations in flood characteristics and building features. This is particularly crucial in countries with unique characteristics, such as those in Central Africa, which also lack specific existing models. The developed INSYDE-BI contributes valuable insights, providing a foundation for informed decision-making in flood-prone regions and facilitating the development of targeted mitigation strategies.

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