

Flood risk assessment and participative process in the data-scarce Metuge district of Mozambique: An exportable approach

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ABSTRACT

Low-income countries are the most vulnerable to floods; moreover, the occurrence and intensity of these disastrous events are progressively increasing worldwide. Quantitative flood risk assessment is the first and primary step that can be made to support local decision makers towards effective flood risk management. However, the lack of data that typically characterizes the Global South hinders the implementation of methods developed for data-rich contexts. The present study aims at proposing a comprehensive and exportable methodology for flood risk assessment, responding to the challenge of data and method deficiencies, by referring to global sources, freely available tools and relying on an intensive field survey. The methodology, including hydrological, hydro-dynamic and damage modelling, and a multi-level participatory process, was developed for a flood prone area in northern Mozambique that is crossed by the Muaguide river. The latter presents a bed completely buried by sediment in many stretches, causing extensive floods which have been more and more frequently in the last years, hitting the surrounding region. The obtained results (Annual Average Damage to roads and buildings of about 300,000 USD/year and an average of about 2000 people at risk per year) increase the knowledge of flood risk in the investigated area and can be a useful support for the design and implementation of effective mitigation measures at local and regional scales.

1. Introduction

The severity and the frequency of extreme weather events are increasing all over the globe. The breakthrough agreement on a new “Loss and Damage” fund reached during COP27 acknowledges the urgent need for new resources to assist low-income countries, which are the most vulnerable to the adverse effects of climate change, even if the least responsible of its causes [1]. In particular, countries in Africa have experienced more than 1500 weather-related disasters in the last four decades and, according to EM-DAT, 47 % of the events that occurred in the last twenty years are floods [2]. Although a new fund to respond to economic losses is a significant progress in assisting these countries, if no preventive steps are taken toward climate change adaptation and improvement of flood risk

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management, the communities of these regions will be exposed to higher risk, even doubling the number of affected people by 2050 [3, 4]. Moreover, as stated in the Sendai Framework for Disaster Risk Reduction and emphasized by the Goal 11 of 2030 Agenda for Sustainable Development, it is necessary to better understand disaster risk in all its aspects and strengthen its governance to minimize catastrophe-related economic losses [5,6]. Thus, to accomplish these goals, the estimation of potential damages caused by catastrophic events like floods is indispensable to ensure an effective allocation of financial resources for risk reduction.

Nevertheless, data scarcity, which typically affects poorest territories [7], hinders quantitative flood risk assessment. With respect to hazard analysis, an effort has been made in the scientific community to develop methodologies for the application of hydrological and hydraulic simulations, even in the lack of suitable hydro-meteorological data. For example, Komi et al. [8] proposed a methodology for ungauged rivers by linking rainfall-runoff and hydraulic modelling of the flood extent in the Oti River Basin, West Africa; Erena et al. [9] used the FLO-2D hydrodynamic model to identify flood prone villages in the city of Dire Dawa in Ethiopia; Ntanganedzeni & Nobert [10] assessed flood risk in Luvuvhu River Catchment in South Africa applying HEC-RAS (Hydrologic Engineering Center-River Analysis System) for the hazard characterization; Zhang et al. [11] assessed flood risk by using a coupled hydrological-hydraulic modelling approach by means of HEC-HMS (Hydrologic Engineering Center - Hydrologic Modeling System) and HEC-RAS softwares; Baioni et al. [12] estimated river discharge, sediment transport, and surface runoff for an ungauged catchment in the Eritrean Foro region using the SWAT (Soil and Water Assessment Tool) suite. On the contrary, most of the available studies on vulnerability and damage assessment have concentrated on qualitative analyses: Komolafe et al. [13] collected several research works on flood vulnerability and risk assessment conducted in Nigeria demonstrating that most of the scholars used remote sensing supported by GIS (Geographic Information System) tools; Weerasinghe et al. [14] combined flood risk levels in a statistical expression of hazard, exposure and vulnerability to qualitatively assess the flood risk of the Western Province of Sri Lanka; Ramkar & Yadav, Kundu et al., Gacu et al. and Nkeki et al. [15–18] proposed geospatial and multi-criteria-based approach to study the flood risk of data-scarce basins in India, Philippines and Nigeria. Considering that quantitative damage assessments may effectively support decision-making based on cost-benefit analysis of alternatives of intervention, a great deal of effort needs to be put into quantitative flood damage modelling in low-income countries.

Mozambique is one of the poorest countries of the world [19,20], although the recovery after a long civil war has led to an extensive agricultural growth [21,22]. Around 70 % of poor households live in rural areas, representing around 18.4 million people exposed to frequent and severe weather-related hazards. Since 1980, 18 tropical cyclones have been registered; the most recent and strongest one was Kenneth, which hit the northern regions in April 2019 causing 45 fatalities and displacing thousands of people [23]. Cyclone Kenneth was highly destructive for the province of Cabo Delgado, which is the poorest in the country and presents the highest amount of population living under vulnerable circumstances [24]. Moreover, the social hardship of this region is aggravated by the conflicts going on since 2017 [25,26] in the northern area of the province, producing thousands of people displacements towards the southern

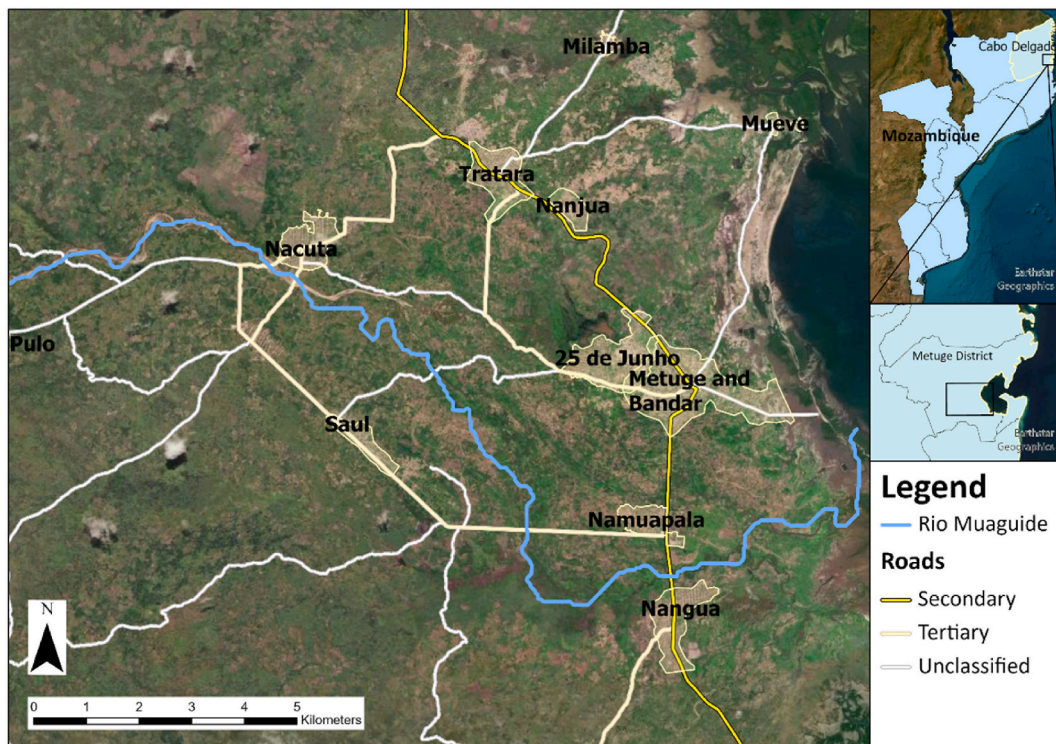


Fig. 1. The lower course of the Muaguide River with surrounding villages. The insets show the location of the area in the Metuge District and in Mozambique.

districts of Cabo Delgado. These are rural districts where the inhabitants live on subsistence agriculture [27]. These districts are crossed by several rivers flowing into the Mozambique Canal; among these, the river Muaguide presents a total length of 130 km running from the Ancuabe to Metuge district. For almost all its course, the river is characterized by a well-defined path, while in the last 15 km it braids into multiple sub-reaches. The branches are extensively buried by sediment deposits, which cause widespread floods during the rainy seasons and, consequently, damages to people and assets, affecting mostly the villages of Namupala, Nacuta and 25 de Junho (Fig. 1).

The area depicted in Fig. 1 is one of the intervention areas of the PRONTIDÃO project (time span 2021–2024), which is an international cooperation to development project funded by the European Union and led by Istituto OIKOS, an Italian non-governmental organization (NGO). Within this area, or in its vicinity, four relevant studies have been performed in the past. Huthoff et al. [28] assessed the flood risk of the Lower Zambezi area in central Mozambique, performing a simplified assessment of damage to population, roads, railway, health facilities, schools and power installations for 7 return periods. Their hazard maps were based on global flood data, satellite imagery of past events, and water depths derived from time series at three hydrological stations. Moreover, they adopted a generalized damage function considering a single water depth per return period, neglecting the spatial variability of the flood and the vulnerability of the different exposed elements. A second study [29] collected information on the hydraulic resources and geological features of the Mozambique's northern basins together with the socio-economic characteristics of the region, without performing hazard or damage evaluation. A third one [30] provided hazard maps of the downstream parts of the Messalo and Muaguide rivers for the return periods of 10, 50, 100, and 500 years, and estimated of the number of affected houses and people at the district level. Finally, Rrokaj et al. [31] proposed a structural flood mitigation measure for the downstream part of the Rio Muaguide investigating the hazard of the area for a 10-year flood event.

This study is a key outcome of the PRONTIDÃO project, addressing critical gaps in previous research on flood risk in Mozambique and more in general, in data-scarce regions. Such gaps can be synthesised in the use of generalized damage functions, the overlooking of the spatial variability of flood hazards, the focus on macro- or meso-scale damage estimates, the lack of detailed damage grading, and the single event approach. Additionally, past research on flood risk in data-scarce regions was often limited to qualitative assessments. To overcome these limitations, this study introduces a comprehensive methodology that integrates hydrological hazard modelling and quantitative vulnerability and damage assessments, specifically targeting the communities of Namupala, Nacuta, and 25 de Junho. Moreover, a core element of this methodology is the introduction of a participatory process, as an essential step for validating the obtained results. In fact, the absence of observed data for the investigated case study made involving local stakeholders the sole viable option for result validation [32]; such a process enables revealing information that can only be obtained from the experiences of locals [33] and allows for validation of the results by comparing them to the community experience of past flood events [34].

The methodology and data adopted to conduct the risk assessment are presented in Section 2. Obtained results are collected in

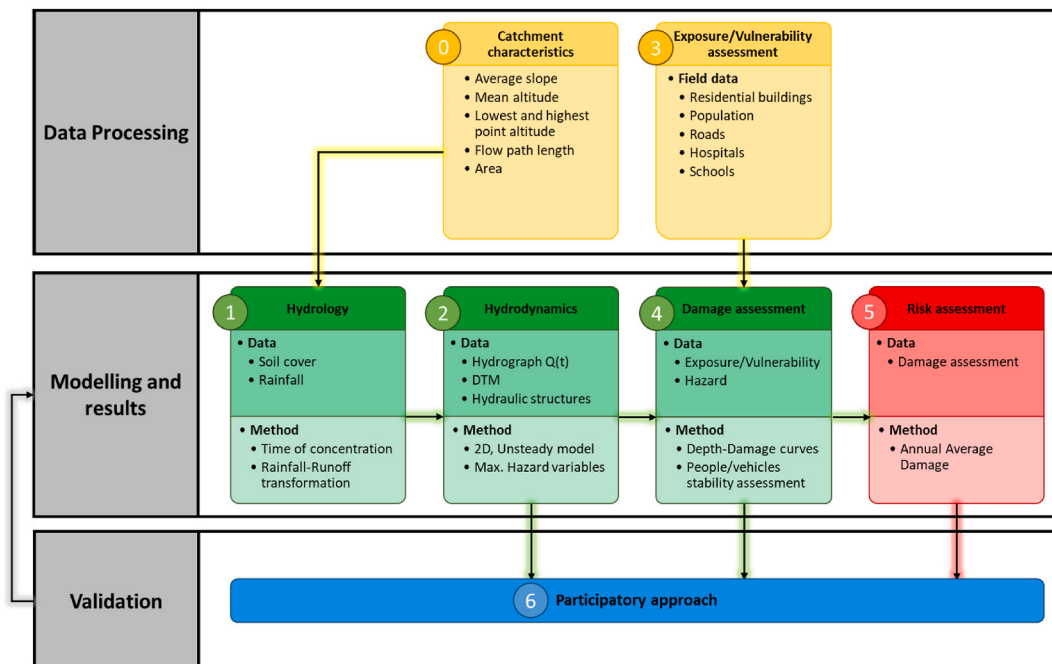


Fig. 2. Framework of the methodology. The yellow sub-blocks refer to data processing and preparation; the modelling sub-blocks are depicted with the green colour; the risk assessment is coloured in red to differentiate it from strictly modelling stages; the participatory process (light blue sub-block) incorporates the results of the modelling chain block. The numbers of each sub-block indicate the order in which they were executed in this study.

Section 3. The participatory process is presented in Section 4. Finally, Section 5 summarises the main conclusions and discussions that emerged from the methodology implementation, emphasizing its applicability in other data poor regions. In particular, Section 5 addresses the discussion of quantitative results, and the limitations and uncertainties encountered, discusses the validation of results achieved through the participatory process as well as its benefit for local communities, and outlines prospects for future research.

2. Materials and methods

The proposed methodology follows the general framework depicted in Fig. 2. The three subsequent main blocks refer to the data processing, the modelling chain and the final validation activity. Each block is further subdivided into operational sub-blocks whose main tasks, data and methods are summarized.

Data scarcity was the most challenging obstacle for the quantitative analysis; therefore, much effort was invested into data research and collection. The three sub-blocks of catchment characterization, hydrology and hydrodynamics, implemented to determine the flood hazard, relied mainly on free global data (rainfall, terrain elevation and soil cover). Conversely, an intensive field survey was required to characterize the vulnerability of the population and infrastructures exposed (sub-block 3) which represents the base of damage and risk analysis (sub-block 4 and 5). Indeed, information on exposure and vulnerability is often lacking in low-income countries, where the scarce data available are often aggregated at regional levels. However, an analysis at a much lower spatial scale is required for most flood risk applications [35] and was within the objectives of this study. As previously introduced, the obtained results were discussed with local stakeholders by means of a participatory process (sub-block 6). As evidenced by the grey arrow in the framework, the results presented here are the final product of an iterative process in which the modelling steps were repeated by adjusting some of the initial assumptions to the feedback gained through the participatory process.

This methodology aims at being reproducible, supporting quantitative flood risk assessments in other similar contexts. Its innovation, with respect to previous flood risk studies in low-income countries, lies in combining quantitative analysis with field surveys and local knowledge of past flood events, gained through participatory activities. The latter not only improve the accuracy of estimates in contexts with limited data, but also enhances resilience by foreseeing dialogue and engagement with different stakeholders, ultimately contributing to more effective Disaster Risk Reduction strategies in Global South countries.

2.1. Hazard assessment

For the hazard assessment, global data sources were relied upon, following an approach similar to that described by Zhang et al. and Rrokaj et al. [11,31]. The hydrologic modelling was based on a Digital Elevation Model (DEM) and land cover maps obtained from freely available global sources, while the rainfall data were acquired for a fee. A detailed summary of the data sources, resolutions, and types of data used in the study is presented in Table 1.

The DEM was sourced from ALOS PALSAR with a spatial resolution of 12.5 m. Land cover information was obtained from multiple sources, including CORINE Land Cover, the JRC Land Cover Map of Africa, the FAO Land Cover Classification Map, and a local land use map provided by the University of UniLurio. Rainfall data were purchased from Meteoblue, which provides climatic variables with a 1-h temporal resolution since 1985.

The hydrological modelling was conducted using the HEC-HMS software. The physical characteristics of the Rio Muaguide watershed (Fig. 3), including its area of 993 km², have been input to the model. To simulate infiltration losses and convert precipitation into surface runoff, the spatially averaged SCS Curve Number method was employed. This method necessitated the calculation of two fundamental parameters, namely the Curve Number (CN) and the lag time. For the determination of the former, a comprehensive analysis of the different land cover maps was carried out to derive a representative CN value. Initially, the basin was divided into sub-basins, for which values of the CN ranging between 70 and 80 were obtained (this range resulted from spatial distribution of land cover and different sources for the maps). Due to this relatively small range, a source-averaged and space-averaged value of 79 representative of the whole basin was used in the following developments. The lag time was defined as 60 % of the time of concentration which resulted equal to 12.6 h. This value was calculated by averaging the results obtained from commonly used formulas in the literature [42–45], suitable for the characteristics of the watershed. The input precipitation data were frequency-based synthetic rainfall events. Rainfall depths were obtained by fitting the Gumbel statistical distribution to the Meteoblue cumulative precipitation annual maxima for different durations to estimate the parameters of Depth-Duration-Frequency (DDF) curves. Four different return period scenarios (2, 10, 50, and 100 years) were considered, each with a fixed 12-h duration for the rainfall event. Corresponding hydrographs and flood peaks were thus generated.

Table 1
Data used in the hydrological modeling.

Data	Source	Spatial or temporal resolution	Data Type
Digital Elevation Model (DEM)	ALOS PALSAR [36]	12.5 m	Raster
Land Cover Map	CORINE Land Cover (CLC 2018) [37]	100 m	Raster
Land Cover Map	JRC Land Cover Map of Africa [38]	1000 m	Raster
Land Cover Map	FAO [39]	100 m	Raster
Local Land Use Map	Lurio University (Unilurio) [40]	[-]	Vector
Rainfall Data	Meteoblue [41]	1 h	Time series

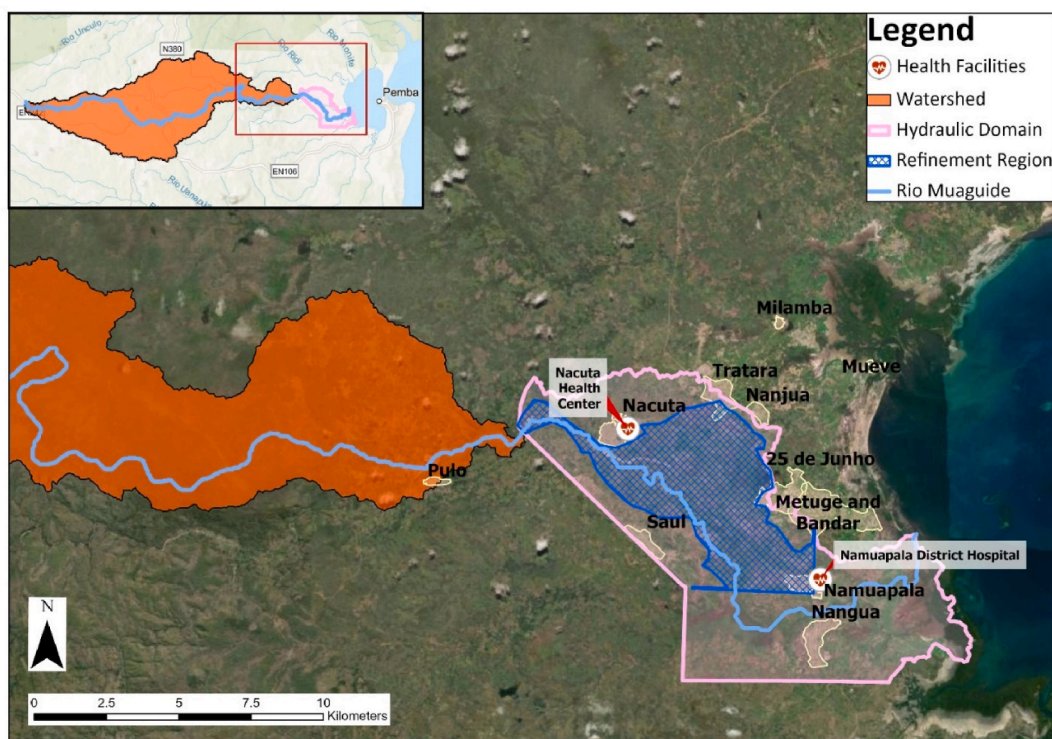


Fig. 3. Watershed, hydraulic domain with mesh refinement area, location of the health centres.

Two-dimensional hydrodynamic modelling was performed using HEC-RAS to determine the flood inundation areas and the corresponding maximum water depths. The computational domain was chosen to encompass the affected villages of the district, crucial road networks, and two significant health centres, with a particular focus on the district's hospital in Namuapala (Fig. 3). A mesh with square cells of 50 m was refined in a region that was impacted by the flood in a preliminary computation. Within this region, the cell size was reduced to 15 m to allow for a more detailed analysis of water flow dynamics, while maintaining compatibility with the resolution of the topographic data. A Manning coefficient of $0.04 \text{ s}/\sqrt{\text{m}}$ was used throughout the domain to represent the surface roughness and determine the corresponding hydro-dynamic resistance. The inflow boundary condition (BC) line was placed where the main channel of the Muaguide intersected the contour of the domain, while the outflow BC was located along the coastline. For the upstream BC the obtained hydrographs were used whereas, for the downstream, the BC of normal depth was set. This specific condition was necessary due to the unreliable DEM inaccuracy around the coastline caused by the presence of mangrove wetlands. Estimating and using sea level as a boundary condition was deemed infeasible for the computation. However, the considerable distance of the study area from the coastline minimises the influence of the downstream boundary condition on the results.

2.2. Exposure and vulnerability assessment

2.2.1. Survey of villages

A three-month field survey was carried out in the three target villages between August and October 2021 to collect information on the exposed assets and their vulnerability, under the guidance of local quarter heads.

Despite the main source of livelihood in this region is subsistence agriculture, the exposure and vulnerability characterizations were devoted to buildings, population and roads. The reason is twofold: first, it was difficult to geolocate cultivated areas because farmers tend to periodically change the location of cultivation fields to avoid previously flooded areas. Second, local farmers have developed resilience to floods over the past decades by predominantly cultivating flood-resistant plants, such as rice, during the rainy season.

This section presents, as an example, the survey conducted in the Namuapala village. As a first step, the area of the village was divided into units represented by the quarters. The perimeter of the latter was obtained by recording the path walked through the smartphone application GaiaGPS which also enabled the travelled route to be geolocated. Fig. 4(a) depicts the division of Namuapala into the three quarters of Primeiro, Unidade and Espanção. The area depicted in yellow refers to a camp for internally displaced people (IDPs) coming from northern districts; however, no exposure data were collected for the camp. In fact, although the Metuge and Pemba districts present the largest number of IDPs in the whole province [46], the population in the refugee camps is constantly changing as many IDPs return to their hometowns and others arrive from the surrounding districts. However, the division of the village into these smaller areas allowed to rapidly proceed with the collection of information provided by the heads of the quarters. For each unit, the number of residential buildings and the number of inhabitants (divided into men, women and children) was collected. Furthermore, in

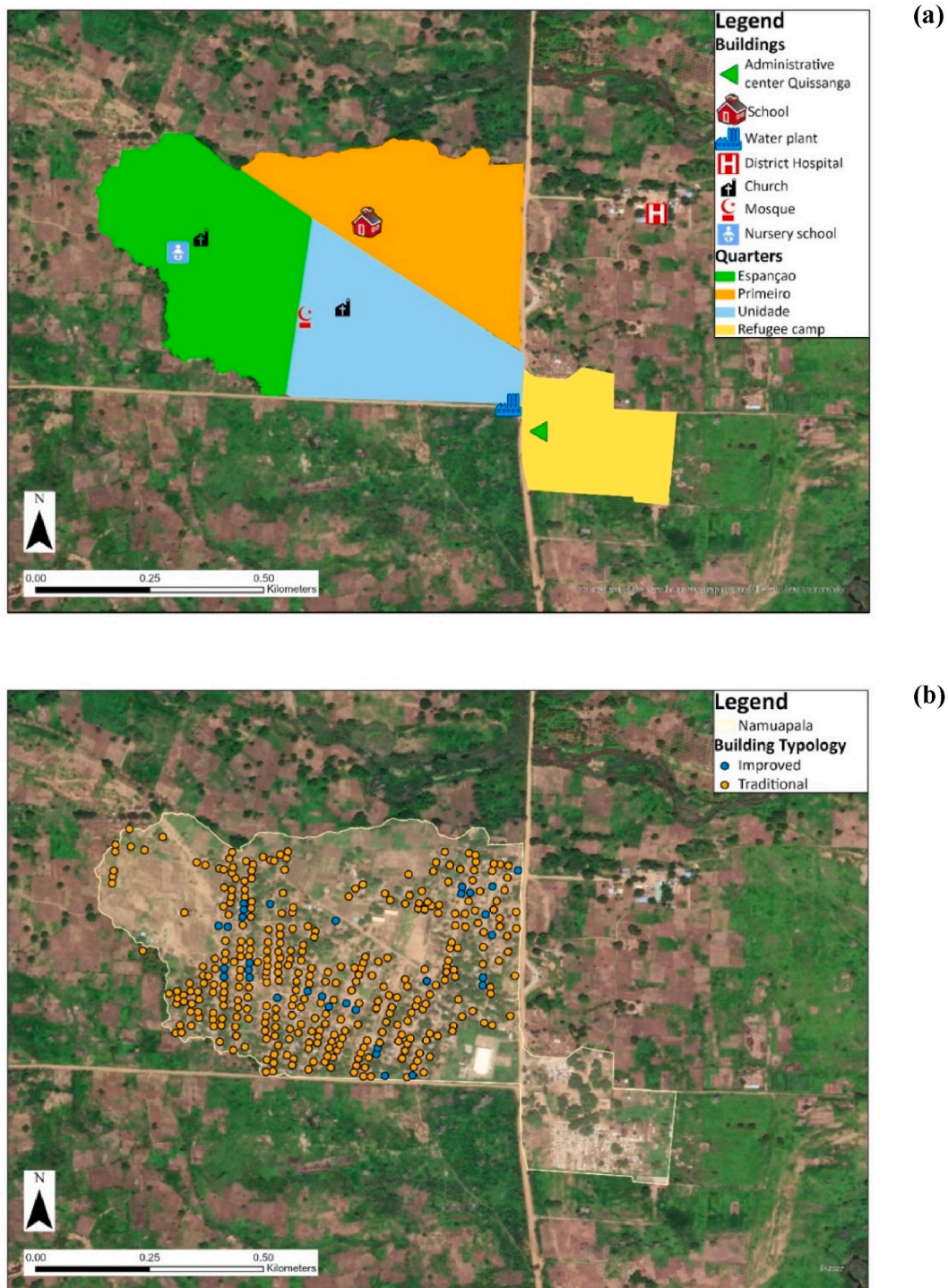


Fig. 4. (a) Result of the field survey in Namuapala village: quarter subdivision, refugee camp, facilities and improved building localization. (b) Map of Namuapala residential buildings.

all the target villages the local guides pointed out two types of residential buildings (Fig. 5): (I) houses of compact mud and thatch, called “traditional”, which are also the majority of the buildings encountered in the study area; (II) dwellings built in mixed material (mud and concrete) or houses built with traditional bricks, called “improved”. According to local expert consultation, a traditional house has a construction cost in Metical (the official currency of Mozambique) of 30,000 MZN (470 USD), whereas an improved house



Fig. 5. (a) Traditional house (b) Improved house.

costs 50,000 MZN (783 USD). To speed up surveying, only the locations of the improved buildings were recorded through the mobile-phone application, while the traditional houses were detected using satellite images. The result of building localization is shown in Fig. 4(b).

Finally, all the strategic buildings such as school, hospital or health facilities, religious and public life meeting centres (see Fig. 4(a)) were mapped and characterized through a photographic documentation. Moreover, the quarter heads facilitated the dialogue with the staff of the various facilities to gather relevant information such as, for the case of the hospitals, the type of services offered and the average number of patients per day. In the study area there are two health facilities located in Namuapala and Nacuta (see Fig. 3). The Namuapala's hospital serves the entire population of the district, which is over 86,800 people. In Nacuta there is a healthcare centre with services mainly focused on maternity and it covers around 25,900 people from the seven surrounding villages of Nacuta, Milamba, Mueve, Pulo, Saul, Tratara and Unidade.

2.2.2. Road survey

The survey involved roads connecting the capital of the province, Pemba, to the target villages of the district. The routes of the roads travelled by car were recorded by GaiaGPS, and the OpenStreetMaps roads' layer was used to complete the paths documented in the field. Moreover, through the mobile application Mapillary, the streets were characterized with a continuous sequence of photographs (Mapillary is a free service offered by OpenStreetMap based on crowdsourcing which allows users to continuously photograph an entire route taken by car, bicycle or foot, providing a street view service even in areas of the Globe not reached by Google Maps). As can be seen in Fig. 6(b), almost all the roads in the study area are unpaved roads and, as stated by local experts, their average construction cost is 1500 MZN per meter (24 USD per meter).

2.3. Damage assessment

2.3.1. Residential buildings

The damage to residential buildings was estimated through damage models which, generally, establish a relationship between local hazard features, the vulnerability of the exposed asset and the expected degree of damage. The so-called "relative damage" is expressed as a ratio, ranging from 0 to 1, of the value of the exposed element. Since no damage models had been produced specifically for this

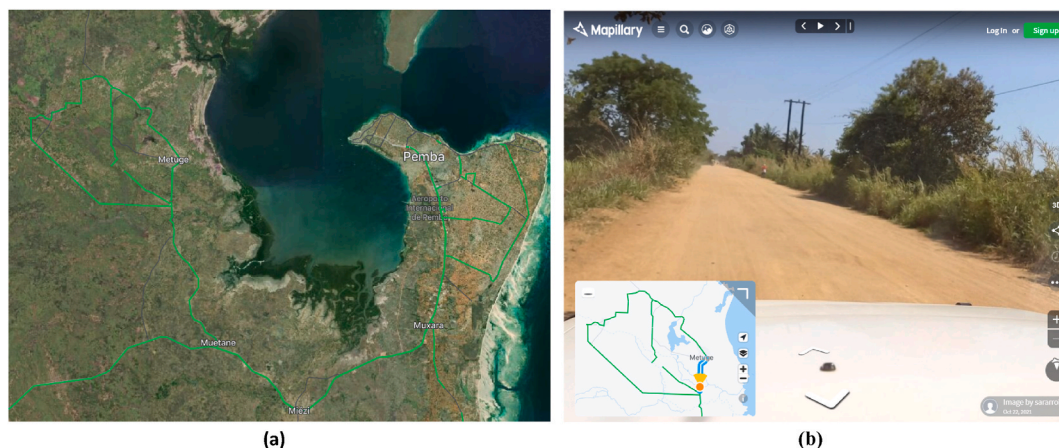


Fig. 6. (a) Screen of the Mapillary web page relative to Pemba and Metuge district; the green lines depict the roads for which photographic documentation is available. (b) Picture stored in Mapillary of the road connecting Namuapala to 25 de Junho.

region, three models developed for other countries were used to perform the damage assessment, as they refer to buildings typologies similar to those present in Metuge. All these models correlated relative damage to water depth at the individual building level (i.e., at the microscale) for different construction typologies. In particular, the first model [47] presented four expert-based curves for different building construction materials present in Ethiopia; the second source obtained by expert judgement [48] provided an empirical damage function for wattle and daub buildings in Khando River catchment in eastern Nepal; the third and last source [35] provided damage models for three building typologies present of the Southern Shire Basin in Malawi. The adopted models are presented in Fig. 7 (a), with only reference to construction typologies observed in the investigated area (traditional and improved buildings). In order to cope with the uncertainty in using non-site-specific models, three separate damage assessments were conducted: worst-case, best-case, and median estimate. These consider the highest, lowest, and median relative damages supplied by the different models for any water depth, respectively. While the worst and best-case estimates provided useful boundaries for understanding potential extremes, the median estimate formed the basis of our analysis. The models obtained by considering the worst-case, best-case, and median estimates for traditional and improved buildings are depicted in Fig. 7(b).

Coherently with the adopted model, the analysis was performed at the level of individual buildings. This choice was also supported by the need of properly identifying affected houses within the villages to recognize social vulnerabilities, need for assistance and temporary shelters.

The relative damage was evaluated excluding water depths below 0.15 m, as they were considered to impose no damage on a structure. The absolute damage was finally obtained by multiplying the relative damage times the construction cost of damaged houses.

2.3.2. Population

The flood impact on people is a controversial and still not well-defined issue, including physical damage like injuries and death, discomfort, impacts on mental and social wellbeing, loss of cultural identity and social cohesion, etc. [49–52]. Its full characterisation requires the availability of several models and data that are not available in the study area. For this reason, the potential damage to population was estimated using the number of exposed people as a proxy, calculated from the number of impacted residential buildings resulted from the microscale damage assessment and the average number of inhabitants per house. The latter was obtained starting from the knowledge of the total population and the number of buildings per quarter gathered from the field survey, and it was equal to 5 to 6 people/house.

2.3.3. Road and hospital accessibility

The impact on roads was assessed using three different types of analysis. First, the physical damage was studied in relative and absolute terms. Second, the usability of the roads was assessed (called “indirect damage” in the following). Third, a map of the road network accessibility was produced based on the previous evaluation.

As for the residential buildings, damage to roads was computed using a depth-damage function available in the literature which, although originally intended for a different context, was developed for roads with physical and vulnerability characteristics similar to those present in the study area. The model, depicted in Fig. 8, was proposed by Ghimire & Shrestha [53] based on damages observed in previous events on unpaved roads in western Georgia. To apply this function, the roads were subdivided in segments of 12.5 m (equal to the cell size of the raster file obtained from the hydraulic model) and the water depth of the corresponding cell was assigned to each segment. Finally, the absolute damage was computed multiplying the relative damage by the construction cost.

The indirect damage was assessed by studying the impact of flooding water on the stability of pedestrians and vehicles possibly present on a road. The stability was evaluated with the model proposed by Lazzarin et al. [54] who introduced a non-dimensional stability parameter, that combines water depth and flow velocity. As for the previous analysis, the road network was subdivided in segments to which the hydraulic variables were assigned. Then, applying the model two maps were produced showing segments that could not be “used” during a flood (one for individuals and one for vehicles).

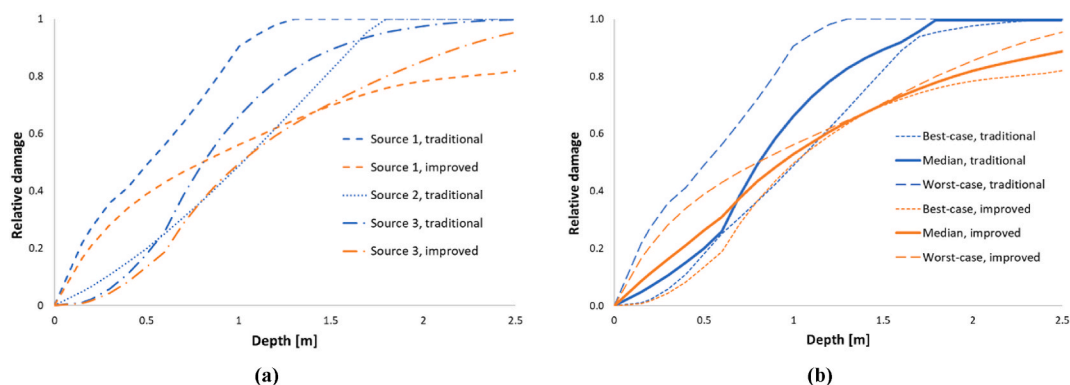


Fig. 7. (a) Literature damage models used for the traditional and improved buildings. Source 1: Englhardt et al., [47]; Source 2: Thapa et al., [48]; Source 3: Wouters et al., [35]. (b) Best-case, worst-case, median curves for traditional and improved buildings.

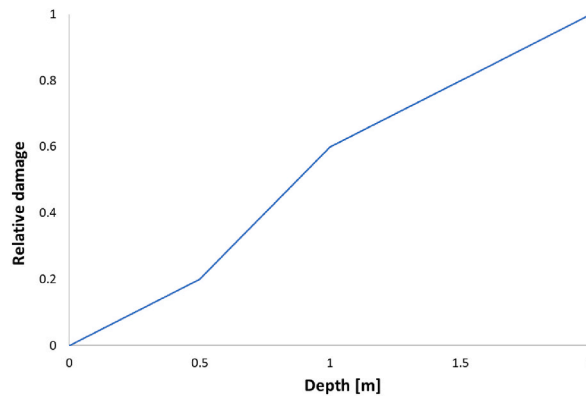


Fig. 8. Damage curve developed by Ghimire & Shrestha, [53] for unpaved roads.

Finally, for each return period, accessibility maps were produced starting from the results of the stability assessment. Whenever a segment resulted impracticable according to stability analysis, the entire road containing that segment was considered unusable as a transportation link within the district. This was used in combination with the information of healthcare services and the population data collected in field to estimate the hospital target population without access to the services during a flood.

2.4. Risk assessment

The estimate of risk most used in flood studies [55,56] is the Annual Average Damage (AAD), which was also used in this analysis. It is expressed as the integral of damage, D , as a function of its exceedance probability, p :

$$AAD = \int_0^1 D(p) dp$$

and was computed as the area below a damage-frequency curve created, in our assessment, with the estimated damages for the four return periods that were considered. The curve was built by assuming that the probability of exceedance of the damage be the same as that of the hydrological event. In the case of buildings and roads, the damage-frequency curves were built for the absolute damage, whereas for the population the curve considered the number of exposed people. In terms of spatial scale, risk for the roads was assessed for the whole district, while risk for population and residential buildings was determined for each target village separately.

3. Results

3.1. Hazard assessment

The hydrographs obtained from the hydrological modelling and used as inflow conditions for the hydrodynamic simulations are depicted in Fig. 9. Fig. 10 presents instead the spatial distribution of the maximum water depth obtained for a return period of 10 years (results for this return period will be shown as a reference in the present section). Identifying a clear river channel from the hazard map was challenging. Instead, the map exhibited numerous disjointed and irregularly shaped flooded areas. This was primarily attributed to the coarse resolution and the irregularities of the DEM used for this analysis. Nonetheless, a distinguishable track of higher water

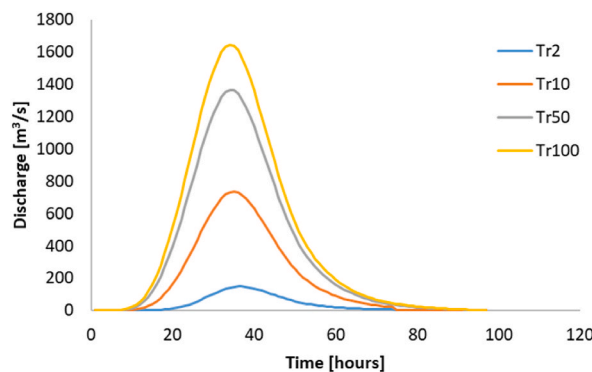


Fig. 9. Flow hydrographs for each return period (Tr).

depths could be observed across the domain from north-west to south-east. This track corresponded to the surroundings of a river branch detected in the field survey we conducted in 2019. In the northern section of the domain there were flooded areas with water depths ranging between 1.5 and 2 m. The field surveys confirmed the presence of another river branch in that area, exchanging water with the lake situated to the north of 25 de Junho (for more details on the river branches see Ref. [31]).

For all the considered scenarios, the village of Namuapala appeared to be the most affected by the flood, with almost the entire village area inundated and most of its relevant buildings impacted, including the school. The district hospital, located in the north-east part of the village, was not directly affected by the flood but it was surrounded by water in almost all the simulated scenarios. The refugee camp, also located in the east, in its southwest part was submerged with water depths lower than 1 m. Nacuta also resulted extensively covered with flood-water, while in 25 de Junho the flooded area was concentrated in the west for all the return periods. In Nacuta and 25 de Junho the water depths did not exceed 1 m.

3.2. Damage assessment

3.2.1. Residential buildings

The damage assessment for residential buildings was represented in terms of both relative and absolute damage. The damage was depicted in a qualitative manner ranging from “Very Low” to “High”. This range was obtained by distributing the damage results, for all return periods, in quartiles for each village. Fig. 11 shows the map of absolute damage (median estimate) for 10-year return period and the village of Namuapala, which was the most affected for the events with 2- and 10-year return period. Nacuta exhibited the highest damage to buildings for return periods higher than 50 years, while 25 Junho was the least damaged village for all the scenarios.

3.2.2. Population

Table 2 reports the total number of people affected per village and the percentage of the total population they correspond to. Coherently with the damage analysis for residential buildings, the population of 25 de Junho was the least exposed to floods for all the scenarios. Furthermore, for all the scenarios except the 2-year one, Nacuta presented larger numbers of affected people compared to Namuapala. In fact, for the scenario with higher return period, although the damage to buildings was larger for Namuapala due to higher water depths, the number of houses exposed was higher in Nacuta, resulting in a higher number of exposed inhabitants. However, the higher numbers of people in Nacuta represented a lower percentage of the total population than in Namuapala.

Additionally, for Namuapala, one can notice an unexpected higher number of exposed people for the 50-years return period scenario with respect to the 100-years return period scenario. This is due to minor differences in the results of the hydrodynamic simulation. In fact, some cells of the computational mesh are flooded in the 50-year event but not in the 100-year event. These specific cells intersect with buildings, resulting in a higher number of exposed people in the 50-year return period scenario.

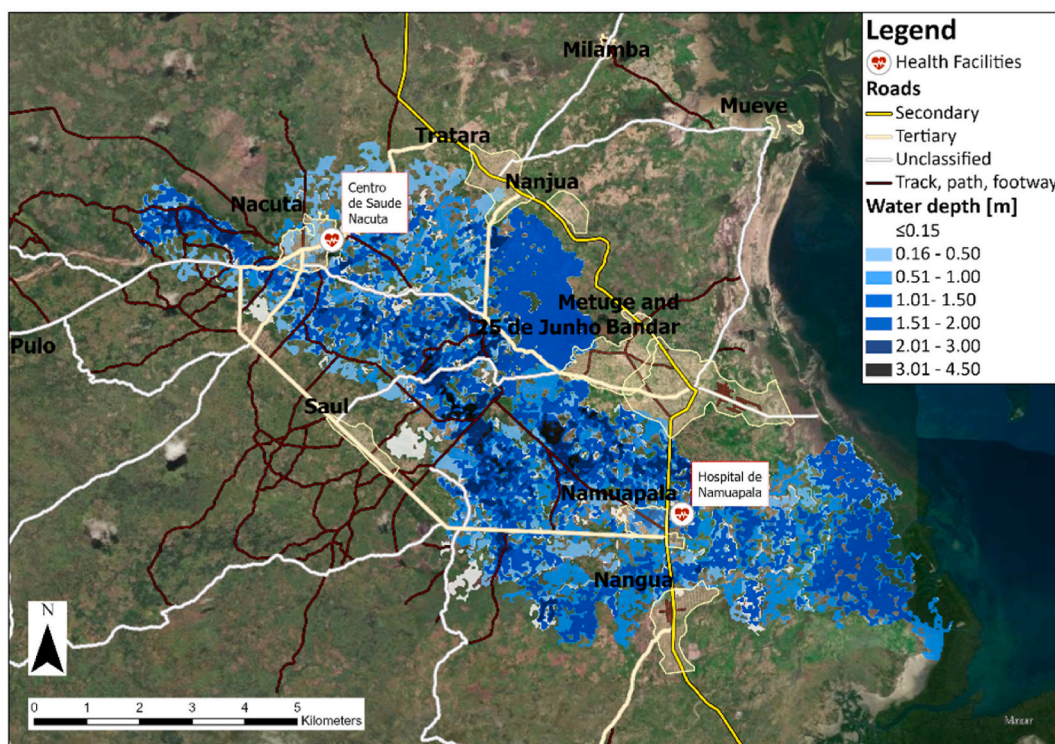


Fig. 10. Hazard map at district level for a 10-year return period, villages, road network and healthcare services.

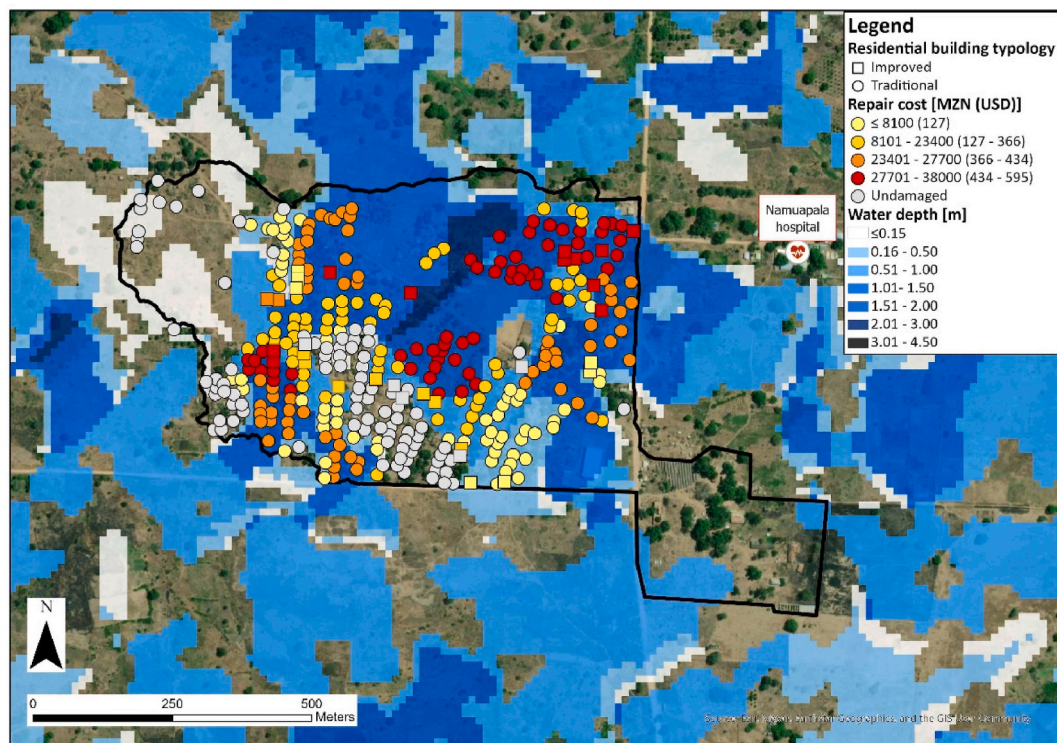


Fig. 11. Absolute damage assessment at microscale, for Namuapala and 10-year return period. The legend presents repair costs in Metical (MZN), with the corresponding value in United States Dollars (USD) shown in parentheses; a conversion factor of 1 MZN = 0.0157 USD is applied.

Table 2

Total number and percentage of affected people in 25 de Junho, Nacuta and Namuapala.

Return period		2 years	10 years	50 years	100 years
25 de Junho	N. people	160	220	281	281
	%population	3	4	5	5
Nacuta	N. people	122	2938	3140	3450
	%population	2	41	44	49
Namuapala	N. people	633	1469	1529	1507
	%population	27	62	65	64

3.2.3. Road and hospital accessibility

The length of the damaged roads varied between 16 and 47 km, respectively for the return periods of 2 and 100 years, compared to a total length of the road network around the domain of 190 km. Accordingly, the stability analysis returned a minimum of 33 km and a maximum of 66 km of inaccessible roads.

The accessibility to health facilities was studied counting the number of people per village with no access to healthcare services during a flood event. Results revealed that for the return periods of 50 and 100 years the centre in Nacuta could not be accessed from any village that it serves, while the accessibility to the Namuapala hospital was prevented for return periods larger than 10 years. The results for the 10-year return period analysis are reported in Fig. 12, which depicts the accessibility assessment, and in Table 3 where the accessibility to health services is summarized in terms of number of people with and without access to the services.

3.3. Risk assessment

The results of the risk assessment are summarized in Table 4 and in the risk map depicted in Fig. 13. Namuapala presented the highest risk in term of residential buildings and Nacuta exhibited the largest number of population at risk, while 25 de Junho resulted to be the least impacted village (see Table 5).

For the residential buildings, although Namuapala was generally the most affected village in both the best-case and median estimates, it was not the most damaged under the worst-case. This is due to a combination of several factors: the number of flooded buildings, the expected water depths, and the differing shapes of the damage “curves” (worst-case, base-case, and median). Generally, Namuapala is exposed to a higher hazard level than Nacuta. This justifies the greater risk in Namuapala, despite the lower building

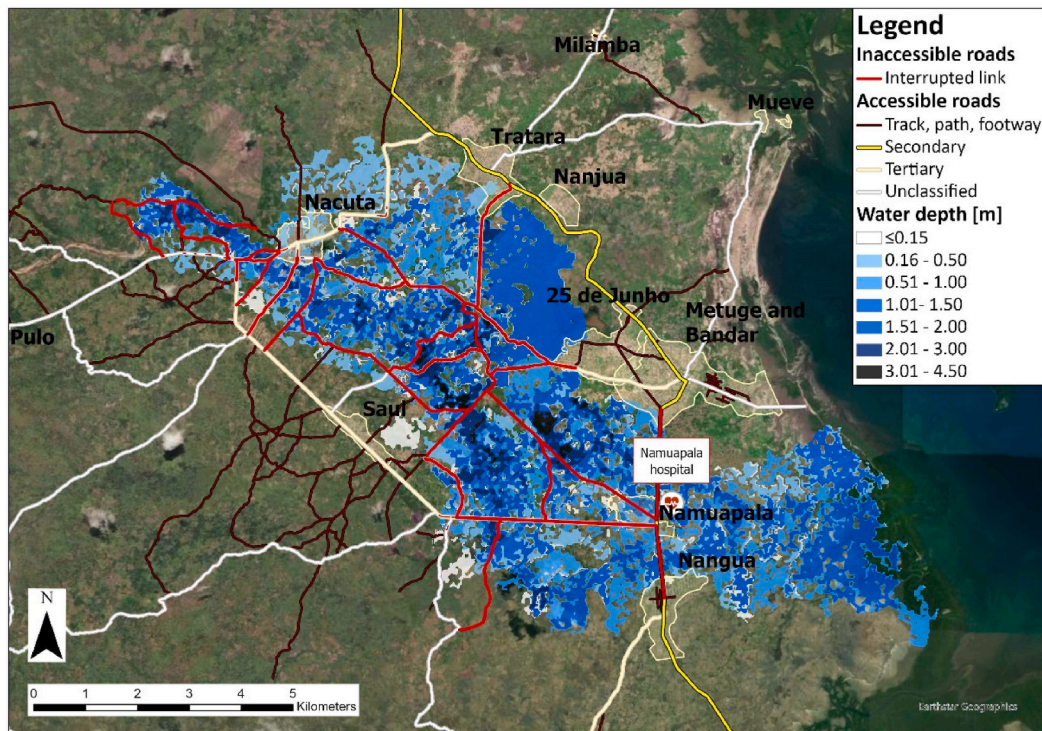


Fig. 12. Accessibility map for a 10-year return period.

Table 3

Result of accessibility assessment to health facilities for 10-years return period.

Health facility	People with access	People without access	Villages without access
Namuapala hospital	–	86,866	25 de Junho, Bandar, Metuge, Milamba, Mueve, Nacuta, Namuapala, Nangua, Nanjua, Pulo, Saul, Tratara, Unidade
Nacuta centre	15,289	8913	Saul, Unidade, Pulo

count compared to Nacuta, when the best-case and the median curves are implemented, which show limited damage values and an upward-concave shape at low water depths. Conversely, the curve for the worst-case scenario not only exhibits a downward concavity but also shows significant damage values even for low water depths. This prevents the higher hazard level from compensating for the lower number of buildings in Namuapala.

Table 4

Result of risk assessment: Annual Average Damage of buildings (median estimate), population, and roads. For roads and residential buildings, the damage per year is expressed in Metical per year (MZN/year), with the corresponding value in United States Dollars per year (USD/year) shown in parentheses; a conversion factor of 1 MZN = 0.0157 USD is applied. For residential buildings, the highest (worst case) and lower (best case) AAD obtained are reported in brackets.

	Residential buildings (Microscale)	Population [People/year]	Roads
25 de Junho	191,000 MZN/year (2974 USD/year) [Worst case: 140,000 MZN/year Best case: 284,000 MZN/year]	139	
Nacuta	1,512,000 MZN/year (23,664 USD/year) [Worst case: 3,149,000 MZN/year Best case: 1,264,000 MZN/year]	919	
Namuapala	1,625,000 MZN /year (25,432 USD/year) [Worst case: 2,329,000 MZN/year Best case: 1,385,000 MZN/year]	713	
Metuge district	3,328,000 MZN/year (52,087 USD/year) [Worst case: 5,762,000 MZN/year Best case: 2,789,000 MZN/year]	1771	14,730,000 MZN/year (230,527 USD/year)

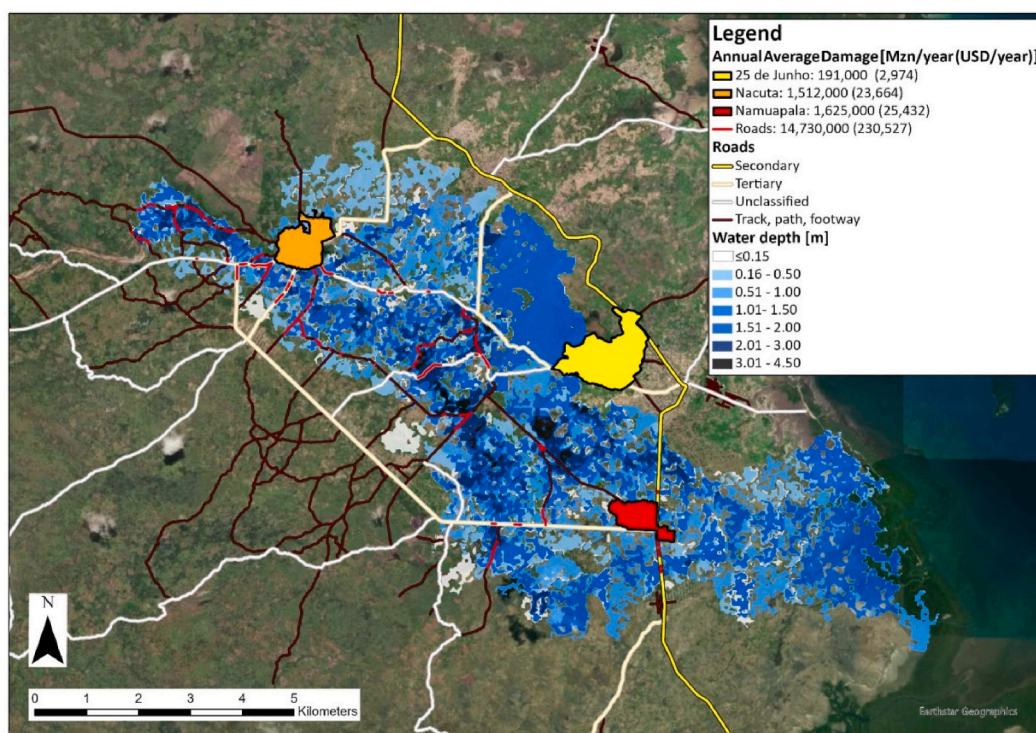


Fig. 13. Risk map. The villages are shown in a colour scale, from green to red, according to their AAD and the roads are depicted as per their category and coloured in red if they present any level of damage. In the legend, the median AAD is expressed in Metical per year (MZN/year), with the corresponding value in United States Dollars per year (USD/year) shown in parentheses; a conversion factor of 1 MZN = 0.0157 USD is applied. The hazard map corresponds to the 10-year return period.

The analysis on the whole district showed that the AAD of the roads was more than four times that of residential buildings (median estimate).

4. Participatory approach

One of the objectives of the PRONTIDÃO project was to involve various stakeholders, from governmental to community level, by means of participative processes, increasing the building capacity of local authorities and empowering the resilience of local population. To achieve the objective, several meetings were organized between 2021 and 2022. The meetings involved three principal types

Table 5

Participatory events: objectives, duration, authorities involved.

Event	Trainings	Round table (presentation of the results)	Workshop with CLGRD of Namuapala
Objective	Knowledge transfer	Validation	Validation and resilience enhancement
Duration	10 days	2 days	2 days
Participants	SDPI; INAM; ARA-NORTE; INGD; INGD CENOE; DPADT; INAHINA; SPA; DPOP; SPI; Municipal Council of Pemba; University of Lurio	SDPI; SDAE; INAM; ARA NORTE; INGD; INGD CENOE; SPA; DPDTA; DPOP	CLGRD

ARA-NORTE: Administração Regional Agua of North Mozambique (*Regional Administration of Water*).

CLGRD: Comité Local de Gestão de Risco de Desastre (*Local Disaster Risk Management Committee*).

DPADT: Direção Provincial de Ambiente e Desenvolvimento Territorial (*Provincial Directorate of Environment and Territorial Development*).

DPOP: Direção Provincial de Obras Publicas (*Provincial Directorate of Public Works*).

INAHINA: Instituto Nacional de Hidrologia (*National Institute of Hydrology*).

INAM: Instituto Nacional de Meteorologia (*Meteorology National Institute*).

INGD: Instituto Nacional de Gestão de Desastre (*National Institute for Disaster Risk Management and Reduction*).

INGD CENOE: Centro Nacional Operativo de Emergência (*National Operative Emergency Center*).

SPA: Serviço Provincial de Ambiente (*Provincial Service for the Environment*).

SDPI: Serviço Distrital de Planeamento e Infraestruturas of Mecufi and Metuge (*District Planning and Infrastructure Service*).

SPI: Serviço Provincial de Infraestruturas (*Provincial Service of Infrastructures*).

of activities, including trainings for local technicians, round tables with representatives of district and provincial institutions, and a co-mapping activity with the volunteers of the CLGRD (Comité Local de Gestão de Risco de Desastre, the local civil protection) of Namuapala. All these events, summarized in Table 5, contributed to the fulfilment of the three main sub-objectives of the participatory process, namely the transfer of knowledge, the validation of the results elaborated, and enhancing the resilience of the population.

4.1. Knowledge transfer

Three workshops on flood risk assessment were held, involving different members of the authorities listed in Table 5. The workshops were devoted to the application of the complete modelling chain presented in this manuscript and to discussions with the attendees, covering the present state-of-the-art practices in Mozambique for flood risk assessment, and the availability and quality of data. From the discussion it was understood that there has been an increasing focus on utilizing, for example, GIS products to assess flood risk in a more technical manner. However, precipitation data registered in Mozambique have a daily temporal resolution, thus preventing the modelling of scenarios characterised by short duration and high intensity rainfall, which are typical for the study area. Furthermore, the incorporation of damage models remains currently absent.

Through these workshops, the local stakeholders were provided with a better understanding of the modelling process and requirements. They recognized the importance of data and the interrelation of past and present studies and, consequently, the importance of collaboration. After training activity, the technicians expressed interest in the continuation of similar training programs, also highlighting the need to address other types of hazards, including drought, fire, and coastal erosion.

4.2. Validation

The two-days co-mapping activity held with the Namuapala CLGRD contributed the most to assessing the reliability of the hazard maps. In the first day, the members of the committee were asked to draw frequently flooded areas on a map of the village, specifying their characteristics (maximum water depths and typical duration). The CLGRD described two events, namely the flood from the Kenneth cyclone in 2019 and a heavy rain of 2021; the two events were found similar to those returned by the hydraulic model for 10-year and 2-year return period scenarios, respectively.

The result of the co-mapping activity (Fig. 14 and Table 6) allowed the subdivision of the village into six zones (old zone, safe inhabited zone, safe expansion zone, hospital zone, southern zone, IDP camp) presenting quite homogeneous hazard characteristics.

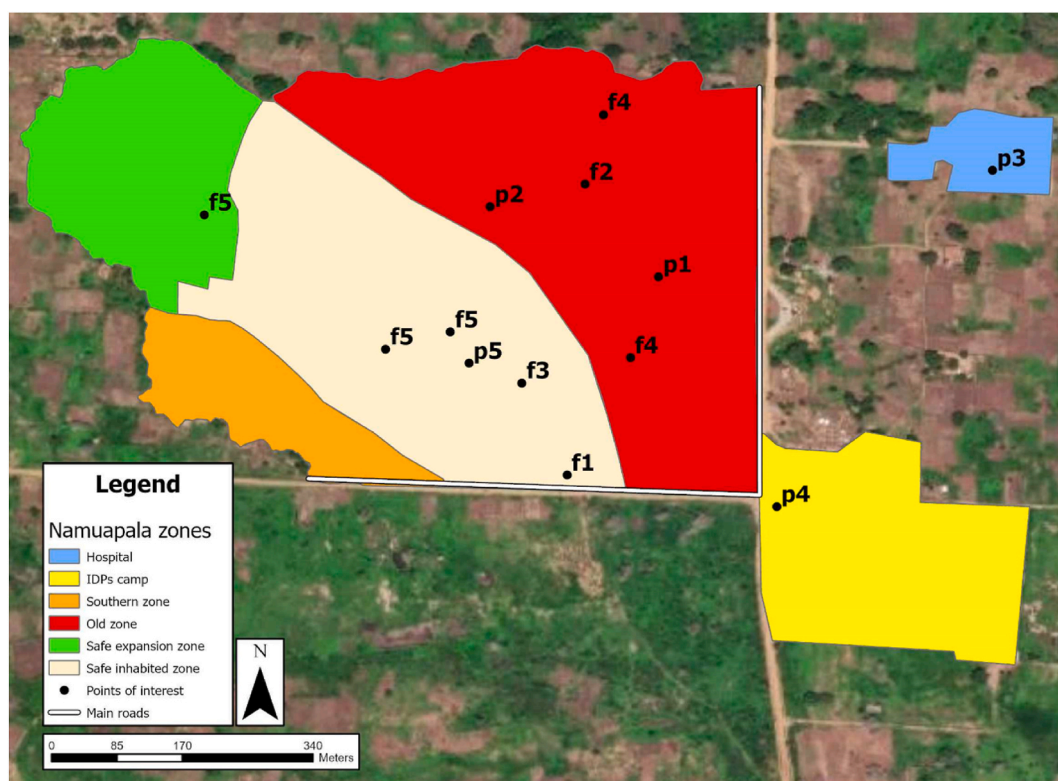


Fig. 14. Subdivision of Namuapala into 6 zones and points of interest for CLGRD. Points: p1 = headquarter of CLGRD; p2 = school; p3 = hospital; p4 = market; p5 = emergency kit house; f1 = leader house; f2 = house of CLGRD coordinator; f3 = house of CLGRD deputy coordinator; f4 = house of radio controllers; f5 = mosque (radio place).

Among these areas, those most prone to risk were the old zone and southern zone where the water may persist for weeks, pointing at the need for drainage channels to facilitate faster runoff. The area labelled as safe expansion zone was reported as owned by the church and presently used for agricultural purposes by Christians. As can be noticed in Table 6, the maximum water depths reported by people involved were generally similar to the water depths obtained from hydraulic modelling for the 2-year and 10-year return periods, except for an overestimation of the water depth in the *safe inhabited zone* and the *safe expansion zone* and an underestimation in the *hospital zone* for the 10-year scenario.

Moreover, the CLGRD members pointed out some relevant assets (labelled in the map of Fig. 14 as “p-” to depict strategic buildings where access during an emergency is important and “f-” to refer to key buildings for emergency communication) whose accessibility was described during the 2019 and 2021 events. Consistently with the hydraulic model’s results, they reported that the school (p2) is placed in a hazardous area and that two main roads are inaccessible for a 10-year return period event. Moreover, they confirmed the inaccessibility of the hospital (p3) even if the model average water depth was quite low compared to that declared by the committee. However, in line with the study findings, the CLGRD did not report any damage to the hospital, since its floor is about half a metre above the surrounding ground level.

The co-mapping activity implemented with the Namupala committee was reproduced in the other target villages. While safe and risky areas delineated by the volunteers in Nacuta confirmed the model’s findings, the CLGRD members of 25 de Junho emphasized the presence of additional flooded areas resulting from heavy rainfall. However, this evidence could not be captured by the hydrologic-hydraulic model presented here.

Considering the damage assessment, the classification of residential buildings into just two vulnerability classes appeared reductive to the stakeholders of the round table, since there could be buildings with different levels of vulnerability. Although this was acknowledged as true, such simplifications were necessary for modelling capabilities. On the contrary, the feedback from the workshops with the technicians and the CLGRD validated the choice of distinguishing the residential buildings into two classes. Furthermore, the committee confirmed that traditional houses are more vulnerable than improved ones, although the latter need more time and resources to be rebuilt.

4.3. Enhancement of population resilience

The only available emergency plan for the study area was developed for the entire district of Metuge and does not provide effective guidance for emergency management at local level by defining safe areas, actions and roles. Thus, the second day of co-mapping activity was devoted to discussing possible improvements in current communication and awareness approaches, as the volunteers of the committee are the first ones acting in case of a warning. The discussion highlighted the importance of placing signals within the village area that could help the volunteers informing the population both in peacetime and during alerts. Through brainstorming, four types of signals were sketched: *safe area*, *flood risk area*, *area where it is dangerous to build* and *evacuation route*. The signals of Fig. 15 follow the drawing of the volunteers, in order to make the reception of information as immediate as possible for the entire population, including people incapable of reading. The placement of such signs can be particularly beneficial to IDPs, who do not have a representative within the CLGRD and are not aware of the flood risk in the area. The location of each signal has been drafted considering the characteristics of the six zones defined on the previous day, placing them in areas where the visibility would be guaranteed for the entire community, including refugees. Finally, the map of Fig. 15 was produced and provided to each CLGRD member, summarizing the information collected during the 2-day activity. The map depicts safer and risky areas, relevant buildings for the committee (such as the house where the emergency kit is stored), public and religious buildings to help in orientation, and the positions of the signals. The design of the awareness campaign was replicated in other target villages enabling the improvement of communication and the increase of the awareness of the whole community of the district.

Table 6

Zones defined with the CLGRD, and related hazard characteristics based on the results of the model (TR = 10 years and TR = 2 years) and the information provided by the committee (2019 and 2021 floods).

Zones	Modelled scenario: 10y return period	CLGRD: 2019 event		Modelled scenario: 2y return period	CLGRD: 2021 event	
	Average Depth	Max. Depth	Water permanence time	Average Depth	Max. Depth	Water permanence time
Old zone	1.27 m	1.00 m	2 weeks	0.23 m	0.50/0.80 m	5 days
Safe inhabited zone	0.97 m	0.10 m	–	0.18 m	–	–
Safe expansion zone	0.27 m	–	–	0.05 m	–	–
Southern zone	1.12 m	0.50 m	1 week	0.14 m	0.20 m	–
Hospital zone	0.08m	0.50 m	–	0.00 m	–	–
IDP Camp	0.73 m	1.00 m	–	0.18m	–	–

5. Discussion and conclusions

5.1. Result significance

In this paper, we presented a chained hydrological-hydrodynamic-risk assessment for river floods that was applied to the Metuge District in Northern Mozambique. The three essential components of risk (hazard, exposure, and vulnerability) were accounted for in a fully quantitative analysis, which represents a novelty with respect to most of the available works conducted in other data-poor countries [13–18] where damage and, thus, risk assessments were performed in qualitative terms. The quantitative risk assessment was obtained implementing a methodology designed to cope with data and modelling deficiencies which typically characterize low-income countries, making it analogously applicable in other similar contexts. In particular, the hazard assessment relied on global data which can be treasured also in other data-scarce regions. The software employed in the analysis are both freely available and widely used in the field of flood hazard assessments, and then easily accessible to other researchers and practitioners. The damage estimates were derived applying literature sources developed for similar building and road typology and performing an intensive field survey. This survey utilized a smartphone application, making the methodology straightforward to replicate in other contexts. Furthermore, the participatory process can be easily implemented in other places with stakeholders operating at different levels.

As a result, the assessment on population revealed an average of 1771 people at risk per year, representing more than 1 % of the district's population. The risk associated with residential buildings and roads resulted in an annual average damage of almost 300,000 USD/year (median estimate). When divided by the district population, this corresponds to 0.5 % of Mozambique's GDP per capita (USD 608 in 2023). This value aligns with the impact of significant flood events occurred in the past in other countries; for example, the 2002 Elbe flood in Germany accounted for approximately 0.7 % of the national GDP [57]. However, the impact of floods can be more severe in low-income countries, where recovery resources are more limited with respect to high-income countries and when income inequality can be observed. In this regard, it is worth noting that Mozambique presents the eleventh highest GINI index globally, according to the World Bank. The fact that Metuge is in one of the poorest provinces in the country further increases the potential impact of a flood.

5.2. Data

Damage modelling, especially if it is performed at the microscale, requires detailed information on the exposed assets and their vulnerability. For the residential sector, the minimum pieces of information are the spatial distribution of the buildings and their monetary values, combined with the construction type [58]. To assess the damage to economic activities, it is first important to identify which main sources of income are relevant for the communities. For the infrastructures, it is essential to have, at least, a comprehensive spatial representation of the roads crossing the area, their characteristics (e.g., main, secondary, pedestrian or paved and unpaved) and costs [59], as well as to detect the presence of strategic buildings along with their physical features (e.g., construction material, elevation above ground level, number of floors) and population market area. Finally, to estimate the population exposed to flood risk and the number of people who need assistance during an emergency, updated population data with an adequate spatial resolution are recommended [60–62]. However, none of these data was available for the study area. Therefore, the field survey became imperative for the objective of risk estimation. Due to the substantial resources needed for fieldwork we recommend, as a best practice, promoting the multi-usability of collected data, not only for risk modelling but also for disaster forensics and loss accounting [63,64]. This was partially achievable in the investigated area because evidence regarding past damage or water elevation was lacking.

For the hazard assessment, collecting detailed topographical and bathymetric information in the field was unfeasible for the vast area that was investigated. Therefore, hydrological and hydraulic modelling referred to the global sources available, although characterised by poor resolutions.

5.3. Validation and stakeholder involvement

The absence of observed data and validated models in the study area made the comparison with stakeholder judgment and expectations crucial for assessing the reliability of the obtained results. Moreover, the participatory activities implemented through multiple meetings with cross-level stakeholders enabled information to be obtained at different spatial scales (from the village to the district level) and to correct some of the assumptions made in the first modelling stages.

With respect to the hazard, the process was key to validate the obtained results. In the prior work of Rrokaj et al. [31], flooded areas returned by hydro-dynamic modelling were compared to the extension of the flooded areas during Cyclone Kenneth (determined by processing satellite images); the comparison was relatively satisfactory but also carried some limitations, like the insufficient temporal resolution of satellite imagery to capture the maximum flood extension, as also highlighted by previous scholars [65–68]. In this regard, the discussion with the CLGRD provided not only information on the maximum flood extensions, but also on the maximum depths and flood water persistence.

Regarding the damage assessment, the comparison with local stakeholders allowed instead to test modelling choices. For example, the choice of distinguishing between only two building vulnerability classes was judged too simplistic by stakeholders, and under representative of the heterogeneity of the buildings of the villages. However, a more detailed classification would have probably turned out to be useless given the deficiency of damage models and records in Mozambique, not justifying a much more detailed field survey.

Overall, the modelling chain presented here was able to capture the diversity of hazard features and damage levels within a village

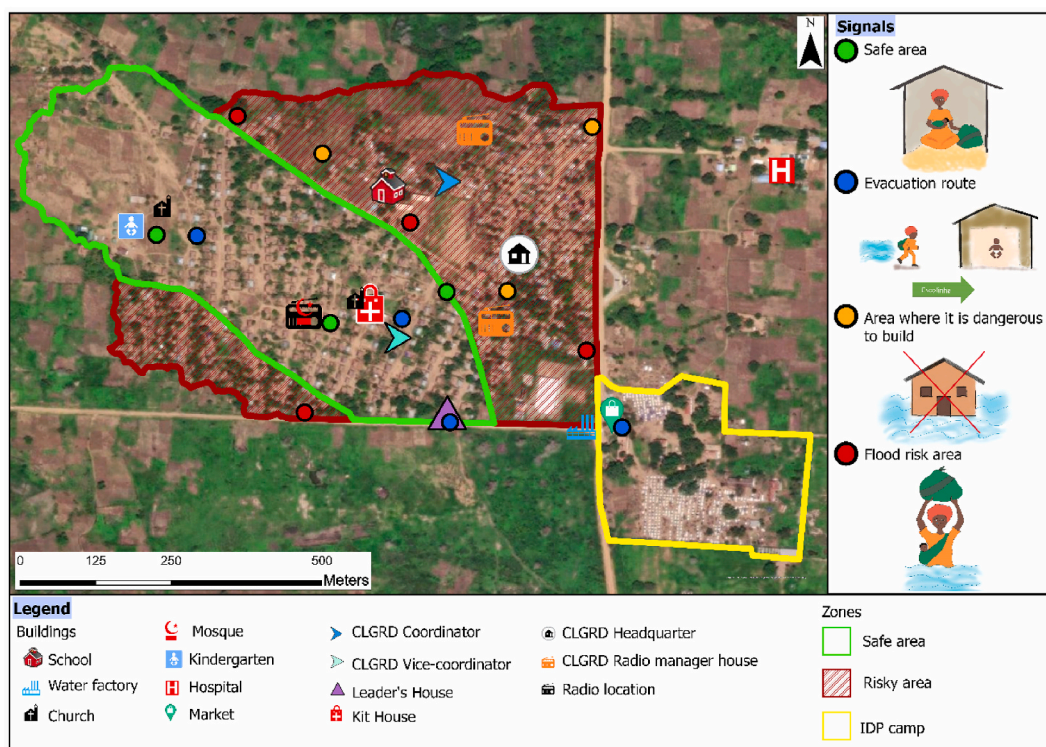


Fig. 15. Map produced with the CLGRD and finally delivered.

(but even within a quarter) despite the use of global data and different sources of uncertainty that will be mentioned below, demonstrating the validity of the implemented approach. Nonetheless, this study responded to the necessity highlighted by previous scholars for participatory approaches, towards the integration of local knowledge into flood risk assessment and management [69–73].

5.4. Benefit for local communities

The stakeholders acknowledged the significance of the present study and expressed the benefits of incorporating it into new contingency and adaptation plans.

The co-mapping activity with the CLGRD of Namuapala evidenced the need to ensure local awareness and for a local emergency plan that is clear, practical, effective, and easily implementable during emergencies. The hazard and damage maps produced at the microscale are especially suited for this, for example, by enabling the identification of safe and shelter areas and of possible isolated villages, planning of rescue and support activities and the definition of evacuation routes.

As emerged from the discussion during the round table, the main interest of governmental entities lies in the study of structural mitigation measures and how to execute them along with priorities of intervention. The results and methodologies presented in this paper constitute valuable information to evaluate and prioritize these measures [74–76]. The knowledge of the AAD for the different exposed assets, at the district level, is a fundamental information of any cost-benefit analysis required to implement effective risk mitigation measures. However, further data on the costs of various interventions are needed. Likewise, the discussion with the CLGRD of Namuapala helped identify small-scale interventions, i.e., designed at the village scale, such as drainage channels in the two riskiest areas. The microscale results enable the evaluation of such interventions, which can be even more feasible than structural measures in the Mozambican context, given the high cost of the latter for a low-income country [77].

5.5. Prospects

In the light of the feedback obtained in the participative process, prospects from both an implementation and a scientific perspective have been recognized.

With respect to the implementation of the methodology in the study area, further studies should be conducted in each village to identify possible local structural and non-structural mitigation measures. In particular, the activity with the CLGRD allowed the identification of vulnerable groups within the community such as IDPs or people leaving in potentially highly damageable houses. Therefore, future research should focus on developing emergency and adaptation plans in collaboration with community members to ensure the creation of tools tailored to the specific needs of each community. Moreover, the present modelling was limited to fluvial

processes with generating and migration of a riverine flood. However, the co-mapping activity also revealed the presence of additional flooded areas due to pluvial floods. Incorporation of more active processes into the quantification of natural risk is, therefore, desirable.

From the scientific side, the feedback obtained in the participatory process was encouraging in terms of the possibility of models utilizing a uniform rainfall on the entire watershed to quantify flood risk. However, the scarce data availability was an obstacle to generating flood events that could account for the spatial variability of occurrence probability at the catchment scale. The assumption of homogeneous return periods of flood peaks throughout a large catchment, as in this case, may be unrealistic and may bias risk estimates for specific return periods [80]. Nevertheless, the existing methodologies that consider the spatial variability of floods require consistent flow [81–84] or rainfall [85,86] data at multiple sites. This problem could potentially be bypassed in data scarce regions by exploring stochastic models for generating rainfall events [87–89].

5.6. Limitations and uncertainties

A most obvious limitation of the data used in the present work is related to the accuracy of the topographic data. It is well known that even refined DEMs lack a satisfactory representation of river reaches. Moreover, satellite-derived elevation models are normally characterized by low horizontal resolution and large vertical uncertainty. For the context studied in this manuscript, no alternative was available as ground surveys for a so large area would have been unfeasible.

The same is true also for hydrological data; in the absence of detailed and long records of rainfall and discharges, one can just rely upon interpolated data for rainfall, conditioned to sparse (in space and time) gauging.

Damage assessment is an even newer business than modelling of natural processes, therefore data and tools are fewer. Despite all the exposure data collected in field, the location of traditional houses was detected by means of satellite images which might have introduced errors in the actual water depth impacting any certain building. Moreover, the paucity of tools for quantitative analysis was overcome adopting models developed in other countries which, however, can affect the accuracy of the results. In fact, depth-damage curves, even if developed for similar assets, are meant to be site-specific.

Furthermore, it is important to emphasize that the flood risk assessment presented in this study is based on current conditions, as incorporating future changes due to climate change remains highly challenging. In fact, accounting for non-stationary conditions in flood risk studies is complex, given that risk is the result of the interactions between hazard, exposure, and vulnerability, all of which change over time [78]. Moreover, climate projections at regional, and thus also local, scales carry significant uncertainties [79].

This complexity and uncertainties are amplified in low-income countries due to the scarcity of data, which not only complicates projections but also limits the accuracy of current state analyses. Nevertheless, improving our understanding of current conditions in data-poor contexts, while imperfect, is still a valuable step toward better risk assessments which, for this study, can serve to put in a clear light the criticalities of a territory. In fact, the quantitative findings presented in the manuscript should be better read in comparative terms rather than in absolute terms.

CRedit authorship contribution statement

Sara Rrokaj: Writing – original draft, Methodology, Investigation. **Daniela Molinari:** Writing – review & editing, Methodology, Conceptualization. **Charlie Dayane Paz Idarraga:** Visualization, Formal analysis. **Ana Maria Rotaru:** Writing – original draft, Formal analysis. **Zeynep Ergün:** Formal analysis. **Abdul Anza:** Validation. **Margherita Porzio:** Resources. **Alice Costa:** Supervision. **Alessio Radice:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sara Rrokaj reports financial support was provided by Istituto Oikos. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data produced are available at the following link: <https://doi.org/10.5281/zenodo.14225604>. Global data used in the hydrologic and hydraulic modelling are available from the cited sources.

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